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COMPOSITES THEORY AND PRACTICE

Andrzej Posmyk

Silesian University of Technology, Faculty of Transport, ul. Krasińskiego 8, 40-019 Katowice, Poland
Corresponding author. E-mail: andrzej.posmyk@polsl.pl

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METHOD OF INVESTIGATING THERMAL CONDUCTIVITY OF INSULATING COMPOSITE MATERIALS DESIGNED FOR MEANS OF TRANSPORT

The paper presents a method to determine the thermal conductivity of composite insulating materials containing ceramic microspheres, in which there is a vacuum. The matrix of the tested composite is acrylic resin, and the strengthening phase is ceramic microspheres. Preparing of samples from such material for testing in a plate apparatus is difficult due to damage to the spheres during processing and the formation of air gaps between the plates. The described method uses the amount of electricity consumed by the water heaters to maintain the set temperature. The essence of this method is to compare the energy consumption of the tank coated with the tested composite material with that by an identical tank coated with an reference insulation with a known thermal conductivity (PUR). A necessary condition is a similar drop in temperature on the test and reference insulations.

Keywords: measuring method, thermal conductivity, composite coating, insulating properties

METODA BADANIA PRZEWODNOŚCI CIEPLNEJ IZOLACYJNYCH MATERIAŁÓW KOMPOZYTOWYCH PRZEZNACZONYCH DO ŚRODKÓW TRANSPORTU

Przedstawiono metodę wyznaczania współczynnika przewodzenia ciepła kompozytowych materiałów izolacyjnych zawierających mikrosfery ceramiczne, w których panuje podciśnienie. Osnową badanego kompozytu jest żywica akrylowa, a fazą umacniającą są ceramiczne mikrosfery. Przygotowanie próbek z takiego materiału do badań w aparacie płytowym jest utrudnione ze względu na uszkodzenia sfer podczas obróbki i powstawanie szczelin powietrznych między płytami. W opisanej metodzie wykorzystano ilość energii elektrycznej zużywanej przez podgrzewacze wody na podtrzymanie zadanej temperatury. Istotą tej metody jest porównanie zużycia energii przez zbiornik pokryty badanym materiałem kompozytowym ze zużyciem energii przez identyczny zbiornik pokryty izolacją odniesienia o znanym współczynniku przewodzenia ciepła (PUR). Warunkiem koniecznym jest podobny spadek temperatury na izolacji badanej i odniesienia.

Słowa kluczowe: metod pomiaru, przewodność cieplna, powłoka kompozytowa, właściwości izolacyjne

INTRODUCTION

Composite materials perform various functions in technical means. At the beginning, composites were used as engineering materials due to their increased tensile strength (up to about 30% compared to the matrix material for aluminum alloys). As a result, engine blocks and pistons as well as brake discs and drums of lower weight are produced [1, 2]. Then composites were used as materials in the thermal economy, among others as heat dissipation heat sinks of electronic components, e.g. processors in on-board computers [3]. Another application was the lubrication of sliding contacts by built-in solid lubricants, e.g. the oldest crankshaft slide bearings made of aluminum alloys with graphite particles [1, 4, 5].

The use of composites as heat insulation and cold-insulation materials is newer and less widespread. One of the first applications of cold insulating composites was the coating of liquid fuel tanks for the space industry. The matrix of such composites is resin, e.g. acrylic, and microspheres of expanded perlite constitute the strengthening phase (λ = 0.0014 W/(mK)) [6]. Today, refrigerated vehicles are insulated with modern composite materials, which allows the dimensions of insulation and the weight of the vehicle to be reduced. The refrigeration chambers of delivery vehicles are made of plastic elements filled with insulating materials. The shapes of these chambers require the use of flexible materials [7].

The definition of a composite states that it must be made of at least two materials with different physical properties, and with a clear boundary between the matrix and the strengthening phase. From the thermodynamic point of view, the phase boundaries represent increased resistance to heat transfer. If the composite is composed of a matrix with an addition of nanoparticles, particles or fibers, its thermal conductivity depends on the fraction of the reinforcing phase. The larger the number of particles, the larger the number of series connected resistances to the heat flow.

