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Dynamic properties of cryogenic temperature sensors

Abstract. *The article presents the results of dynamic tests of the most popular temperature sensors at low temperatures. The resistance sensors (Pt100) and thermocouples (type E and T) were tested. Measurements were carried out in the vacuum cryostat cooled by the closed cycle helium crycooler. The analysis of the temperature characteristics of sensors, the sensitivity and the influence of external factors on the measurement were presented in the paper.*

Streszczenie. *W artykule przedstawiono wyniki badań dynamicznych najbardziej popularnych czujników temperatury w warunkach kriogenicznych. Badaniom zostały poddane czujniki rezystancyjne (Pt100) oraz czujniki termoelektryczne (typ E i T). Pomiary zostały zrealizowane w kriostacie próżniowym współpracującym z kriochłodziarką helową. Przedstawiono analizę charakterystyk temperaturowych czujników, ich czułości oraz wpływ czynników zewnętrznych na pomiar.* ***Właściwości dynamiczne czujników temperatury w warunkach kriogenicznych****.*

Keywords: cryogenics, temperature sensors.
Słowa kluczowe: kriogenika, czujniki temperatury.

Introduction

Temperature measurements in cryogenic conditions (below 123 K) are the key element of many materials research, particularly in the field of superconductivity. Superconducting materials achieve their unique properties at very low temperatures. Critical temperatures for low-temperature superconductors are below 20 K. The so-called high temperature superconductors have critical temperatures of 90÷110 K. The timely measurement of low temperatures is very important in controlling operation of the superconducting systems, especially in emergency situations [1].

A variety of thermometers are used to measure cryogenic temperatures. The most important cryogenic thermometers are: gas, helium vapour pressure, helium melting pressure, Coulomb blockade, noise, capacitance, magnetic with nuclear or electronic paramagnetic and the most popular electric sensors, i.e. resistance, thermoelectric and pn-junction. The fundamental properties of cryogenic sensors are known and well studied [2,3]. Unfortunately, there are no clear reports in the literature about the dynamic properties in this temperature range.

The article presents results of dynamic tests of the most popular electrical temperature sensors in the range of 20÷120 K. The resistance sensors (Pt100) and thermocouples (type E and T) were tested. Measurements were carried out in the vacuum cryostat cooled by the closed cycle helium crycooler. The silicon diode DT-670-SD connected to the temperature controller was used as a reference sensor. The analysis of the dynamic temperature characteristics of sensors, the sensitivity and the influence of external factors on the measurement were presented in the paper.

Temperature sensors in cryogenic systems

In the process of proper selection of the sensor one should take into account typical parameters such as the temperature range, sensitivity, measurement resolution, repeatability and uncertainty but also other parameters like the size and thermal capacity of the sensor, response time, time stability, the susceptibility to environmental effects (magnetic fields, ionizing radiation), the effect of temperature on the mechanical and thermal properties of the sensor. The economic aspects, mostly resulting from the complexity of the measurement system and the specific design of the sensor, are also very important. It should be noted that the electrical and thermal properties of materials in cryogenic temperatures have a strongly non-linear characteristics. Therefore, the response characteristics of the sensors operating in this temperature range are also non-linear and individual [4]. The heat transfer from the environment to the sensors through the electrical feedthroughs and leads is an additional problem resulting from the nature of the measuring system and a large temperature gradient.

Temperature measurement using most of the cryogenic sensors is made by contact method, i.e. a sensor is directly connected to the tested body. In this case the total measurement uncertainty consists of three major components. The first component results from changes in the temperature distribution in vicinity of the point of contact of the sensor with a test body. It can be reduced by using sensors with low thermal capacity, small size and good thermal conductivity and the emissivity similar to the tested object. The thermal resistance of the connection between the sensor and the object is the cause of the existence of the second uncertainty component. The contact resistance and the resulting temperature gradient can be reduced by increasing the clamping force of the joint and the appropriate surface preparation to ensure the good thermal contact. In fact, the temperature measured by the sensor is a difference between the ambient temperature and temperature of the tested object. It is the third component of the uncertainty of the contact method. In the vacuum cryostats heat exchange occurs practically only by radiation, which significantly reduces the temperature difference between the ambient and the object. In closed cryogenic systems with the vacuum insulation, the uncertainty related to existence of the electrical feedthroughs may occur. The feedthrough causes the additional heat leak to the cooled space (fourth uncertainty component). This component can be reduced by using the leads with low thermal conductivity and decrease of the leads cross-section.

