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Energy Efficiency of High-temperature Installations and Method of Determining Thermal Properties of Pipe Insulation Materials

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1. Introduction

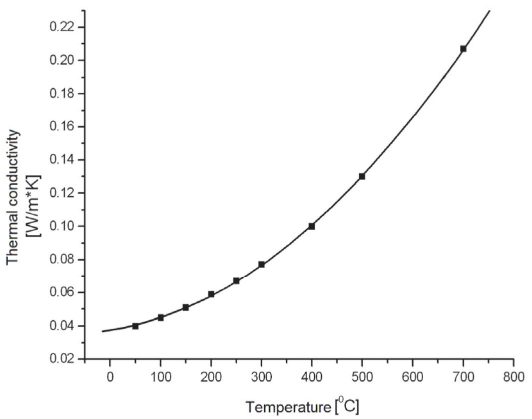
It is estimated that the potential energy savings that can be generated in production plants in Poland connected with thermal modernisation of industrial installations shall amount to 27 PJ and carbon dioxide emissions can be reduced by 2.2 million tonnes of CO_2 annually. The potential annual savings shall exceed the energy consumption of more than 400,000 households or the reduction of CO_2 emissions by 1.1 million mid-range cars each with a mileage of 12,500 km per year (Gürtler A. 2014).

One of the most important elements which influences the improvement of energy efficiency of high-temperature industrial installations is the proper selection of materials which hinder the escape of heat from the installation. The fundamental issue is the choice of an appropriate material/product to carry out the thermal modernization investment, whose parameter determining the insulation properties is the thermal conductivity coefficient (λ, [W/m·K]) in a given temperature at which the material/product will operate. Thanks to such information, it is possible to properly and correctly design a thermal modernization of a high-temperature installation, which should include an optimal solution taking into account the costs and the rate of return on the investment. The above issues were the subject of Cammerer's work (Cammerer J.S. 1967), where problems related to the calculation and application of insulation in industry, as well as measurement techniques in high and low temperature technical and industrial installations were considered.

What constitutes a problem prevailing on the Polish market is the limited possibility to determine the thermal properties of materials/products for thermal insulation at high temperatures (above 100°C to 800°C), including pipe materials. This article aims at presenting a method of determining the heat conductivity coefficient for this type of materials; it also specifies the necessary requirements for apparatus for this type of tests and describes the investment losses related to improper determination of thermal parameters.

2. Legal requirements for determining the thermal properties of materials for thermal insulation of industrial installations

The basic standard specifying the manner of presenting thermal properties of insulation materials at temperatures other than those used for general construction (in general construction materials are characterized by the determination of thermal conductivity coefficient in only one temperature, in 10°C) is EN ISO 13787:2003 "Thermal insulation products for building equipment and industrial installations – Determination of declared thermal conductivity." It applies to both flat products (Miros A. 2012) and pipe products. The requirement of the above mentioned standard is for the producer to present the dependence of thermal conductivity coefficient on the average temperature in the form of a curve or a table (Fig. 1).



Temperature [°C]	Thermal conductivity [W/m·K]
50	0.040
100	0.045
150	0.051
200	0.059
250	0.067
300	0.077
400	0.100
500	0.130
700	0.207

Fig. 1. Declared thermal conductivity curve and table for mineral wool sample

Applying EN ISO 13787:2003 results directly from the standards for thermal insulation products for building equipment and industrial installations, i.e. a package of standards in the range from EN 14303 to EN 14320 as well as EN 15599 and EN 13055. However, if the determination of thermal properties concerns products for high-temperature applications, i.e. temperatures at which thermally insulating organic materials cannot be used (over the long-term influence at 180°C) (Miros A. 2016), then we talk only about such inorganic materials as: mineral wool (glass wool, rock wool), foamed glass, silicate products, expanded perlite, expanded clay, ceramic wool and aerogel mats (Table 1). For most products: mineral wool, silicate products, expanded perlite, expanded clay and foam glass, an appropriate standard specification has been prepared (EN 14303:2015, EN 14306:2015, EN 15599-1:2010); however, there are no appropriate standards developed for ceramic wool and aerogel mats as yet.

