FACTORS INFLUENCING MEASUREMENTS OF THE THERMAL CONDUCTIVITY BY HOT BALL METHOD

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Abstract

The paper discusses the principle and the construction of the hot ball sensor for measurement of the thermal conductivity. The sensor in a form of a small ball generates heat and simultaneously measures the temperature response. Real properties of the hot ball, contact thermal resistance between the hot ball and the surrounding material and the influence of the connecting wires are analyzed. Reliability of the hot ball sensor has been studied considering reassembling and the use of 6 individual hot ball sensors. Reproducibility below 1% was found in the whole range of thermal conductivities using fixed setup. Reassembling using the same material made uncertainty within 2% percent and variation in thermal conductivity data within 7% when different hot ball sensors were used.

Key words: transient methods, hot ball method, disturbing effects, contact thermal resistance, heat capacity of the hot ball

1 Introduction

Recently a new class of dynamic methods – transient methods for measuring thermophysical properties has started to spread in research laboratories as well as in technology. The principal difference between classical and transient methods consists in variability of specimen size, measuring time and number of measured parameters. Transient methods need significantly shorter time for a measurement and possess high variability in specimen size. Some transient methods can determine the specific heat, thermal diffusivity and thermal conductivity within a single measurement [1- 4]. A set of new innovative instruments started to spread on the marked that are based on transient methods. Recently portable instruments and monitoring systems have been introduced onto market. Construction of such devices has evoked a search for suitable sensors that would provide information on the thermophysical properties of tested objects. By now a principle of the hot wire in the needle probe [5] and in the hot bridge [6] has been the most often used in portable instruments. Recently, a principle of a hot ball sensor in two components configuration, i.e. a heat source and a thermometer fixed apart from each other has been published [7].

The present paper deals with the hot ball sensor in a single component configuration i.e. when a heat source and a thermometer are unified in a single unit. The working equation is derived. Disturbing factors, the real properties of the ball, the thermal contact between the ball and the surrounding medium and the connecting wires to the hot ball sensor are analyzed. Construction of the hot ball, the corresponding instrument and the measurement methodology is discussed. The calibration based on the materials that have been tested within the intercomparison measurements is performed.

2 Hot Ball Sensor

Model of the hot ball sensor is shown in Fig. 1. A heat source in a form of a small ball starts to deliver constant heat for t > 0 and simultaneously it measures the temperature response (Fig. 2. The temperature response is of a transient form stabilizing to a constant value T_m after some time.

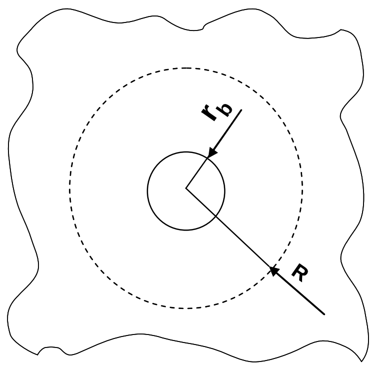

Fig. 1. Model of the hot ball method.

This moment is used to determine the thermal conductivity of the surrounding medium. It should be stressed that the steady state regime of the hot ball has nothing to do with the one used in the Guarded Hot Plate technique. The latter is based on the existence of the heat and the cold plates (heater and sink) while the former utilizes physics of the heat spread from the spherical heat source. The heat penetrates to sphere with radius R during the temperature stabilization to T_m. Thus the determined thermal conductivity corresponds to material within this sphere. Then an averaged value is to be determined for inhomogenous materials.

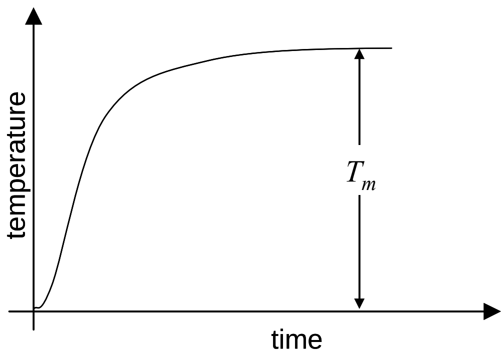

Fig. 2.: The temperature response corresponding to ball heat output q = const. for t > 0.

3 Theory of Hot Ball Sensor

The working equation of the hot ball sensor is based on an ideal model. The ideal model assumes a constant heat flux F per surface unit from the empty sphere of radius r_b into the infinitive medium starting to be delivered for times t > 0. Then the temperature distribution within the medium is characterized by the function [8]

$$T(r,t) = \frac{r_b^2 F}{r\lambda}\left\{\mathrm{erfc}\left(\frac{r-r_b}{2\sqrt{at}}\right) - \exp\left(\frac{r-r_b}{r_b}+\frac{at}{r_b^2}\right)\mathrm{erfc}\left(\frac{r-r_b}{2\sqrt{at}}+\frac{\sqrt{at}}{r_b}\right)\right\} \tag{1}$$

where erfc(x) is error function defined by $\mathrm{erfc}(x) = 1 - \frac{2}{\pi}\int_0^x \exp\left(-\zeta^2\right)d\zeta$ and λ and a are thermal conductivity and thermal diffusivity of the surrounding medium, respectively. The equation (1) is a solution of partial differential equation for heat conduction for $r \geq r_b$ considering boundary and initial conditions

$$T(r,t) = 0, \quad t = 0,$$

$$\lambda \frac{\partial T(r,t)}{\partial r} = -F, \; F = const, \; r = r_b, \; t > 0.$$