The manufacturers of refrigerated vehicles sometimes need a simple tool to control the thermal conductivity of insulation materials (λ) because it changes over time caused by diffusion. There are several ways to determine thermal conductivity, including computational [8] and measurement methods [9]. In measurement methods, for example, measurement of the heat flux or the energy used to maintain the temperature is used. In the first method, the temperature is measured on the cold and warm side, and on this basis the heat flux and thermal conductivity are calculated. A device using this method is, for example, the Poensgen apparatus or a tubular device [9]. A disadvantage of the plate apparatus affecting the inaccuracy of the measurements is the high accuracy of specimen production with specified dimensions (250x300x25 mm). In addition, conductivity standards are required to calibrate the devices. Insulating composites containing microspheres cannot be machined due to the possibility of damaging the spheres and increasing the inaccuracy of the measurement. Making panels with the layer casting method does not provide high flatness or parallelism of the surface, due to uneven solvent evaporation.

In the second method, used for example to measure heat losses by water heaters, the method measures the amount of energy consumed by the heating element to maintain a constant temperature inside a heated chamber placed in a room with a constant temperature [9]. The thermal conductivity is calculated using the appropriate formula. It is a comparative method because it requires measurement of the energy consumption by a tank insulated with a known material λ and a tank with the tested insulation. In this method, surface flatness of the samples is not required.

The use of impulse methods measuring thermal conductivity (diffusivity) is limited due to the high reflectivity of ceramic spheres (> 90%).

Taking into account the difficulties in preparing samples for plate apparatus and laser methods as well as the inaccuracy of calculations using the mixture rule [10, 11] in the Department of Motor Vehicle Operation, the possibility of applying the energy consumption method to maintain a constant temperature in water heaters to determine the conductivity of composite insulation coatings with ceramic microspheres was checked. These coatings can be used to insulate vehicles transporting food.

MATERIALS AND METHODS

A composite insulating material based on acrylic resin filled with ceramic microspheres was used for the tests (Fig.1). The thermal conductivity (λ) was determined on the measurement stand (Fig. 2) built according to standard [9].

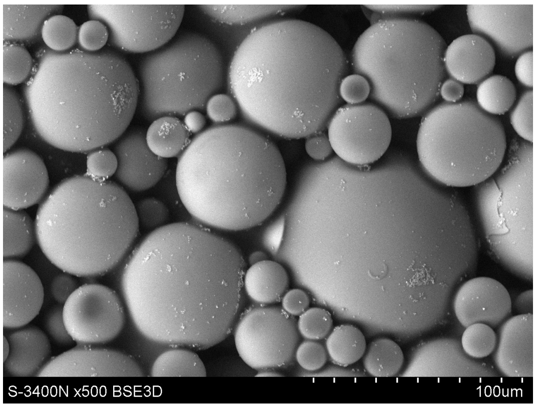

Fig. 1. View of composite insulating coating surface (spheres on acrylic matrix)

Rys. 1. Widok powierzchni izolacyjnej powłoki kompozytowej (sfery na tle akrylu)

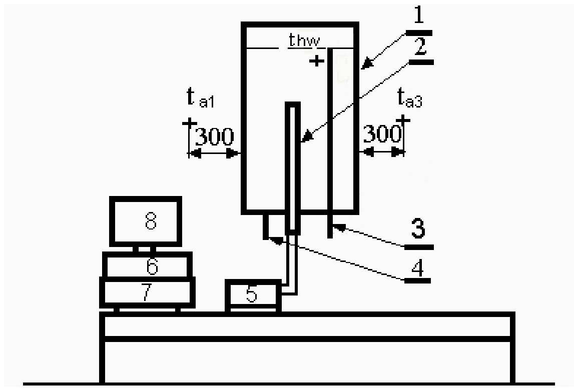

Fig. 2. Diagram of measuring stand: 1 - water heater with insulation, 2 - heating element, 3 - water outlet, 4 - water inlet, 5 - energy meter, 6 - PC, 7 - Spider, 8 - monitor

