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Review

Experimental methods of the magnetocaloric effect studies

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ABSTRACT

The methods of experimental investigations of the magnetocaloric parameters (adiabatic temperature change and isothermal magnetic entropy change caused by external magnetic field) are reviewed and discussed. The direct and indirect methods are compared and their advantages and disadvantages are considered. Possible influence of the used methods on the obtained results is regarded. The main attention is paid to the direct methods of measurements. The realization of the dynamic mode of the direct adiabatic temperature change measurement is considered. Importance of the magnetocaloric measurements in dynamic mode for characterization of the magnetocaloric materials suitable for using as working bodies in magnetic heat machines is shown. The methods of the experimental data processing are discussed.

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Méthodes expérimentales pour l'étude de l'effet magnétocalorique

Mots clés : Effet magnétocalorique ; Froid magnétique ; Méthodes directes ; Méthodes indirectes ; Magnétocalorique direct Mesures

1. Introduction

The study of the magnetocaloric effect (MCE) in magnetic materials is of great importance both from fundamental and practical points of view. On the one hand, MCE can give additional information about magnetic state and magnetic phase transition of a material under investigation. On the other hand, the essential interest to MCE is related with its possible application in magnetic refrigerators. The MCE is characterized by two magnetocaloric parameters: the

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Nomenclature

C	heat capacity [J kg^{-1} K^{-1}]
ΔH	magnetic field change [T]
ΔS_M	isothermal magnetic entropy change [J kg^{-1} K^{-1}]
ΔT	adiabatic temperature change [K]
δH	periodic magnetic field changes [T]
δT	periodic temperature changes [K]
f	frequency [Hz]
H	magnetic field (given in units of an induction) [T]
M	magnetization [emu g^{-1}]
M_s	saturation magnetization [emu g^{-1}]
MCE	magnetocaloric effect
MMS	magnetocaloric measuring setup
min	minute
S	total entropy [J kg^{-1} K^{-1}]
S_0	entropy at zero temperature [J kg^{-1} K^{-1}]
T	temperature [K]
T_{ac}	periodical variation of the sample temperature in heat capacity measurements [K]
T_c	Curie temperature [K]
x_0	ferromagnetic fraction at zero field

Subscripts

0	zero temperature/field
ac	periodic variation
C	Curie
f	final
H	at constant magnetic field
i	initial
M	magnetic
s	saturation
T	at constant temperature

adiabatic temperature change ΔT and the isothermal magnetic entropy change ΔS_M under magnetic field changing. It should be noted, that ΔT is directly associated with temperature span, and the ΔS_M determines the cooling capacity in magnetic refrigerators.

ΔT can be determined using the direct and indirect methods. Today the indirect methods are used much more often than the direct techniques, probably because it is considered that there are usually large difficulties in carrying out the direct ΔT measurements. At the same time, only direct measurements of the ΔT can give information about dynamic magnetocaloric properties of a material, namely, dependence of $\Delta T(T, H)$ on magnetic field change rate. In addition, the problem of the possibility of using the indirect methods for accurate MCE determination in materials undergoing the first-order magnetic phase transition remains open. Direct and indirect methods are discussed in more detail below.

1.1. *Indirect and direct MCE measurement methods*

The indirect methods permit to calculate $\Delta S_M(T, H)$ of the sample from magnetization and/or $\Delta T(T, H)$ and $\Delta S_M(T, H)$ from heat capacity data. The magnetic entropy change $\Delta S_M(T, H)$ is related to the magnetization (M), magnetic field (H) and absolute temperature (T) through one of the Maxwell's relations:

$$\left(\frac{\partial S_M(T,\ H)}{\partial H}\right)_T = \left(\frac{\partial M(T,\ H)}{\partial T}\right)_H, \tag{1}$$

which after integration yields:

$$\Delta S_M = \int_{H_i}^{H_f} \left(\frac{\partial M}{\partial T}\right)_H dH, \tag{2}$$

Thereby the numerical calculations with the help of the Equation (2) give the value of the magnetic entropy change in the desired temperatures and field range. The method described above is widely used to determine the temperature and field dependences of the magnetic entropy change from magnetization data (Tishin and Spichkin, 2003).