Function (1) gives a working equation (2) of the measuring method in long time approximation $t \to \infty$ assuming that temperature is measured at the surface of the empty sphere $r = r_b$

$$\lambda = \frac{q}{4\pi r_b T_m (t \to \infty)} \tag{2}$$

where the heat flux of the empty sphere F is recalculated to the overall heat ball production q according $F = q / 4\pi r_b^2$, and T_m is stabilized value of the temperature response. The empty sphere represents an ideal hot ball of radius r_b characterized by a negligible heat capacity and high thermal conductivity $\lambda_b \to \infty$. Similar methodology has been applied for deriving the working equation of the hot wire method [1].

The measuring method based on function (1) belongs, in fact, among the class of transient ones. Nevertheless, the heat source of the spherical symmetry possesses a special feature i.e. it yields the steady state in long times and this moment is utilized to measure the thermal conductivity.

4 Analysis of disturbing effects

A hot ball must be constructed of parts generating constant heat on one hand and measuring the temperature response on the other hand. Then real properties of the ball and its thermal contact to the surrounding medium – the tested material influence the measuring process. In addition the electrical wires connecting the ball might influence the measuring process. Theoretical analysis of such hot ball structure requires a sophisticated mathematical approach that might not always provide the expected information. Therefore, we accept simplified models of the ball represented by a homogenous material ascribed to the heater as well as to the thermometer. Two models will be analyzed, namely a heat capacity model and a steady state model. Both models concern the properties of a real heat source. Influence of the connecting wires will be analysed experimentally, only as this effect requires too complicated theoretical model.

Heat capacity model. Assuming that the ball is a perfect conductor, the measured temperature can be ascribed to the surface temperature of the ball as the Eq. (2) requires. Such ball has its own heat capacity causing a deviation from the ideal model. In addition some contact thermal resistance 1/H (*H* - contact thermal conductance) between the ball and the medium might exist. A model including the heat capacity of the ball *Mc** (M and c* are mass and specific heat of the ball, respectively) and the contact thermal resistance 1/*H* is characterized by the function valid for large values of time[9]

$$T_b(t) = \frac{q}{4\pi\lambda r_b}\left[\frac{1+r_b h}{r_b h} - \left(\frac{r_b}{\sqrt{\pi a t}}\right) - \frac{r_b^{\,2}\left[2+r_b h(2-f)\right]}{2hf\pi^2\sqrt{at}}\right] + \dots\dots \qquad (3)$$

where $f = 4\pi r_b^{\,3}\rho\frac{c}{Mc^*}$, *q* is heat supplied over the surface at $r = r_b$, *M* is mass and c^* the specific heat of the ball, respectively and *c, ρ* are specific heat and density of the medium, respectively and $h = H/\lambda$, *H* is contact thermal conductance. The Eq. (3) is a solution of partial differential equation for heat conduction considering the boundary and initial conditions

$$\lambda\frac{\partial T_{med}(r,t)}{\partial t} + H(T_b - T_{med}) = 0,\quad r = r_b,\quad t > 0,$$

$$H(T_b - T_m) + c^* M\frac{\partial T_b}{\partial t} = F,\quad r = r_b,\quad t > 0.$$

The heat capacity of the ball *Mc** and the contact thermal resistance *1/H* disturbs the transient and thus it influences the measuring process. Assuming that the parameters of the ball are the following: heat output $q = 6$ mW, radius $r_b = 1$ mm, and of the tested material: density $\rho = 1000$ kg m^{-3}, thermal conductivity $\lambda = 0.5$ W m^{-1} K^{-1} and the thermal diffusivity $a = 0.5$ mm^2·sec^{-1} one obtains transients using function (3) shown in Fig. 3 and 4 for a set of the ball heat capacities *Mc** and contact thermal conductances. The used input data represent the most often used experimental conditions. The calculations have been performed considering medium made of polymer.

A negligible influence of the heat capacity of the ball *Mc** has been found in the broad range of the parameter $Mc^* = 10^{-5} \div 1$ J m^{-3} K^{-1} (Fig. 3). The calculations have been performed considering rather non-ideal contact thermal conductance, i.e. $H = 1000$ W m^{-2} K^{-1}. Rather strong influence of the contact resistance on transient has been found (see Fig. 4). Calculations have shown that the contact thermal conductivity *H* should reach $H > 6\,000$ W m^{-2} K^{-1} to keep conditions of the ideal model.