Table 1. High temperature thermal insulation materials together with their estimated maximum temperature of application and relevant document of reference

Thermal insulation product	Form of product	Estimated maximum temperature of application [°C]	Document of reference
mineral wool	mats/slabs	800	EN 14303:2015
foam glass	stiff slabs	430	EN 14305:2015
silicate products	stiff slabs	1000	EN 14306:2015
expanded perlite	granulate	800	EN 15599-1:2010
expanded clay	granulate	750	EN 13055:2016
ceramic wool	mats	1400	NTA/ETA*)
aerogel	mats	650	NTA /ETA*)

*) NTA – National Technical Assessments, ETA – European Technical Assessment

As aerogel mats are increasingly frequently used to insulate industrial installations, in the absence of an appropriate standard specification, the manufacturer (or authorised representative body) should, prior to launching the product's sale, obtain a special document that allows the product to be legally introduced to the market. Such a document may be a European or National Technical Assessment [until 31.12.2016, such a document was a technical approval, which was replaced by a National Technical Assessment (in accordance with Regulation of 17.11.2016, item 1968)]. The relevant documents (European technical assessment) issued hitherto for the European market do not, however, contain any determined thermal properties in the whole scope of application. For example, for a product whose scope of application is up to 200°C (http://www.core-prosystems.co.uk/thermal-insulation/aerogel-spaceloft-insulation) the thermal conductivity coefficient was determined only at one temperature, i.e. 10°C (ETA - 11/0471). The λ_{10} parameter does not provide information about thermal insulation at other temperatures (Furmański 2013) – Fig. 2, which may pose a considerable problem in the proper design of an investment project for the thermal modernisation of an industrial installation.

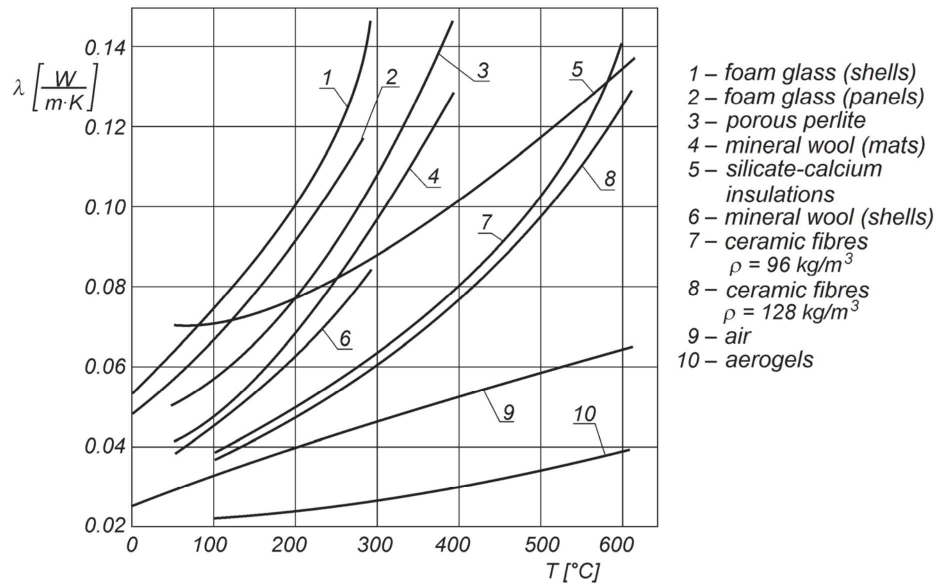


Fig. 2. Thermal conductivity change of different insulation materials vs. temperature (Furmański 2013)

The determination of thermal properties of materials at high temperatures may be hampered by costly and specialist requirements for measuring equipment and limited access to the appropriate accredited measuring methodology in Poland.