Maxwell's relations, strictly speaking, can be used for calculations of the magnetic entropy change from magnetizations curves only in case of the second-order phase transition, because the derivative of the magnetization with respect to temperature $\partial M/\partial T$ becomes infinite at the first-order transition. In case of the first-order magnetic phase transition, the magnetic entropy change can be determined using the Clapeyron – Clausius equation:

$$\frac{dH}{dT} = -\frac{\Delta S_M}{\Delta M}, \tag{3}$$

where ΔS_M and ΔM are the differences in magnetic part of the entropy and magnetization between the different magnetic states at the temperature of transition.

However, the infinite $\partial M/\partial T$ can arise only in ideal first-order phase transition and in real materials it is finite in general. Meanwhile, it is important to note that, by definition, the Maxwell's relations can only be correctly applied if the system is in thermodynamic equilibrium and homogeneous (Amaral and Amaral, 2010). Amaral and Amaral (2010) used the Maxwell's relations and the Clapeyron – Clausius equation to calculate the magnetic entropy change from the magnetization data in case of the first-order magnetic phase transition. It was reported that ΔS_M values obtained from the Maxwell's relations and from the Clapeyron – Clausius equation need not necessarily agree, and are indeed not directly comparable.

Giguere et al. (1999) conducted direct and indirect measurements of ΔT on $Gd_5Si_2Ge_2$. As a result, it was found that the ΔT determined directly was significantly smaller than the ΔT calculated via the indirect method as an isentropic difference between the zero field total entropy $S(H = 0,T)$ and the total entropy S (H, T) at nonzero magnetic field H (Pecharsky and Gschneidner, 1999). $S(H = 0,T)$ was calculated using zero field heat capacity and S (H, T) was calculated using $S(H = 0,T)$ and ΔS_M calculated from magnetization data with the help of Maxwell's relations. On the contrary then ΔS_M was determined from Clapeyron – Clausius equation, calculated indirectly ΔT

showed good agreement with the direct measurements data. Giguere et al. (1999) considered this discrepancy in the frame of thermodynamics of first-order phase transition and concluded that the Maxwell's relations were not usable for $Gd_5Si_2Ge_2$ unlike Clapeyron – Clausius equation.

Gschneidner et al. (2000) and Sun et al. (2000) disputed the conclusions of Giguere et al. (1999). It was reported that direct measurements of ΔT conducted by Giguere et al. (1999) were made under nonequilibrium conditions, and obtained values cannot be compared with the results of indirect determination of ΔT from heat capacity data derived at nearly equilibrium conditions. In the direct measurements conducted by Giguere et al. (1999) the sample was moved to the high magnetic field (7 T) for a few seconds. Gschneidner et al. (2000) noted that when the rate of the magnetic field change was around 2 T min^{-1} (i.e. under the nearly equilibrium conditions) in the direct measurements obtained value was in good agreement with the nearly equilibrium values estimated from heat capacity data recorded on the same material.

Caron et al. (2009) report the method to determine the magnetic entropy change in materials with hysteretic first-order transitions. It was noted that the "colossal" peaks in the entropy change arise not from the application of the Maxwell's relations. The cause of these peaks is incorrect magnetization isotherms measurements in the materials that undergo the first-order magnetic phase transition. Caron et al. (2009) noted that usually isothermal magnetization measurements are made as follows: initially the sample is cooled down to lowest measurement temperature, and then the magnetic isotherms are measured at each desired (and stabilized) temperature under heating up to the highest measurement temperature. It was reported that namely described measurement process leads to the "colossal" peaks in the $\Delta S_M(T)$ curves. In order to eliminate the huge peaks Caron et al. (2009) suggested to heat the sample above the magnetic ordering temperature previous to each magnetic isotherm measurements in order to convert it each time in initial not ordered (paramagnetic) state. This measurement process was applied to $MnFeP_{0.8}Ge_{0.2}$, $La(Fe,Si)_{13}$, $Mn_{0.99}Cu_{0.01}As$ and $Gd_5Ge_{2.3}Si_{1.7}$ single crystal and it was found that the unphysical peaks on the $\Delta S_M(T)$ curves were not observed.