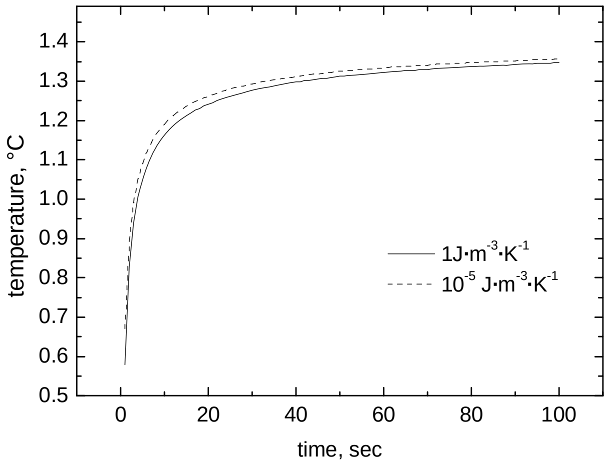

Fig. 3. Transients calculated using (3). Parameter heat capacity of the ball Mc^*.

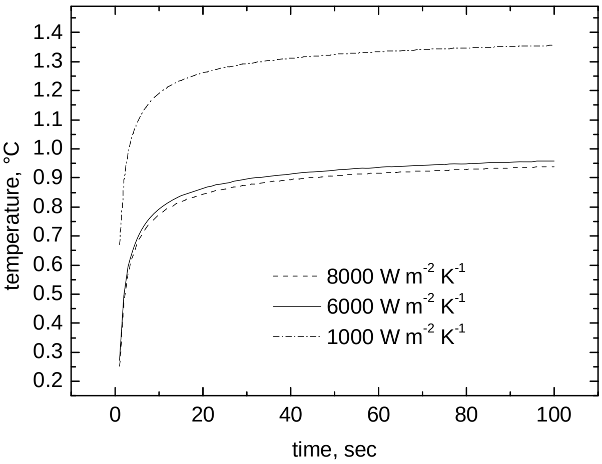

Fig. 4. Transients calculated using (3). Parameter contact thermal conductance H.

A criterion of the steady state regime has been searched due to the calculation of transient (3) considering real ball parameters (contact thermal conductance H = 10 000 W m^{-2} K^{-1} and heat capacity Mc^* = 4·10^{-5} J m^{-3} K^{-1}) and parameters of the medium (density ρ = 1000 kg m^{-3}, thermal conductivity λ = 0.5 W m^{-1} K^{-1} and the thermal diffusivity a = 0.5 mm^2 s^{-1}). The working equation (2) has been used for thermal conductivity evaluation using point by point (value T_m in eqation (2)) of the scanned temperature response. A 5% deviation (0.5 – λ_{com})/0.5 from the thermal conductivity input λ_{in} = 0.5 W m^{-1} K^{-1} has been found after 65 s (see Fig. 5).

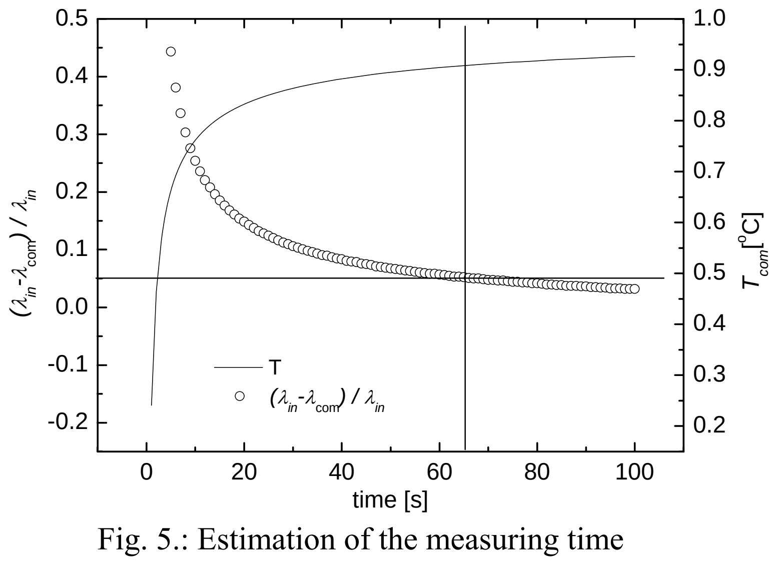

Fig. 5.: Estimation of the measuring time

This test has shown that the steady state regime can be accepted after 65 s for materials of thermal conductivity λ = 0.5 W m^{-1} K^{-1}. A deviation can be reduced in case of longer measuring time.