Rys. 2. Schemat stanowiska pomiarowego: 1 - podgrzewacz z badaną izolacją, 2 - element grzejny, 3 - wylot wody, 4 - wlot wody, 5 - miernik energii, 6 - PC, 7 - Spider, 8 - monitor

Two water heaters (1) with a capacity of 10 L mounted on the wall were used to build the station. On one of them a composite coating of three thicknesses was applied by spraying (Fig. 3) and the other one was equipped with factory applied insulation (PUR). The energy consumed by the heaters was controlled by a class 0.5 electricity meter (6) connected to an automatic temperature control system with the heater (2). The tanks were filled with a metered amount of water through stub (4), and they were emptied through the stub pipe (3) of the duct. A thermocouple for measuring the temperature of the hot water (t_{hw}) was placed 25 mm under the outlet of the duct. Thermocouples for measuring the ambient temperature (t_a) were placed 300 mm from the heater housing on the left (t_{a1}), in front of it (t_{a2}) and on the right (t_{a3}).

The temperatures were recorded with a Spider (8) equipped with SR01 temperature measurement cards compatible with Catman Easy 2.1 (7) software. The inaccuracy of the thermocouple (Ni-Cr/Ni type K) is

1.5%, and the SR01 measuring cards 0.2% of the measured value. The average square error of the measuring path, taking into account the inaccuracy of the measuring devices, thickness of insulation materials and temperature stabilization in the laboratory, did not exceed 10% for a 2.4 mm thick coating and 5% for a 4.8 mm thick coating.

The factory mounted tank was seasoned for a year because the λ of PUR foam grows for about 3 months due to the diffusion of the foaming gas. The view of the tank with the applied composite coating is shown in Figure 3b.

a)

b)

Fig. 3. Tank used for investigations before (a) and after (b) coating (ϕ = 200 mm, L = 300 mm)

Rys. 3. Zbiornik użyty do badań przed (a) i po nałożeniu (b) izolacji (ϕ = 200 mm, L = 300 mm)

In order to obtain accurate results, the following conditions must be met:

1. The tested coating has a uniform thickness over the entire surface of the heater (th_c = 2.4; 3.6; 4.8 mm, average of 24 measurements, σ = 0.2 mm for the thickness of 2.4 mm and 0.1 for 4.8 mm).
2. The applied PUR layer has a uniform thickness over the entire surface of the heater: average of 24 measurements th_{PUR} = 20 mm and $\lambda_{20\text{-}PUR}$ = = 0.023 W/(mK) (Unfulfilled condition, because the thickness of the upper cap is higher (22.1)).
3. The laboratory has a constant temperature when measuring the energy consumption of both water heaters ($t_{a1} = t_{a2} = t_{a3}$ = 20÷21°C - automatically adjusted).
4. The capacity of both heaters is identical and filled with the same amount of water, that is 9.6 l.;
5. The automatic heater control switches the heating system on and off at the same steady-state temperatures (68÷70°C).
6. Both insulating materials have the same share of conduction, radiation and convection in heat transfer (This is not satisfied due to the greater reflexivity of ceramic spheres than PUR);
7. The temperature difference for both tanks is constant ($\Delta t = t_{hw} - t_a$), that is the hot water (t_{hw} = = 68÷70°C) and the air in the laboratory (t_a = 20÷ ÷21°C).
8. The energy consumption of the heaters is measured with a 0.5 class meter with a resolution of 0.1 Wh. Measurements were performed three times on each tank, according to the standard, for 4 consecutive days. During the first day (up to 4 hours), the tanks warmed up to reach the established thermodynamic state. The energy consumption was constant for 3 consecutive days. The recorded temperature waveforms from the first 4 hours are shown in Figure 4.