Levitin et al. (1997) suggested a method for ΔT determination using adiabatic magnetization measurements. This technique consists in comparing of the isothermal and adiabatic $M(H)$ curves. The adiabatic magnetization curve measured at some initial temperature will intersect the isothermal magnetization curves derived at higher temperatures. The points of the intersection determine the $\Delta T(H)$ dependence. The capability of this method was demonstrated on paramagnetic single crystal $Gd_3Ga_5O_{12}$ by Levitin et al. (1997). The adiabatic measurements were made in a pulsed magnetic field at an initial temperature of 4.2 K with the field rising rate of about 50 kT s^{-1}. As a result the $\Delta T(H)$ curve was obtained and ΔT was found to be 46 K for $\Delta H = 40$ T at initial temperature of 4.2 K.

The adiabatic temperature change and the magnetic entropy change can be also evaluated from the heat capacity temperature dependences measured in different magnetic fields. If the experimental dependence of material's heat capacity $C(T, H)$ is known its total entropy $S(T, H)$ can be calculated using following equation:

$$S(T,H) = \int_0^T \frac{C(T,H)}{T} dT + S_0, \quad (4)$$

where S_0 is the entropy at zero temperature. The isothermal magnetic entropy change can be determined from the total entropy dependences obtained in initial (H_i) and final (H_f) magnetic fields:

$$\Delta S_M(H_f,T) = \Delta S(H_f,T) = S(H_f,T) - S(H_i,T), \quad (5)$$

and ΔT can be obtained as:

$$\Delta T(H_f,T) = T(S,H_f) - T(S,H_i), \quad (6)$$

where $T(S, H_f)$ and $T(S, H_i)$ are the temperatures in the fields H_f and H_i at constant total entropy S. This method was used by Brown (1976), Pecharsky and Gschneidner (1999), Lee (2004) and others.

The problem of MCE measuring around the first order magnetic phase transition in which the coexistence of two magnetostructural phases is observed was considered by Guillou et al. (2012). They measured the MCE of $Eu_{0.58}$ $Sr_{0.42}$ MnO_3 from magnetization and heat capacity measurements. Special attention was paid to MCE measurements when the applied field is less than the transition field (around 1 T for $Eu_{0.58}$ $Sr_{0.42}$ MnO_3) which induces the first order magnetic phase transition. Direct measurements were made under quasi adiabatic conditions. It was noted that the indirect methods based on Eqs. (1) and (2) and Eqs. (3) and (4) has problems. The $Eu_{0.58}$ $Sr_{0.42}$ MnO_3 demonstrates the ferromagnetic and spin-glass phase coexistence area. In case of magnetic measurements in the fields around 1 T the Maxwell's relations determine only the temperature dependence of the preformed ferromagnetic fraction, which not corresponds to ΔS_M. As for the caloric measurements the problem is that the magnetic state at zero field (at ground state using for ΔS_M determination) can show coexistence of ferromagnetic and spin-glass states. In order to take into account the presence of these two phases coexistence it was suggested to use the temperature curve of ferromagnetic fraction $x_0(T)$ in zero field. It was obtained that the maximum of ΔS_M evaluated with the use of $x_0(T)$ curve is $-0.4\,J\,kg^{-1}\,K^{-1}$ which an order of magnitude less than the value obtained without the use of this technique. It was reported that the appropriate estimated value of ΔT (~0.2 K) is in a good agreement with the results of direct ΔT measurements (~0.1 K) conducted by Guillou et al. (2012).