Steady state model. The previous analysis was based on the assumption that the ball is a perfect heat conductor. This corresponds to the experimental setup of high difference in thermal conductivity between the ball body and the surrounding medium – tested material. However, the ball properties are given by producer. Therefore, we look for criterion of a thermal conductivity range of the tested materials to obtain reliable results. As the transient properties were discussed in the previous case the steady state regime is to be analyzed, only. In case the ball and the surrounding medium represent different materials a solution of the partial differential equation is to be sought. The function has the form [10]

$$T_b(r) = q\frac{\left[r_b^2 - r^2 + \frac{2}{H} r_b \lambda_b + 2r_b^2\left(\frac{\lambda_b}{\lambda}\right)\right]}{8\pi\lambda_b r_b^3} \quad \text{for } r < r_b \tag{4}$$

and

$$T(r) = \frac{q}{4\pi r\lambda} \quad \text{for } r > r_b \tag{5}$$

where $T_b(r)$ and $T(r)$ characterize temperature distribution within the ball and the medium, respectively, $1/H$ is the thermal contact resistance, r_b and λ_b is the ball radius and its thermal conductivity, respectively and q is the overall heat production of the ball during time unit.

The functions (4) and (5) have been found by solution of partial differential equation for heat conduction considering the boundary and initial conditions

$$T_b(r) = T(r) = 0, \quad t = 0,$$

$$\lambda_b \frac{\partial T_b(r,t)}{\partial r} = \lambda \frac{\partial T_{med}(r,t)}{\partial r}, \quad r = r_b, \quad t > 0$$

$$\lambda \frac{\partial T_{med}(r,t)}{\partial r} + h(T_b - T_{med}) = 0, \quad r = r_b, \quad t > 0.$$

Analysis of the influence of contact thermal resistance has been performed considering different materials of the ball (thermal conductivity range λ_b from 0.2 up to 1 W m^{-1} K^{-1}) and two different values of the contact thermal conductance H =10000 and 1000 W m^{-2} K^{-1} (Fig. 6 left). The surrounding medium represents material of thermal conductivity λ = 0.5 W m^{-1} K^{-1}. A ball radius is to be 1 mm and a heat output of the ball q = 0.006 W. The shape of the temperature distribution inside the ball is the same, just it is shifted towards the higher values in the case of non-ideal contact. No influence on the temperature distribution in medium can be recognized. This follows from the Eq. (5). In practice a ball of specific thermophysical properties is used for a range of materials having different thermal conductivity. Then weight of the thermal contact conductance on measuring process depends on thermal conductivity of the testing material. Fig. 6 righ gives an overview on the role of the thermal contact between the ball and the medium. The plots have been calculated for the thermal contact conductance H = 1000 W m^{-2} K^{-1}. Clearly the temperature drop at the thermal contact is the same for all of the medium thermal conductivities assuming the identical ball heat output q = 0.006 W. Nevertheless, its weight is negligible for a medium of low thermal conductivity.

Variation of the thermal conductivity of the medium influences its temperature distribution strongly, providing the same ball heat output q = 0.006 W is used while no changes can be found within the ball and at the thermal contact. Above statement is of high importance considering the measuring regime. Looking at the temperature distribution within the ball and the medium one can find that for low thermal conductivity medium the temperature gradient within the ball can be neglected, i.e. the conditions of the ideal model are nearly reached.

The measured average temperature instead of the ball surface temperature and the temperature drop at contact cause data shift when Eq. (2) is used. However, this shift remains the same for different surrounding mediums. Thus a correction based on calibration using standard materials could be introduced. Reliable measurements can be obtained for the materials of low thermal conductivity.

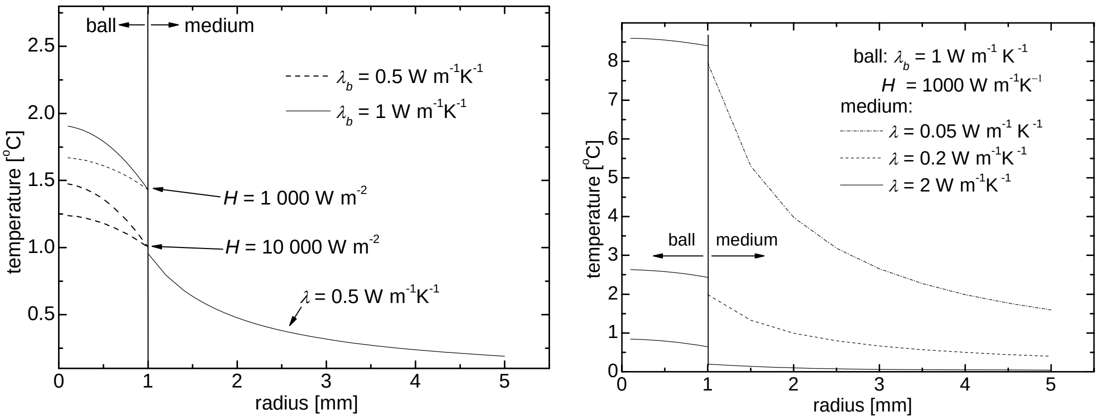

Fig. 6. Temperature distribution within the ball and the surrounding medium. Parameters: thermal conductivity of the ball λ_b and surrounding medium λ, and the contact thermal conductance between the ball and the medium H.