3. Requirements for apparatus measuring thermal conductivity coefficient

Thermal insulation products usually take the shape of an insulated surface. Usually insulated surfaces are flat surfaces (e.g. building walls, tank walls), convex surfaces (e.g. silos, curved-surface tanks) or pipes (e.g. heat pipes, elbows). For the most part, materials used for insulation, i.e. mats, slabs and pipe sections, come in such shapes. In the case of elastic materials, there is an additional option to adjust the insulation to surface irregularities, arches, curves, etc. without having to cut the material, which can result in thermal bridges. What constitutes an entirely different issue is insulation of valves due to irregular and non-standard dimensions and shapes (www.keafer.pl). When it comes to filling materials (granulates), the shape of the insulated surface is not important; however, it is crucial to protect the material against decrement during exploitation.

Determination of thermal conductivity coefficient value for thermally insulating products is performed applying the method in steady-state conditions on two types of apparatus, depending on the shape of the product, on the apparatus for flat-rolled (ISO 8302:1991) or pipe (EN ISO 8497:1996) products. It is not advisable to carry out only measurements of thermal conductivity coefficient for flat-rolled products due to a significant difference between internal structures of flat-rolled and pipe (cylindrical) products as well as due to the fact that thermal properties often depend on the direction of heat flow, which results in the fact that the measurement of unidirectional heat flow, as in the case of flat-rolled products, may not be representative (EN ISO 8497:1996). The measurement of the conductivity coefficient should be performed in apparatus constructed in accordance with the guidelines contained in the ISO 8302:1991 standard (ISO 8302:1991, EN 1946-2:1999) for flat-rolled products and (EN ISO 8497:1996) for pipe products (the issues connected with measuring thermal conductivity coefficient of flat-rolled products have been discussed in Miros. A 2013a).

The thermal conductivity test [W/(m·K)] for pipe sections is based on the measurement of the thermal flux flowing through a sample under the influence of the temperature gradient generated in the heat pipe (1) (EN ISO 8497:1996):

$$\lambda = \frac{\ln(D_2 - D_0)}{2\pi L} \cdot \frac{\Theta}{\left(T_0 - T_2\right)} \tag{1}$$

where:

Θ – the heat flux [W],

D – the pipe diameter [m],

T – the surface temperature [K],

L – the measurement length [m],

indices $_{0.2}$ – the internal and external surface.

Below there are presented issues related to the newly constructed two-chamber apparatus for measuring the thermal conductivity coefficient in the steady-state conditions for pipe products (pipe sections) with configuration:

1. Temperature range of the sample from the cold side: -50°C - 500°C.
2. Temperature range of the sample from the heat side: -30°C - 700°C.

3. Average temperature of measurement from -40°C (with ΔT: 20K) to 600°C (ΔT_{max}=200K).
4. The range of temperature differences (ΔT) between the cold side and the heat side of the sample:
    a. ΔT=20K in the range from -40°C to 500°C.
    b. ΔT_{max}=750K in $T_{average}$= 325°C (in the system when the temperature of test pipe T_{max}=700°C).
5. Measuring range of thermal conductivity coefficient value from 0.015 to 0.6 W/(m·K).
6. Minimum length of sample = 1 m.
7. Range of diameters of the measured sample: from 32 mm to 394 mm.
8. A set of test pipes with a diameter of 22 mm, 42 mm, 48 mm, 194 mm.
9. Number of thermocouples/sensors per one test pipe: 4.

Fig. 3. The two-chamber pipe apparatus for thermal conductivity tests within the temperature range from -40 to 600°C

When constructing a test apparatus for measuring the thermal conductivity coefficient of pipe products (pipe sections), the following issues connected with measurement uncertainties should be considered in order to obtain repeatable and reliable results:

- temperature imbalance between sections (measuring and guarding) of the heating pipe
- measuring section area,
- emission performance of test surfaces,
- edge heat losses at the ends of heat pipe,
- linearity of the apparatus.