At the present time the indirect methods of the isothermal magnetic entropy and adiabatic temperature changes determination have a number of above mentioned disadvantages, which do not arise when the adiabatic temperature change is measured directly. The method for direct measurements of the ΔT was proposed by Weiss and Forrer (1926). The first measurements in strong magnetic field were made by Clark and Callen (1969). The temperature of the sample was measured by a thermocouple. Kuhrt et al. (1985) used the differential thermocouple, which measures the temperature difference between a massive copper sample holder and the sample for ΔT measurements. Usually direct methods include measurements of the sample temperatures T_i and T_f when the external magnetic fields H_i and H_f are applied (T_i, T_f, H_i and H_f

are initial and final temperatures and magnetic fields, respectively). ΔT is then determined as the difference between T_i and T_f values.

The pulsed magnetic fields were used to conduct the direct ΔT measurements by Borovikov et al. (1981) (ΔT measurement accuracy 0.5 K) and Ponomarev (1986). Dan'kov et al. (1997) concluded that the pulse field apparatus allowed measurement of the MCE with an accuracy of 8–15%, depending on the temperature range and MCE value.

Canepa et al. (2005) measured the MCE of three eutectic compositions: Gd–Gd_7Pd_3 ($Gd_{76}Pd_{24}$), Gd–GdZn ($Gd_{73}Zn_{27}$), Gd–GdCd ($Gd_{75}Cd_{25}$). To perform direct $\Delta T(T)$ measurements Canepa et al. (2005) modified the probe produced by Oxford Laboratories. The sample holder consisted of two Teflon plates, which provided thermal isolation. The sample, consisted of two plates, was inserted between the Teflon plates, which were placed in the copper sample holder with a heater. ΔT was measured by a thermocouple, whose junction was jammed between the sample plates. The sample holder was closed with a copper-brass cylinder. The measurements was performed under high vacuum conditions (10^{-7} bar) and the measuring insert was placed between the pole gaps of electromagnet in a cylinder filled with liquid nitrogen. Magnetic field was increased up to 1 T with a rate of 1 T s^{-1} and the sample could be heated from 100 up to 340 K at a rate of about 1 K min^{-1} or slower. It was reported that the maximum ΔT measured for $Gd_{76}Pd_{24}$, $Gd_{73}Zn_{27}$, $Gd_{75}Cd_{25}$ with the help of the setup described above was about 1.7 K for magnetic field change of 1 T.

Lin et al. (2006) reported a direct measurement of the adiabatic temperature change in polycrystalline $La_{0.67}Ca_{0.33}MnO_3$. They used the differential thermocouple for the ΔT determination in which the measuring junction was fixed between the two plates of the sample, and the reference one was fixed between the two plates of the Al_2O_3. The sample and two Al_2O_3 plates were mounted on the plastic bar, which was held in plastic tube. The plastic tube was inserted in a bath through which the isothermal liquid flew, providing heating or cooling of the sample. ΔT induced by a magnetic field change of 2.02 T measured using this setup reached of 2.4 K near $T_c = 266$ K.

In the direct methods described above the magnetic field was created by electromagnets or superconducting solenoids and the magnetic field change was provided by switching the electric current in the magnets or solenoids on/off ("switching on" technique). It is also possible to change the magnetic field by inserting the sample holder with a sample into a static magnetic field. Such measurements allow to overcome the difficulties in "switching on" technique associated with long field rising times (up to several minutes), leading to low field changing rates. The problems, related with long time of the field changing in electromagnets and superconducting solenoids can be also overcome by using of Halbach-type permanent magnet magnetic field sources with variable magnetic field. Measurements using static magnetic fields and moving sample were made by Nikitin et al. (1985), Tishin (1988), Gopal et al. (1997), Dinesen et al. (2002). The estimation of the total error in the MCE measurements obtained by Tishin (1988) was about 10%. Dinesen et al. (2002) made direct measurements of the MCE in $La_{0.6}Ca_{0.4}MnO_3$ ceramic perovskite in static magnetic field. The temperature difference was determined by differential thermocouple and magnetic field was generated by electromagnet. The sample holder made of Teflon moved inside and out of the electromagnet pole gap. In this way the field could be applied or removed in less than one second. The maximum of the temperature change of about 0.5 K was observed with a field change of 0.7 T.

