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Thermometers in Low Magnetic Fields

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Abstract In this article the effect of low amplitude DC magnetic fields on different types of thermometers is discussed. By means of a precision water-cooled electromagnet, the effect of a magnetic field on platinum resistance thermometers, thermistors, and type T, J, and K thermocouples was investigated, while thermometers were thermally stabilized in thermostatic baths. Four different baths were used for temperatures from 77 K (−196 °C) to 353 K (80 °C): liquid nitrogen bath (nitrogen boiling point at atmospheric pressure), ice-point bath, room-temperature air bath, and hot-water bath. The generated DC magnetic field of high relative precision (2×10^{-4} at 1 T, 4×10^{-5} short-term stability) and high relative uniformity (2×10^{-5} over 1 cm^2, 10 mm gap) had a magnetic flux density of 1 T in the center of the gap between the magnet pole caps. The results indicate a magnetic effect of up to 100 mK due to a 1 T magnetic field for the types of thermocouples composed of ferromagnetic materials (Fe, Cr, Ni). For platinum resistance thermometers, thermistors, and non-magnetic type T thermocouples, the detected magnetic effect was weaker, i.e., under 10 mK.

Keywords Magnetic effect · Magnetic flux density · Resistance thermometers · Thermistors · Thermocouples

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1 Introduction

Reliable thermometry is one of the bases for scientific research in various scientific fields, including experiments employing magnetic fields. Many studies have investigated both the temperature dependence of magnetic materials, standards, and sensors and the magnetic dependence of temperature sensors and thermometers [1–13]. Most thermometers for laboratory and industrial use are subject to AC and DC extraneous magnetic fields, e.g., electromagnetic field sources such as fans, heaters, Earth magnetic field, power lines, medical devices such as MRI scanners, mobile phones, etc. Additionally, thermometers' sensors themselves are at least partly composed of ferromagnetic materials, thus making their readings susceptible to surrounding extraneous magnetic fields.

In the past, numerous studies on the magnetic field effect on thermometers were published. The magnetic effects were investigated primarily in DC magnetic fields of various ranges, i.e., from lower fields of a couple of 100 mT to higher fields of several teslas [6–12]. In these studies the emphasis was mainly on a detailed description of temperature measurements and not on magnetic measurements, especially regarding the field uniformity and time stability of the apparatuses for magnet field generation.

Due to growing interest in thermometry in superconducting materials, cryogenic temperature regulation, and instrumentation (e.g., SQUID devices), the majority of experiments were conducted in the temperature range below 100 K. The reported magnetic effects were typically on the order of millikelvins at fields of a couple of teslas, i.e., around 10^{-5} to 10^{-4} relative temperature error ($|\Delta T|/T$), mostly depending on the type of the thermometer, the magnetic flux density of the field, and the temperature range [6].

In [6], predominantly magnetic effects in higher magnetic fields (from 2.5 T to 19 T) are evaluated. We were more interested in magnetic fields with lower flux densities. In this article, we are discussing the correlation of the temperature indication for various types of temperature sensors (platinum resistance thermometers, thermocouples, and thermistors) due to a DC magnetic flux density of 1 T in the temperature range from 77.36 K (liquid nitrogen boiling point at atmospheric pressure) to 353 K (water bath).

2 Measurements

The measuring setup was composed of a large water-cooled vertical-axis electromagnet and auxiliary instrumentation for powering the magnet and measuring and recording the temperature. Platinum resistance thermometers, thermocouples, and thermistors were tested, while maintained in thermally stabled baths (liquid nitrogen, ice-point, closed air container, hot-water bath) in constant-temperature conditions.

2.1 Measuring Setup

2.1.1 Magnetic-Field Generation

The magnetic field was generated by a water-cooled H-frame electromagnet (Model 3472 by GMW) with an adjustable air gap (Fig. 1). The pole cap had a diameter of 75 mm, and its magnetic field homogeneity with an air gap of 10 mm allowed an absorption-type nuclear magnetic resonance magnetometer [14] with a high-field probe to be used [15]. Measurements of the magnetic field amplitude in the air gap were carried out at 10 mm and 20 mm [16].

Using the magnet, DC magnetic fields of high relative precision (2×10^{-4} at 1 T), excellent short-term stability of 4×10^{-5} and high relative uniformity (2×10^{-5} over 1 cm^2 at 10 mm gap and 2×10^{-3} over 1 cm^2 at 59 mm gap) with magnetic flux densities of up to 2 T in the center of the 10 mm gap could be generated.

To accommodate the size of the thermal bath used in measurements, the smallest possible air gap was determined to be 59 mm. With a smaller gap, the bath would have to be smaller in size (lower), resulting in a lower thermal capacity. A larger gap could result in a strong decrease in the generated magnetic flux density. Figure 2 shows the vertical magnetic field in the center plane across the air gap and in its close proximity for the 59 mm gap size. During the experiments, the extraneous magnetic fields were less than 2 μT (50 Hz) and less than 50 μT (DC).