The construction of the test pipe consists in independent control of the temperatures of the measuring section and the guarding section. Due to this design of the heat pipe, an **imbalance in temperature** between these sections may occur during the measurement. The occurrence of the imbalance causes heat flux, partly through the sample and partly through the gap that separates the sections. The narrower the gap, the greater the imbalance error. On the other hand, in the design of the apparatus, it is taken into account that increasing the gap width increases the uncertainty of determining the measurement area. In the case of measurements at high temperatures, the radiation impact increases by increasing the thermal flux through the gap (EN ISO 8497:1996, EN 1946-5:2000, Miros 2013b). This effect may be minimised by low thermal conductivity filling material (CEN/TS 15548-1:2011), but the unbalanced thermal flux through both the sample and the apparatus (both gaps) shall be less than 1 % of the thermal flux delivered to the sample through the centre of the test pipe (according to the recommendations in EN 1946-5:2002).

The aforementioned gap, which separates the heating and guarding sections, plays an important role in determining the **measuring section area**, which is defined as a field surrounded by a line delineating the centre of the gap (Fig. 3). This field is not equal under all test conditions to the actual measuring field of the sample, which is cut through by the heat flux supplied by the central part of the pipe (EN ISO 8497:1996).

In order to estimate the uncertainty error in defining the field through which a thermal flux of the size Θ passes, two extreme cases related to the minimum and maximum thickness of the tested sample should be considered.

In the case of a minimum thickness sample (5 mm), the field through which the heat flux supplied by the measuring section of test pipe passes approaches the field defined by the edges of the measuring section gap. The actual length of the measuring field shall then aspire to a value of 600 mm (the physical length of the test section).

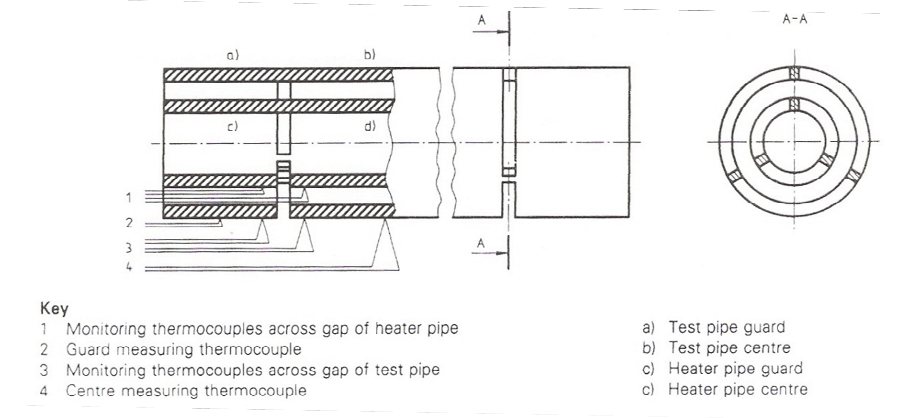


Fig. 4 Guarded end apparatus (EN ISO 8497:1996)

For the maximum thickness sample, in accordance with EN 1946-5:2000, if the thickness of the sample is much larger than the width of the gap (e.g. 10 times), the field boundary will be defined by lines passing through the centre of the gaps, i.e. twice as large (because there are two gaps) as half the width of the gap (in this case it is 6 mm for sample thicknesses from 60 mm to 100 mm). Therefore, the uncertainty caused by defining the measuring field through which the thermal flux of the size Θ passes can be determined through the difference between the extreme values of the length of the measuring section (600 and 606 mm), i.e. 1%.

The test surfaces of the apparatus shall have the highest possible heat dissipation capacity. Determination of **the emissivity of the test surface** consists in determining the density of the thermal flux passing through the air layer (in steady-state conditions, with no convection) at various temperature differences (ΔT).