Direct techniques also include the noncontact thermoacoustic method of MCE measurements proposed by Gopal et al. (1995). In thermoacoustic method the small ac magnetic field causes the infinitesimal periodic temperature changes δT induced in the sample due to the MCE. These temperature changes cause periodic heating of the neighboring gas layer which begins to expand and contract, producing thermoacoustic waves. Thermoacoustic waves then are detected by a microphone and lock-in amplifier. This method can be attributed to both direct and indirect methods, because ΔT is calculated from obtained experimental values, but the measured value is the response of the sample under investigation arising in the ac magnetic field due to the MCE.

The thermoacoustic method was first applied by Gopal et al. (1995) to ΔT determination for Gd and $Gd_{91.8}Dy_{8.2}$ and $Gd_{89.9}Er_{10.1}$ alloys. The measuring cell with the sample was placed between the poles of electromagnet, which allowed to obtain static magnetic fields up to 0.45 T. The ac magnetic field directed parallel to the static field was generated by the modulation coils placed on the electromagnet poles. The value of the ac field was up to $\delta H = 0.025$ T and its frequency was 4 Hz. The temperature of the cell was measured by a thermistor placed on its wall. The pressure response microphone was located outside the magnetic field area in order to minimize the stray induced by the magnetic field. The voltage of the microphone signal is proportional to the temperature change δT which usually is the order of tens millikelvin. The system was calibrated using Gd on the basis of equation:

$$dT = -\frac{T}{C_H}\left(\frac{\partial M}{\partial T}\right)_H dH, \tag{7}$$

and known data for Gd magnetization $M(H, T)$ and heat capacity $C(H, T)$. The measurable quantity in this method is $\delta T/\delta H$. With the help of the molecular field theory it was shown that at a given temperature δT is a linear function of the square magnetization δM^2. Thus, one can convert measured $\delta T/\delta H$ into $\delta T/\delta M^2$ for $M > M_s$ where M_s is the saturation magnetization using magnetization data and obtain the slope of the $\Delta T(M^2)$ dependence which then can be convert to the $\Delta T(H)$ dependence. The magnetization data was obtained by SQUID magnetometer. Gopal et al. (1995) reported that the maximum of the Gd adiabatic temperature change ΔT determined on the basis of the measured δT caused by the ac magnetic field 0.02 T at dc field 0.45 T and magnetization data was about 2 K, which corresponds to $\Delta T/\Delta H$ value of 4.4 K T^{-1}. It should be noted that this value of $\Delta T/\Delta H$ is approximately two times greater than the values 1.9–2.9 K T^{-1} obtained by other direct and indirect methods (Tishin and Spichkin, 2003).

Guimaraes et al. (2009, 2010) reported another scheme for the thermoacoustic measurements of the adiabatic temperature change in Gd and $Gd_5(Ge_{1-x}Si_x)_4$ compounds. It was noted that the magnetization data are required only for the calibration of the setup (see Eq. (7)). In the method the isotherms $\delta T(H)$ were measured in static magnetic field increasing from zero to 5 T. Then the adiabatic temperature

change ΔT for the field H and the temperature T was determined by integration of the $\delta T(H)$ curves over H. The design of the measurement apparatus used by Guimaraes et al. (2009) was similar to that used by Gopal et al. (1995), but ac magnetic field had higher frequency –270 Hz.