Resisitive sensors (RTD – resistive temperature detector), thermocouples and semiconductor diodes are the most common cryogenic sensors used in the temperature range of 1-100 K. Resistive sensors with a positive temperature coefficient (PTC) are made of pure metals (platinum, copper, nickel) or pure metals with small impurities (rhodium-iron, platinum-cobalt). A negative temperature coefficient (NTC) sensors include sensors made of germanium, carbon glass, zirconium oxynitride (CERNOX^{TM}), ruthenium oxide (ROX^{TM}) [3]. Platinum sensors are the most commonly used RTDs due to high measurement accuracy over a wide temperature range of

15-725 K. The International Temperature Scale of 1990 (ITS-90) uses the platinum thermometer as a primary thermometer in range of 13.8033-1234.93 K [5]. A standard platinum sensors, constructed in the form of hermetic capsule with a platinum wire wounded inside, provide the highest level of precision. Unfortunately, these sensors are large and characterized by long response time and are therefore impractical. Thin film resistors, deposited on a ceramic or glass, are a competitive solution (smaller size and shorter response time). A less stability, a smaller range of measured temperatures and a significant hysteresis effect are their major disadvantages. A four probe method is required for an exact measurement of resistance to the eliminate of the contact phenomena. This is connected with the necessity of doubling the number of electrical feedthroughs in the cryostat.

Thermocouples are characterized by the simplest construction among all electrical sensors for temperature measurement, and thus the lowest unit price. The most important advantages of thermocouples are: small dimensions of the junction; small heat capacity; short response time; repeatable temperature characteristics; negligible self-heating effect; negligible effect of the magnetic field. Unfortunately, thermocouples require the use of complicated conditioning circuits, providing to take into account the temperature of free end and amplification of low signals. In the cryogenic systems, thermoelectric power measurement problem is particularly difficult because of large distances between the junction and measuring instruments and the use the vacuum feedthroughs. Thermocouples of type E (chromel-constantan), type T (copper-constantan) and type K (chromel-alumel) are the most popular in cryogenic applications. Type E thermocouples is particularly recommended to use in this temperature range due to the high thermoelectric power, the low thermal conductivity of both legs and non-magnetic properties. Below 10 K chromel - Au/Fe (0,03% or 0,07% Fe) thermocouples are used [2,3].

Temperature measurement by semiconductor diodes uses temperature dependence of the voltage drop in p-n junction at a constant current. Diode sensors are made of silicon, GaAs or GaAlAs [3]. They are characterized by the wide temperature range (1÷500 K) and the large voltage signal. The relatively high power dissipation and significant sensivity to magnetic field (Si) are the main problems in applications of such sensors in cryogenics. Accurate measurements require an individual calibration of each sensor.

Experiment

In presented studies the responses of two groups of temperature sensors (RTD and thermocouples) to dynamic and quasi-static temperature changes of the reference object (heat exchanger) were observed. The heat exchanger in the form of a copper disk (Ø140x10 mm) was cooled by closed cycle helium cryocooler ARS DE-210AF. The temperature of the heat exchanger was controlled by the precise temperature controller Lakeshore 331. Tested sensors: thin layer RTD (Pt100 – 2 x 2.3 x 0.65 mm), thermocouples (type E, type T – wire Ø0,15 mm, junction Ø0,5 mm) and a reference sensor (silicon diode DT-670-SD Lakeshore) were symmetrically placed on the surface of the heat exchanger (Fig.1) [4,6].