The axial heat flux from the test section to the sample guarding section affects the maximum thickness of the sample - the uncertainty associated with **edge losses of heat at the ends of the pipe**. For an apparatus with no end insulation, the end temperature ratio is (2) (EN ISO 8497:1996):

$$e = \frac{(T_e - T_2)}{(T_1 - T_2)} \tag{2}$$

where:

T_e – temperature at the ends of the sample (assumed as uniform)

T_1 – temperature of the heat side of the sample

T_2 – temperature of the cold side of the sample

Table 2. Calculation of extreme cases (extreme diameters of test heat pipe and extreme possible thicknesses of sample) of the edge heat loss on the end of heat pipe

Diameter of test pipe [m] d_0	Sample thickness [m] d_2	Sample diameter [m] $d_0 + 2d_2$	Equivalent sample thickness [m] d_{eq}	End temperature ratio e	Heat losses at pipe ends [%] E_e
0.022	0.005	0.032	0.0060	0	**0.00**
0.022	0.1	0.222	0.2566	0	**1.93**
0.044	0.005	0.054	0.0055	0	**0.00**
0.044	0.1	0.244	0.2090	0	**0.70**
0.048	0.005	0.058	0.0055	0	**0.00**
0.048	0.1	0.248	0.2036	0	**0.61**
0.194	0.005	0.204	0.0051	0	**0.00**
0.194	0.1	0.394	0.1396	0	**0.05**
0.022	0.005	0.032	0.0060	1	**0.00**
0.022	0.1	0.222	0.2566	1	**-1.87**
0.044	0.005	0.054	0.0055	1	**0.00**
0.044	0.1	0.244	0.2090	1	**-0.69**
0.048	0.005	0.058	0.0055	1	**0.00**
0.048	0.1	0.248	0.2036	1	**-0.60**
0.194	0.005	0.204	0.0051	1	**0.00**
0.194	0.1	0.394	0.1396	1	**-0.05**

The above table presents some of the calculations for extreme cases (extreme diameters of the test pipe and extreme possible sample thicknesses). The uncertainty due to edge losses at the pipe ends is greater than 1% in only two cases where the test pipe has the smallest diameter (22 mm) and the thickness of the test sample is the largest (100 mm) as well as when the edge temperature of the test sample is practically equal to the temperature of the centre ($T_e = T_2$) or the edge temperature of the test sample is practically equal to the temperature of heater pipe ($T_e = T_1$).

One of the most important criteria for the assessment of systematic errors of the apparatus is the determination of its **linearity test**. It consists in recording possible changes in the thermal conductivity coefficient at a specific average test temperature, but with different temperature differences (ΔT). Generally, the test results of the thermal conductivity coefficient should not differ from each other.

The above measurements are carried out also in other average temperatures, which of course depend on the range of the test apparatus (ISO 8302:1991, EN ISO 8497:1996, EN 1946-5:2000).

Table 3. The results of linearity test of pipe apparatus for mineral wool sample

Thermal conductivity coefficient λ [W/m·K]	Average temperature 10°C	Average temperature 300°C	Average temperature 700°C
for ΔT=10°C	0.03874	0.08274	0.19387
for ΔT=20°C	0.03842	0.08237	0.19152
for ΔT=40°C	0.03820	0.08209	0.19447
average λ	0.03145	0.07224	0.19329
Standard deviation λ	2.727E-4	3.26E-4	1.56E-3
Coefficient of variation [%]	0.86709	0.4503	0.8071

4. Analysis of losses due to incorrect determination of the thermal conductivity coefficient

The following example shows how important it is to determine the correct value of the thermal conductivity coefficient of thermal insulation, which has been taken from Annex C of the standard EN ISO 12241:2008 (EN ISO 12241:2008) as an illustration for calculating the temperature drop over the pipe length.