Recently the results of the direct measurements of the dynamic magnetocaloric properties ΔT and ΔS_M, i.e. theirs behavior on the magnetic field change rate were reported (Spichkin et al., 2009; Tishin et al., 2007). The dynamic magnetocaloric properties investigations are quite important especially from the practical point of view for development of designs of magnetic refrigerators. The largest MCE are found in materials with first-order magnetic phase transitions that may have substantial hysteresis which may be sensitive to the magnetic field change rate and affect parameters of magnetic refrigeration device. Therefore, it is important to study a magnetocaloric material in order to verify $\Delta T(H)$ curves behavior at various magnetic field rates. It should be noted that only direct methods can give information about dynamic magnetocaloric properties.

Tishin et al. (2007) conducted the measurements of adiabatic temperature change on high purity Gd polycrystal and high purity Gd, Tb and Dy single crystals in a dynamic mode. In this way ΔT values between the initial and final fields are continuously recorded at magnetic field sweep rates of 0.05 and 0.5 T s^{-1}. ΔT was measured by thermocouple, one junction of which was attached directly to the sample and another was fixed on the non-magnetic sample holder. The temperature of the sample was controlled by an electric heater and stabilized with an accuracy of 0.1 K. The sample holder was placed in an outer case of the measuring insert. The insert was dipped into a Dewar filled with liquid nitrogen so that the sample was between the poles of the electromagnet. The magnetic field generated by an electromagnet was measured by a Hall sensor. The thermocouple and the Hall sensor signals were recorded simultaneously under control of computer, which allowed to obtain continuous $\Delta T(H)$ curves. It was noted that the $\Delta T(H)$ behaviors at different field sweep rates are not the same.

Another experimental apparatus for direct MCE measurements called Magnetocaloric Measuring Setup (MMS) was presented in the work of Spichkin et al. (2009). The MMS permits to make the adiabatic temperature change measurements in a dynamic mode and in general has the same configuration as the apparatus described above except that the magnetic field was created by a Halbach permanent magnet magnetic field source, which allow one to conduct measurements in the fields up to 1.7 T.

The magnetic field source of MMS consists of two coaxial Halbach cylinders – inner and outer, which rotate one relative to another by electromotor. The field in the working bore is a sum of the fields of the outer and inner cylinders. The apparatus consist of the following main parts: measuring insert, cryogenic Dewar, variable magnetic field source, ΔT measuring system, temperature measuring and control system, magnetic field measuring and control system and control computer. The setup allows carrying out measurements in multicycled mode when the magnetic field is changing periodically many times. The multicycled mode repeats the process acting in real magnetic refrigerators. Authors measured the $\Delta T(H)$ curves of the polycrystalline Gd by the direct dynamic method at the magnetic field change rate of 1.5, 3 and 5 T s^{-1} using the described setup. In addition, they demonstrated the ΔT on time dependence of the polycrystalline Gd obtained in multicycle mode at the magnetic field change rate of 1.5 T s^{-1}.

1.2. *Experimental setup for dynamic MCE and heat capacity measurements*

So, as it can be seen from the previous section there are many methods of MCE measurements, but no one experimental setup for today allows to determine as ΔT, as ΔS_M in one apparatus. At the same time experimentalists need both parameters to characterize magnetocaloric properties. For new applications of MCE it is also necessary to measure MCE with high sensitivity and accuracy. Here we present the apparatus, which permits to conduct the high sensitive direct ΔT measurements in dynamic mode as well as to measure temperature and field dependences of heat capacity. The general scheme of this setup is based on the method presented in the work of Sullivan and Seidel (1968) allowing one to determine heat capacity by application of alternating heating to the sample under investigation and detection of the periodical change of the sample temperature using a lock-in technique (ac-calorimetry). In addition to the heat capacity similar method can be applied to the adiabatic temperature change determination which is caused by alternating magnetic field. The method of ac calorimetry does not need strict thermo insulation of the sample and is characterized by high sensitivity and accuracy (Sullivan and Seidel, 1968).