Kapton tape of a thickness 50 microns was used for electrical insulation between the exchanger and all sensors. The heat exchanger was equipped with an additional resistive heater supplied from the independently controlled current source. The heater was used in the study of the dynamic properties, as a heat source providing the independent control of the rate of the temperature change. Block diagram of the whole measurement system is presented in Fig.2. A thermocouple module consists of the voltage amplifiers (gain 50) and V/I converters and is located inside the cryostat (attached to the inner side of the vacuum feedthroughs). This solution has allowed to eliminate the effect of the thermoelectric phenomena in the feedthroughs. In addition, thermocouple module is equipped with a system for controlling and stabilizing the temperature of the free ends.

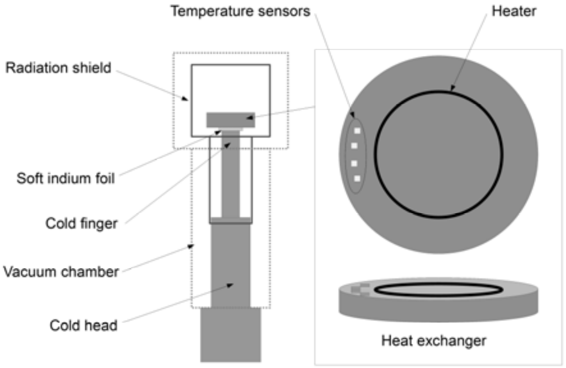

Fig.1. Sensors arrangement in cryostat

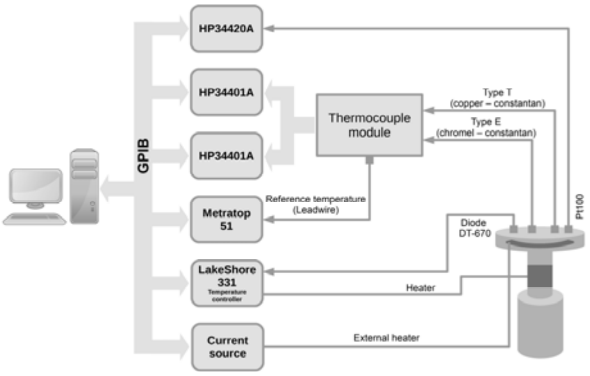

Fig.2. Block diagram of the measurement system

Fig.3 and Fig.4 show the transient responses of the tested sensors, which result from the dynamic cooling of the heat exchanger. In the range of 60÷20K a change the dynamics of the cooling process, associated with changes in the thermal properties of copper (twofold increase in thermal conductivity) has been observed, which results in the responses of all sensors.

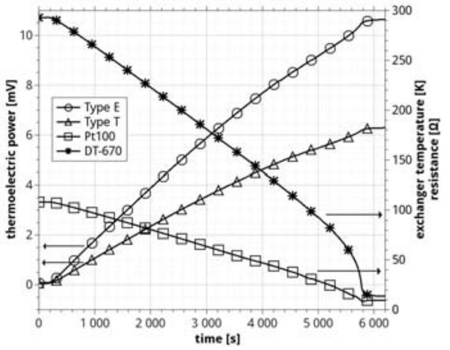

Fig.3. Time-dependence measurement during natural cooling (dynamics resulting from parameters of the cryostat)

Taking diode DT-670 as a reference sensor the linearization of temperature changes has been made using an independent heater placed directly on the exchanger (Fig.4). Adding additional controlled heat load of heat exchanger introduces only a slight non-linearities on the diode characteristic in the range of 40÷50K, corresponding to change in the dynamics of the cooling process. A significant deformation of characteristics of thermocouples and Pt100 sensor is observed in the same temperature range and the largest relative change was noted for thermocouples (Fig. 4). This results directly from the good dynamic properties of thermocouples (short response time).