The following input data have been specified in the standard:

- temperature of the medium (hot flux): t_m = 250 [°C]
- mass of the medium flux: m = 45000 [kg/h]
- specific heat: C_p = 2.233 [kJ/(kg·K)]
- ambient air temperature: t_{amb} =- 10 [°C]
- diameter of the pipe: D_i = 0.40 [m]
- length of the pipe: l = 2500 [m];
- thickness of the insulation: d = 0.12 [m]
- thermal conductivity at temperature of 120°C: λ_{120} = 0.061 [W/m·K]
- outer diameter of the pipe, $D_e = D_i + 2d$ = 0.64 [m]

Based on equation (3) (EN ISO 12241:2008), an approximate temperature drop along the length has been estimated [°C]:

$$\Delta t = \frac{(q_l \cdot l \cdot 3.6)}{\left(m \cdot C_p\right)} = 19.0 \tag{3}$$

where:
q_l – the linear density of the heat flux [W/m] is (4) (EN ISO 12241:2008):

$$q_l = \frac{(t_{amb} - t_m) \cdot 2\pi\lambda}{\left(\ln \frac{D_e}{D_i}\right)} = 212.02 \tag{4}$$

As the above formulae show, the thermal conductivity coefficient is directly proportional to the temperature drop; thus, if the measured thermal conductivity coefficient was higher by 10%, i.e. not λ_{120} = 0.0610 [W/m·K], but λ_{120} = 0.0671 [W/m·K], then the temperature drop would also be higher by 10 % (Δt = 20.89 [°C]), and thus so would the costs of delivering the medium would increase.

However, there is another error, the consequences of which are much more serious. The aforementioned situation of determining the thermal conductivity coefficient at only one temperature (λ_{10}) from the entire range of high-temperature insulation application results in much greater differences. Using this example and assuming that the change in the thermal conductivity coefficient is similar to the changes shown in Fig. 1, the difference between λ_{10} = 0.038 [W/m·K] and λ_{120} = 0.048 [W/m·K] would be more than 26 % of the difference between the designed and actual temperature of the medium along the length of the pipe. Such a thermal modernization investment would not make any sense in practical terms.

5. Conclusions

The key element when designing and investing in thermal modernization is a reliable and accurate determination of the insulation parameters of individual elements, in particular the materials constituting the basic thermal insulation. However, without proper equipment and appropriate technical background, it is not possible to determine the thermal conductivity coefficient of the material/product, and the consequence of improper selection of insulation parameters may result in long-term losses for the investor. Therefore, the thermal parameters of materials dedicated to industrial installations should be determined over the entire range of use (without extrapolation to higher temperatures), on a selected, proven apparatus for measuring the thermal conductivity coefficient and in accordance with the appropriate standard procedure.

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Abstract

The article describes a method of determining the thermal conductivity coefficient value of high temperature insulation materials (over 100°C up to 800°C), especially of pipe products. Necessary requirements for the pipe test apparatus together with results of pipe apparatus requirement tests have been shown here. Moreover, an example of investment losses related to improper determination of thermal parameters of an insulating material has been presented.

Keywords:
thermal conductivity coefficient, pipe apparatus, high temperature insulation

Efektywność energetyczna instalacji wysokotemperaturowych a metoda wyznaczania charakterystyki cieplnej rurowych materiałów termoizolacyjnych

Streszczenie

Artykuł przedstawia sposób określania współczynnika przewodzenia ciepła dla materiałów/wyrobów do izolacji cieplnej w wysokich temperaturach (powyżej 100°C do 800°C), w szczególności materiałów rurowych. Przedstawiono niezbędne wymagania dla aparatów do badań współczynnika przewodzenia ciepła wyrobów rurowych wraz z wynikami pomiarów właściwości użytkowych aparatu. Przedstawiono przykład strat inwestycyjnych związanymi z niewłaściwym określeniem parametrów cieplnych materiału izolacyjnego.

Słowa kluczowe:
współczynnik przewodzenia ciepła, aparat rurowy, wysokotemperaturowe izolacje