Fig. 1 shows a schematic drawing of the experimental setup. It consists of the following main components: Dewar; measuring insert with the sample holder; Halbach-type permanent magnet magnetic field source with variable magnetic field; temperature change measuring system, including digital voltmeter, lock-in amplifier and reference signal former consisting of the light chopper and optocoupler, temperature measuring and control system with temperature controller; magnetic field measuring system with Hall sensor and gaussmeter; and control computer. The sample and the heater feeding by alternating sinusoidal current used in heat capacity measurements are mounted to the non-magnetic plate. The plate is suspended on the brass sample holder by threads and the sample holder is placed inside evacuated case, which provides the adiabatic conditions. In ΔT measurements the sample holder with the sample is located in the ac magnetic field changing at the frequency f, which causes the periodical sample temperature change due to MCE. The ΔT signal is measured by the thermocouple, the measuring junction of which is placed on the sample and the reference one is fixed on the sample holder. The signal from thermocouple is detected by the lock-in amplifier and the amplitude of this signal is proportional to the adiabatic temperature change. So, with the help of lock-in amplifier it can be possible to measure $\Delta T(T)$ curves at constant magnetic field amplitude with high accuracy and sensitivity. It is also possible to measure $\Delta T(H)$ curves at constant temperature with usual accuracy with the help of digital voltmeter (see Fig. 1).

The reference signal for the lock-in amplifier is generated by a light chopper of the reference signal former mounted

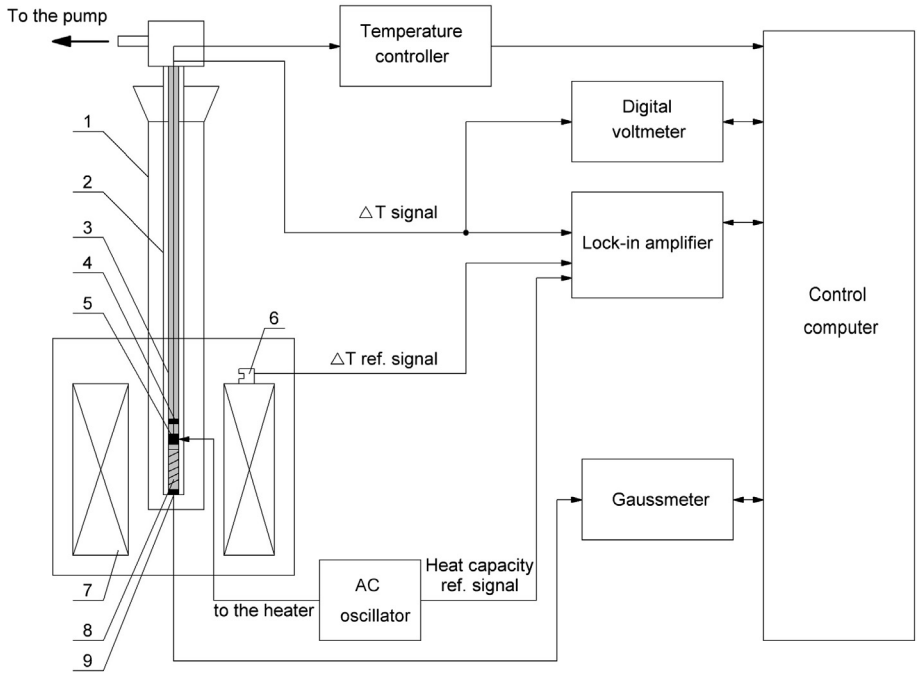


Fig. 1 – The schematic drawing of the apparatus for direct measurements of the MCE: 1 – Dewar, 2 – outer case of the measuring insert, 3 – sample holder, 4 – resistive temperature sensor, 5 – sample with a thermocouple junction and the heater feeding by alternating current, 6 – reference signal former, 7 – variable magnetic field source, 8 – heater, 9 – Hall sensor.

directly on the one of the rotated Halbach cylinders. The frequency of the field changing can be varied up to 1 Hz, which corresponds to the magnetic field change rate of 6 T s^{-1}. The temperature variation and stabilization are provided by cooling with the help of liquid nitrogen and heating by the resistive heater on the sample holder. The temperature of the sample is measured by resistive temperature sensor fixed on the sample holder and thermocouple, and the temperature controller permits to set and keep necessary measurement temperature. It is also possible to replace the Habach-type field source by a solenoid to conduct measurements in weak fields (up to 0.1 T). The solenoid in this case is feeding by alternating current from an amplifier and generator and the reference signal for lock-in amplifier is taken from this generator.