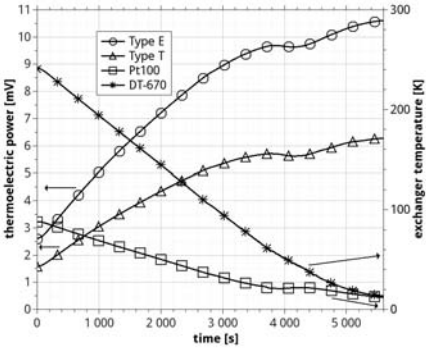

Fig.4. Time-dependence measurement with limited cooling dynamics (turning on the heater at 3600 s, ~ 70 K)

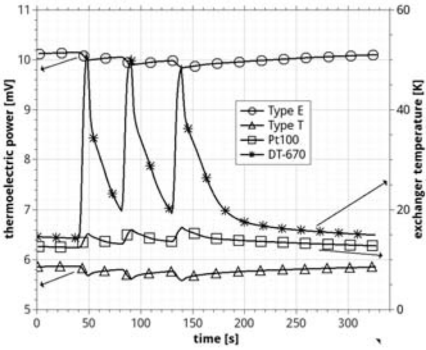

Fig.5. Thermal pulses at low temperatures (20K÷50 K)

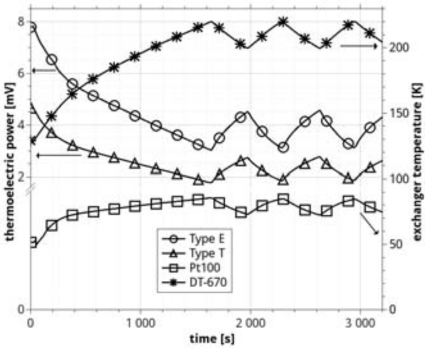

Fig.6. Thermal pulses at medium temperatures (200K÷220 K)

In order to observe and analyze the dynamic responses of sensors, the studies for fast thermal pulses in the range of 20÷50 K and 200÷220 K have been carried out (Fig.5 and Fig.6). At low temperatures (Fig.5), in contrast to the medium temperature range (Fig.6), the sensors responses for consecutive pulses indicate no short-time reproducibility. This is due to the insufficient dynamic responses of the reference sensor below 100K, which can also be seen in Fig. 4. Fig. 7 shows the quasi-static temperature characteristic of tested sensors. Obtained results confirm decrease in the sensitivity of thermocouples for T <30K, while maintaining the best dynamic properties. Good dynamic properties of thermocouples are directly related to their small size.

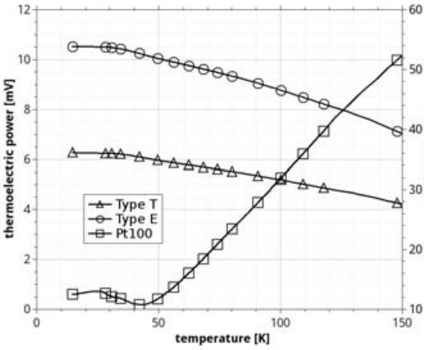

Fig.7. Temperature characteristics of tested sensors

The characteristic of the Pt100 sensor shows the irreproducibility of parameters and the hysteresis effect. These are the consequences of the connection of platinum and the ceramic substrate, wherein the different temperature coefficients of expansion cause plastic deformation of platinum at low temperatures [7].

Summary

A simple structure and low manufacturing costs determine the wide range of applications of thermocouples. Possibility of making small size sensors allows to obtain a very good dynamic properties, which was confirmed by studies carried out. The concept of the thermocouple module presented by the authors allows multipoint temperature measurements in the cryostat without having to increase the number of vacuum feedthroughs. Presented results have confirmed that the sensitivity of thermoelectric sensors is significantly reduced below 30K. Thin layer Pt100 sensor has a low repeatability of characteristics below 100K due to the structural internal stresses (Fig.7), which excludes its use in cryogenic systems despite the relatively good dynamic properties.

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