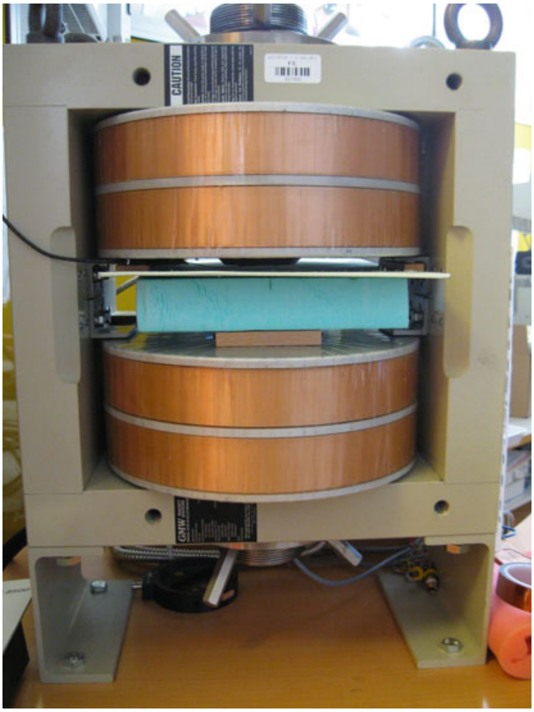

Fig. 1 Water-cooled electromagnet with thermally insulated bath containing thermometers

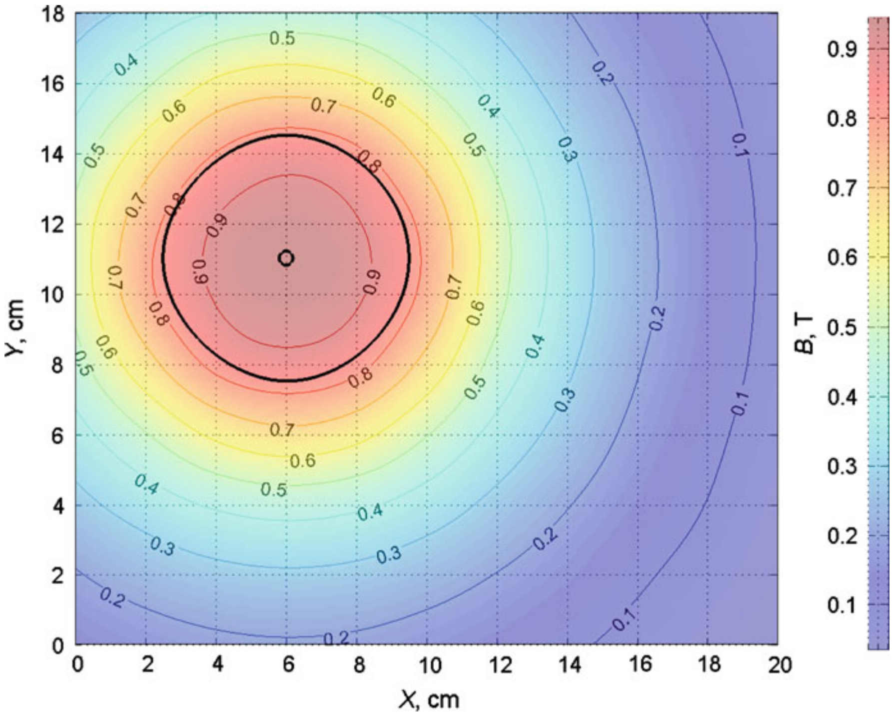

Fig. 2 Vertical magnetic field in the center plane across the air gap and in its close proximity (air gap = 59 mm). Outer black circle represents the pole cap position and its size. Central black circle indicates the position of the thermometer under test

2.1.2 Temperature Measurements in the Bath

2.1.2.1 Sensors Two types of resistance thermometers, class A non-encapsulated platinum thin-film resistance thermometers (DM-334 by Labfacility) and two-terminal industrial NTC thermistors (62S3KF354G by Betatherm), and three types of thermocouples were tested. A non-magnetic type T thermocouple (copper–constantan, range from 200 °C to 350 °C) and, as the most common general purpose thermocouple, a type K thermocouple (chromel–alumel, range from −200 °C to +1350 °C) were used. Due to its higher ferromagnetic material content, the type J thermocouple (iron–constantan, −40 °C to + 750°C range), although not intended for temperature measurements in the cryogenic part of the ITS-90 scale, was used as the third type of thermocouples. Thermocouples' cold junctions were positioned in an ice-point bath.

2.1.2.2 Temperature Measurements The temperature was measured by means of platinum resistance thermometers and thermistors, coupled via a four-wire connection to an ohmmeter (34420A by Agilent Technologies and 34401A by Agilent Technologies, respectively). Additionally, the temperature was measured by thermocouples, coupled via a two-wire connection to a voltmeter (34420A by Agilent Technologies) and their cold junctions at the ice point. Temperature measurement instruments were calibrated prior to this study and their temperature dependence evaluated [17]. For better short-term stability, the thermometers were positioned into an aluminum thermal equalizing block.