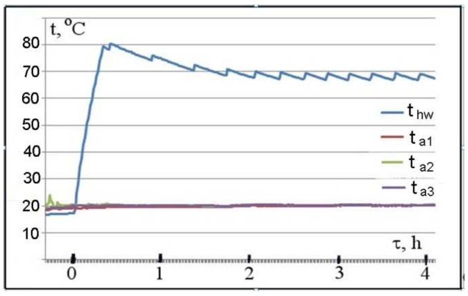

Fig. 4. Course of temperatures during 4 first hours - warming up of heater: t_{hw} - temperature of heated water, t_{a1}, t_{a2}, t_{a3} - ambient temperature at 300 mm distance from heater on left, in front of and on right side

Rys. 4. Przebieg temperatury w pierwszych 4 godzinach - rozgrzewanie zbiornika: t_{hw} - temperatura grzanej wody, t_{a1}, t_{a2}, t_{a3} - temperatura otoczenia w odległości 300 mm z lewej strony podgrzewacza, przed i z prawej strony

RESULTS AND DISCUSSION

On the basis of the results of energy consumption by the heaters, the computational thermal conductivity of the tested composite coating (λ_c) was determined by the comparative method from the relation:

$$\Delta t = \frac{thc}{\lambda PUR}\Phi C = \frac{thPUR}{\lambda PUR}\Phi PUR \qquad (1)$$

where: Φ - heat flow through the insulation [W]; Δt - temperature difference on both sides of the insulation ($\Delta t = t_{hw} - t_a$ = const); t_{hw} - temperature of hot water in the heater; t_a - ambient temperature of the heater (average of t_{a1}, t_{a2} and t_{a3}); λ - thermal conductivity [W/(mK)]; th - insulation thickness [m].

The thermal conductivity values calculated in accordance with recommendations in standards [9, 11] for the given coating thickness are presented in Table 1. The dependence of λ on composite coating thickness (th) can be described using the logarithmic equation

$$\lambda = 0.00531+0.03\ln(th) \qquad (2)$$

for which significance coefficient α = 0.005, correlation R = 0.995 and standard deviation σ = 0.0010. The graphic interpretation of the equation is presented in Figure 5.

TABLE 1. **Calculated λ_c for given coating thickness (*th*) at temperature 68÷70°C**

TABELA 1. **Obliczone λ_c dla zadanych grubości powłoki (*th*) w temperaturze 68÷70°C**

Coating thickness th [m]	0.0024	0.0036	0.0048
λ_c [W/(mK)]	0.0032	0.0043	0.0053

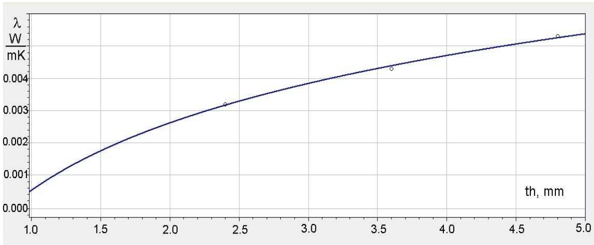

Fig. 5. Dependence of λ on composite layer thickness (*th*) described by logarithmic equation

Rys. 5. Zależność λ od grubości (*th*) powłoki kompozytowej opisana równaniem logarytmicznym

CONCLUSIONS

The presented method of determining the thermal conductivity of composite materials containing hollow microspheres (difficult for sample preparation by cutting) allows the approximate value of λ to be easily determined with an average error, depending on the accuracy of applying the coating to the barrier. The accuracy of thermal conductivity (λ) measurement depends on the precision of spraying the coating, guaranteeing a homogeneous layer thickness (*th*) as well as on the accuracy of determining the thermal conductivity of the reference material - PUR. Usually, the λ given by producers and in standards is measured at 20°C. The influence of the deviation in the coating thickness in the described method is lower than using a lambda meter with cold and hot plates owing to the influence of air gaps in the latter method.

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