5 Experiment

The strategy of the theory verification is based on the calibration of the hot ball sensors by the Eq. (2) rewritten in a form

$$q/T_m = 4\pi r_b \lambda = A\lambda \tag{6}$$

where A is a constant $A = 4\pi r_b$. The ratio q/T_m is a linear function of thermal conductivity that will be tested using different materials. In principle, the hot ball sensor is an absolute method for measuring the thermal conductivity providing that the assumptions given by the theory are completed. In addition the function (6) will be plotted using ball radius r_b = 1.05 mm. A difference between the experimental data and the theoretical function should indicate the weight of the thermal contact and the temperature gradient within the ball.

Table 1 gives basic characteristics of the tested materials along with the experimental parameters used during measurements. The tested specimen consisted of two blocks and the sensor was placed in the contact of the two specimen surfaces. To improve the thermal contact a groove was made into one specimen block in which the ball was placed. A contact paste (Middland Silicones Ltd) was used for the thermal contact improvements of the ball and the specimen. While testing a porous structure the contact surfaces were covered by epoxy varnish to prevent the paste diffusion into material. A hot ball sensor has been immersed into paste or fluid in case of not solid materials. The solidified materials have been tested in a setup configuration arranged prior to solidification by immersion of a ball into the tested medium.

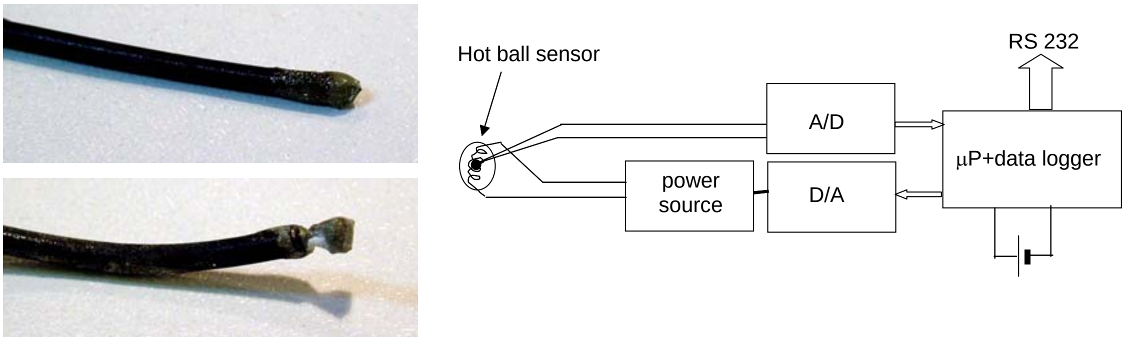

Fig. 7. Photos of two balls prepared in different design (left) and the scheme of instrument for measuring thermal conductivity by the hot ball method (right).

Table 1. Materials and experimental parameters for calibration hot ball sensor.

Material	Thermal conductivity [W·m^{-1}·K^{-1}]	Structure	q [mW]	Block size [mm]
Cement Paste	-	water-powder mixture	5.0	-
Stiffened Paste	-	opened pores	5.0	-
Hardened Paste	-	opened pores	5.0	-
Water	0.52 (25^{o}C)	fluid	4.5	-
Ice	2.2 (-5^{o}C)	compact	4.5	-
Basetect	-	paste	2.5	-
Sandstone	1.9	opened pores	6.5	50x50x20
PMMA	0.19	compact	2.5	ϕ50, length 25
Aerated Concrete	0.155	opened pores anisotropic	2.5	150x150x50
Calcium Silicate	0.097	opened pores	1.5	150x150x50
Phenolic Foam	0.06	opened pores	2.0	150x150x50
Styrodur	0.0435	cosed pores	3.5	150x100x30
Air	0.027	gas	1.5	
Wood Composite	0.025	ribbons	6.0	300x300x40

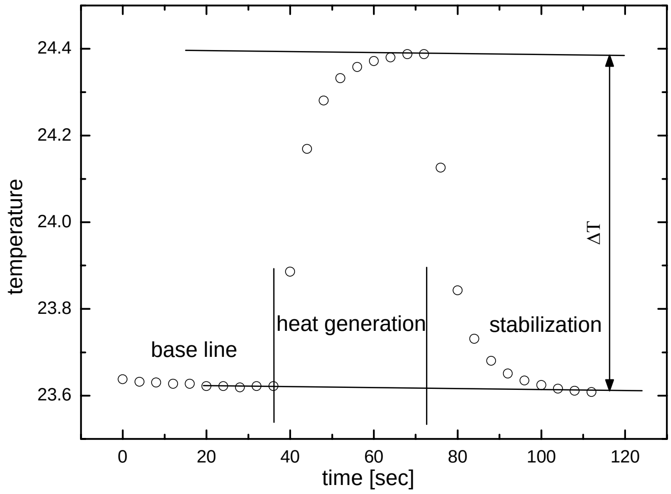

Fig. 8.: Signal of the hot ball sensor measured by monitoring system RTM 1.01.