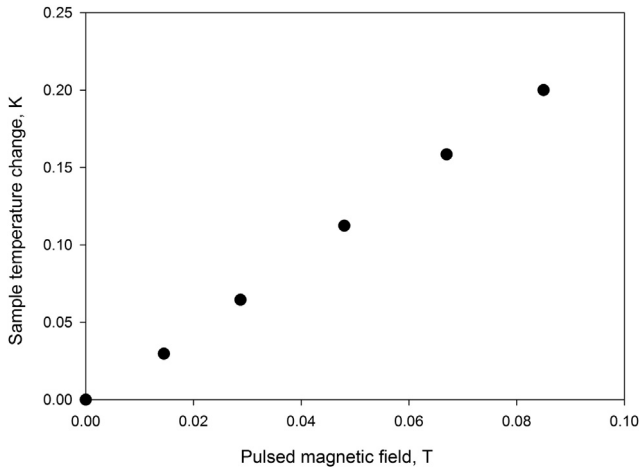


Fig. 2 – Temperature change of Gd at various weak magnetic fields measured with the use of non synchronous part of the setup.

Furthermore the measurements can be conducted at the pulsed magnetic field when the solenoid is connected to the source of the pulsed current based on the capacitor bank. In this case the temperature change can be measured by the digital voltmeter.

In addition to ΔT measurements the presented experimental setup allows ac-measuring of the heat capacity. In order to determine the heat capacity sinusoidal heat at frequency f is applied to the sample with the help of the heater fixed on the sample plate and feeding by alternating current, which causes periodical variation of the sample temperature T_{ac}. T_{ac} is measured by the thermocouple placed on the sample and the lock-in amplifier. The heat capacity is determined from T_{ac}, which, according to Sullivan and Seidel (1968), is inversely proportional to the heat capacity. The heat capacity measurements can be made in zero and nonzero static field, the latter is created at necessary value by the Halbach-type field source. Then $\Delta S_M(T, H)$ can be determined on the basis of the method described above (Eq. (4), (5)). The experimental setup allows one to conduct the ΔT and heat capacity measurements at the temperatures from 78 K to 380 K and in the fields up to 1.8 T.

In this work we present results of the preliminary test measurements of the Gd temperature change at weak (up to 0.1 T) pulsed magnetic fields. The pulsed magnetic field was created by the solenoid and source of the pulsed current. In these measurements we tested the non synchronous part of the setup, in which the temperature change was measured by

the digital voltmeter with usual accuracy. The several experimental points obtained at room temperature were plotted on $\Delta T - H$ diagram showed in Fig. 2. As mentioned above these results are preliminary but in spite of this the values of $\Delta T/\Delta H$ are in a good agreement with the values of 1.9–2.9 K T^{-1} obtained by other direct and indirect methods (Tishin and Spichkin, 2003).

2. Conclusion

In conclusion, various methods of ΔS_M and ΔT measurements are considered. Direct and indirect methods of adiabatic temperature change determination are discussed and their advantages and disadvantages are reviewed. Importance of the direct ΔT measurements in dynamic mode and its possible realizations are shown. The experimental setup for high sensitive direct ΔT measurements in dynamic mode based on the lock-in detection is presented. The apparatus also allows to measure temperature and field dependences of the heat capacity. ΔT and heat capacity can be measured in the temperature interval from 78 to 380 K and in the fields up to 1.8 T.

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