RTM 1.01 instrument has been used for measurements. Scheme of the instrument is shown in Fig. 7. Typical measurement signal is shown in Fig. 8 along with the characteristic points used for the calculation of the thermal conductivity. The measuring procedure consists of the specimen temperature measurement representing base line, switching on the heating and simultaneously scanning the ball temperature. When the ball temperature has stabilized, the heating is interrupted and a period of temperature equilibration follows. When the temperature in the specimen is equilibrated the next measurement may be realized. The repetition rate of the measurements depends on thermal conductivity and it takes from 10 up to 60 minutes.

6 Results

A test of the measurement reliability has been performed provided that the ball heat output varies in a broad range. The ball radius r_b = 1.05 mm has been used. The results are shown in Fig. 9 left. Data on thermal conductivity are stable in the range 2.5 – 30 mW within $\delta\lambda$ = +/- 0.0007 $W \cdot m^{-1} \cdot K^{-1}$. The measured data are shifted to higher values (see Table I). The shift is constant within a broad range of ball heat output. The test has shown that the measured data are not influenced by the ball heat output.

A test of steady-state regime has been made using the PMMA and measuring parameters q = 0.0025 W, ball radius r_b = 1.05 mm and measuring period (heating time) 3000 s. The scanned temperature along with the calculated thermal conductivity is shown in Fig. 9 right. Equation (2) was used for data evaluation point by point of the scanned temperature response. A small temperature increase was found after the heating was switched off. Therefore the base line was approximated by a line that connects third and 210th point. Then the temperature T_m, included in the calculation, is established as a difference between this base line and a response point. Data on thermal conductivity started to be stabilized above 500 s.

Sensors are not of a regular ball shape therefore one may assume that data may be scattered comparing individual sensors. In addition, the groove made in the used materials is also not of the regular shape. Therefore, in order to obtain an overview on data statistics the following strategy of the experimentation has been chosen. Eight different sensors were tested. At least 5 measurements at fixed setup and 2 re-assembling have been realized for every sensor/material configuration. A reassembling consists of cleaning the groove, a deposition of the contact paste at the groove point where the ball is fixed, fixing the ball into the groove and assembling both parts of the tested materials together into one unit.This procedure was applied for phenolic foam, calcium silicate, PMMA and sandstone, only. Data obtained on a set of materials specified in Table 1 are shown in Fig. 10.

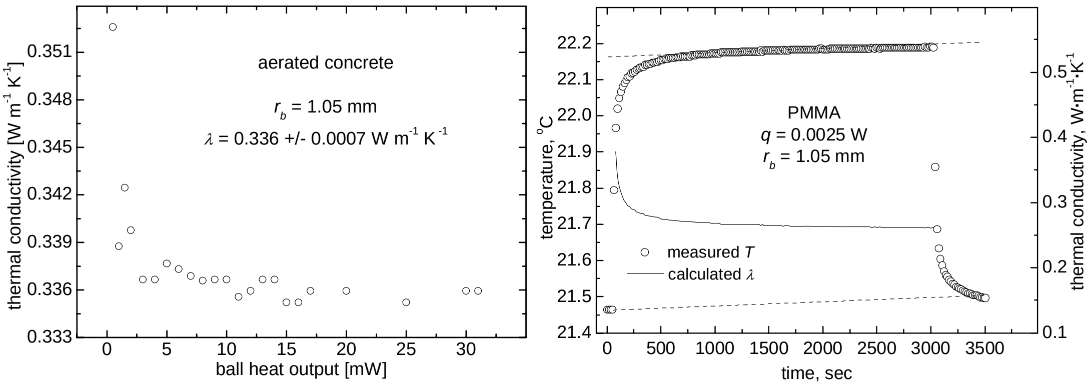

Fig. 9. Thermal conductivity of the aerated concrete as a function of the ball heat output (left), temperature response and thermal conductivity of the PMMA as a function of the time (right).

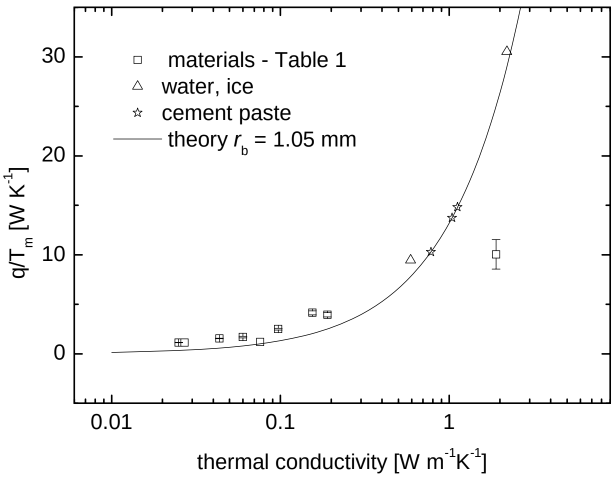

Fig. 10. Calibration function of the hot ball sensors. The full line follows ideal model (Eq. (6)) using ball radius q = 1.05 mm.

Analysis of data statistics has shown that the measurement reproducibility of the assembled specimen setup is rather high. Data scatter well below 1%. Reassembling induces data scattering within 3-5%. The highest contribution to the data scattering has been obtained in combination of the re-assembling and use of different sensors. The corresponding error bars are shown in Fig. 10. Two sets of sensors marked as HB300 (see Fig. 7 left – upper photo) and HB 400 (see Fig. 7 left – lower photo) have been included in calibration. Three kinds of materials have been tested, namely gas, fluids, paste and solids. Fluid (water) and paste (cement powder + water mixture, basetect) indicate significantly smaller deviations from the theoretical values. Similar feature can be found for solidified materials (cement paste, ice). The thermal contact between the ball and the surrounding material has been established already in fluid state and it survived after solidification. Therefore a small deviation from the theoretical values can be found even for this kind of materials. A clear data shift can be found for all other solid materials. Data are shifted to higher values for low thermal conductivity materials and to lower values for high thermal conductivity materials.

7 Discussion

A theoretical curve is plotted in the Fig. 10. using Eq. (6) where the ball radius is assumed to be r_b = 1.05 mm. A data shift to higher values (a difference between the experimental and theoretical value) can be found for low thermal conductivity range and to lower ones for high thermal conductivity range. To analyze the possible sources of data shift the working Eq. (2) is rewritten in a form

$$\lambda_{app} = \frac{q_o + q_w}{4\pi r_b (T_m + \delta T_b + \delta T_c)} = \lambda \frac{\left(1 + \frac{q_w}{q_o}\right)}{\left(1 + \frac{\delta T_b}{T_m} + \frac{\delta T_c}{T_m}\right)} \tag{7}$$

where λ follows ideal model (Eq. (2)) considering ball heat output q_o, $q = q_w + q_o$ is overall ball heat output, δT_b - temperature drop across the radius of the ball, δT_c – temperature drop at the thermal contact and q_w the heat loss through the connecting wires. A temperature T_m and a ball heat output q_o has to be used in Eq. (2) to obtain the correct data (see Fig. 11).

Two limiting cases can be found at the measurement considering Eq. (7). When high thermal conductivity materials are measured the lower value λ_{app} in comparison to the real one λ is calculated due to the significant contribution of both drops of temperature, a drop within the ball and a drop at the contact (see Fig. 11). The heat loss q_w is negligible as heat transport from the ball to the surrounding medium is highly effective. In addition, a changeable thermal contact may be achieved due to reassembling. This is a case of sandstone where data on thermal conductivity are shifted down (see Fig. 10) and, in addition high data scattering is found due to reassembling and use of different sensors. Generally, the higher thermal conductivity of the medium the stronger influence of the thermal contact on measuring process can be found.

An opposite situation can be found when low thermal materials are measured. Then both of the temperature drops, a drop within the ball and a drop at the contact are negligible but the heat loss through the wires q_w starts to play a role in the measuring process. This disturbing factor shifts the calculated thermal conductivity to the higher values.

The ball and thermal contact properties as well as heat loss through the connecting wires have been estimated using the Egs. (2), (4), (5) and (6) and scans of the temperature response from experiments on some materials given in Table 1. While measuring process of the high thermal conductivity materials is influenced by the hot ball and the contact properties the heat loss through the contact wires affects the experiment for low thermal conductivity materials.

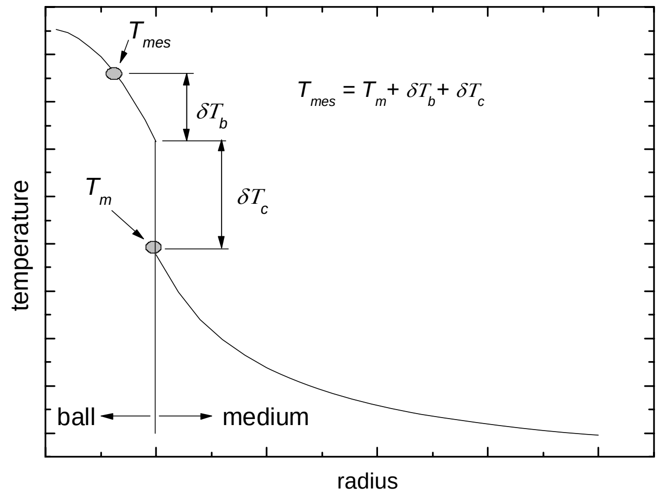

Fig. 11.Temperature distribution within the ball, thermal contact and the medium during the experiment.

Considering experimental data measured by the hot ball sensor (radius r_b = 1.05 mm) on sandstone and using ball heat output q = 0.006 W and measuring time 11 s one obtains experimental temperature response T_m = 0.676 ^{o}C. Using Eg. (2) one obtains q/T_{meas} = 8.875 J K^{-1} and apparent thermal conductivity λ_{app} = 0.6424 W m^{-1} K^{-1}. Using real thermal conductivity of sandstone λ = 1.9 W m^{-1} K^{-1} (Table 1) one obtains theoretical value q_o/T_m = 26.26 J K^{-1} (see Fig. 10). We assume that heat loss through the connecting wires is negligible $q_w \rightarrow 0$ due to high thermal conductivity of sandstone. Using (7) one obtains $\delta T_b + \delta T_b = 1.96 T_m$ that yields $\delta T_b + \delta T_b$ = 0.449^{o}C while theoretical temperature response corresponding to point T_m shown in Fig. 11 has value T_m = 0.229^{o}C, only. Thus the ball and the thermal contact properties strongly influence the resulting value of the thermal conductivity. Using Eqs. (4) and (5) one can estimate the contact thermal conductivity *H.* Assuming that the hot ball works in a regime of nearly perfect conductor the contact thermal conductivity is around H = 160 W m^{-1} K^{-1}. The estimated value is too low. However, data scattering of the thermal conductivity indicates that the thermal contact plays a serious role. In addition thermal conductivity of the ball is around $\lambda_b \sim 1$ W m^{-1} K^{-1} that is comparable to the sandstone thus one needs to include thermal properties of the ball into analysis, too. Then the resulted thermal contact conductivity would be higher.

The assumption has been accepted for experiments with low thermal conductivity materials that the ball and the thermal contact properties do not influence the measuring process, i.e. $\delta T_b/T_m + \delta T_b/T_m \rightarrow 0$ and the heat loss through the connecting wires affects the measuring process. Then we obtain estimations for heat loss through the connecting wires q_w/q_0 (Eq. 7) given in Table 2. Estimations have been performed in the following way: Using the ball heat output q one measures the temperature response T_{meas}. Using Eq. (2) one obtains q/T_{meas} and apparent thermal conductivity λ_{app}. Using real thermal conductivity λ (Table 1) one obtains the theoretical value q_o/T_m (see Fig. 10). Using (7) one obtains q_w and the theoretical ball heat output corresponding to the point T_m (T_m is a true value as $\delta T_b/T_m + \delta T_b/T_m \rightarrow 0$) shown in Fig. 11 has value q_o, only. Thus the connecting wires to represent a disturbing factor shifting data on thermal conductivity to higher values. Looking at Table 2 in detail one can find that q_w/q_0 grows with lowering the thermal conductivity of the measured materials, i.e. heat loss through the connecting wires increases with lowering the thermal conductivity of the surrounding material. Data corresponding to wood composite is an exception from the above mentioned rule due to its structure.

Table 2.: Estimations of heat loss through the connecting wires.

Material	q [mW]	T_{meas} [^{o}C]	q/T_{mes} [J K^{-1}]	λ_{app} [W m^{-1} K^{-1}]	q_0/T_m [J K^{-1}]	q_w [mW]	q_0 [mW]	q_w/q_0
PMMA	2.5	0.731	3.42	0.248	2.622	0.576	1.9	0.303
Calcium silicate	1.5	0.651	2.35	0.178	1.28	0.666	0.833	0.800
Phenolic foam	2	1.453	1.44	0.110	0.792	0.860	1.14	0.750
Styrodur	3.5	3.04	1.166	0.088	0.573	1.75	1.74	1.00
Wood composite	6	4.305	1.44	0.109	0.329	4.58	1.42	3.22

Measurement accuracy by a hot ball method requires a more detailed experimental as well as a theoretical analysis. While experimentation with different diameters of the connecting wires may help to optimise the hot ball method for testing low thermal conductivity materials a new approach has to be worked out for measurement of high thermal conductivity materials where contact thermal resistance plays a predominant role.

8 Conclusion

A new version of the transient method – the hot ball method for measuring thermal conductivity has been presented. The method is based on delivering constant heat by a heat source in the form of a ball into the non-limited surrounding medium for times $t > 0$. A working equation of the hot ball based on a model of the empty sphere in a non-limited surrounding medium has been found. Theoretical analysis of the measuring process based on a model of a ball made of the perfect conductor working in transient regime and a model of a ball made of the real material working in the steady state regime have been presented. The analysis gives a criterion for the thermal conductivity of the ball material λ_0 and surrounding medium λ. Good measurements can be obtained for $\lambda_0 > \lambda$. A hot ball sensor has been constructed consisting of two elements a heater and a thermometer. Both elements are fixed in a ball by epoxy resin. Diameter of the ball ranges within 2÷2.3 mm. A verification of the theory has been performed using a set of materials having the thermal conductivity in the range from 0.027 up to 2.2 W m^{-1} K^{-1}. Additional study needs to be performed in order to clear measurement uncertainty in detail.

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