2.1.2.3 Temperature Baths Four different baths were used: liquid nitrogen bath, ice-point bath, closed room-temperature air container, and hot-water bath. The volume and thus heat capacity of the designed baths had to be sufficient to ensure adequate temperature stability at a maximal magnetic flux density. Volumes of the baths were typically sufficient to enable short-term temperature stability of a couple of tens of milikelvins over a period of 30 min, thus enabling us to perform tests with magnetic fields. A hot-water bath was used only to examine the magnetic effects above room temperature and was not thermally stabilized.

Prior to the measurement, the temperature short-term and long-term stability of the bath was determined [18]. The temperature stability and spatial homogeneity of the bath was determined by connecting a series of platinum resistance thermometers to a multichannel thermometer system composed of a scanner (7001 Switch System by Keithley and 7067 4 Wire Scanner Card by Keithley) and a multimeter (34420A by Agilent Technologies).

The final version of the housing for the liquid nitrogen bath was built from polystyrene foam insulation board (Styrodur C by BASF), providing a 25 cm × 12 cm × 4 cm (1.2 dm^3) closed volume for the media. The ice-point bath was realized by means of a polystyrene foam insulation (Styrodur C by BASF) container, filled with a mixture of water and crushed ice, ensuring a temperature of approximately 0.0 °C with an uncertainty of a couple millikelvins at normal air pressure [19]. The water used was not specially treated and not demineralized; hence, the temperature of the ice point was about +0.03 °C. It has to be noted that the realized ice point was not providing a reference as 0 °C, but was merely representing a source of a very stable temperature with time. The closed air container was rubber foam insulated and maintained at room temperature of the controlled laboratory environment. The water bath was built from polystyrene foam insulation (Styrodur C by BASF), ensuring about 1.5 L of bath media volume.

2.2 Procedures

2.2.1 Measuring Procedure

Each temperature sensor was maintained at a constant temperature inside a thermal equilibrium container (bath), while it was subjected to a changing magnetic field. To test the effects of the magnetic field amplitude and its direction, the magnetic field was generated in both directions.

3 Results

Initially, the temperature stability of different media baths was measured and is presented in Table 1. Afterwards, a series of experiments were performed to evaluate the

Table 1 Temperature stability of different media baths

Bath	Media	Bath temperature[a] (°C)	SD[b] (mK)
Nitrogen boiling point	Liquid nitrogen	196	50
Ice-point	Ice and water	0	10
Air	Stationary air	18	30
Water	Water	80	[c]

[a] Average value of bath temperature during a period of 30 min, measured by an encapsulated Pt resistance thermometer
[b] Standard deviation of the measured temperatures from the average value of the stationary state
[c] Water bath was not temperature stabilized and had temporal stability of 0.25 K · min^{-1}

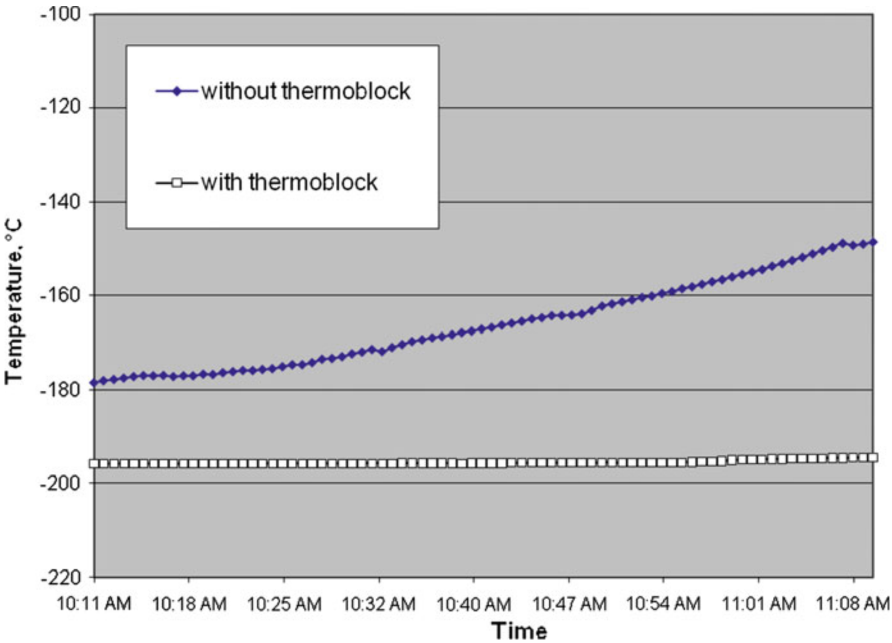

Fig. 3 Short-term 60 min stability of the fully immersed encapsulated platinum resistance thermometer at nitrogen boiling point with and without the usage of an aluminum thermal equalizing block

magnetic effect of up to 1 T magnetic field on seven thermometers of three different types (resistance thermometers, thermocouples, and thermistors). Figure 3 shows the improvement in short-term stability of the thermometers' readings, when using an aluminum thermal equalizing block.

Figures 4 and 5 show the magnetic flux density in the center of the magnet gap versus time (upper graph) and the corresponding temperature difference between sensors (lower graph). In our experiments, apart from the instrumentation measuring uncertainty, the bath thermal uniformity and temporal stability, and also the spatial distribution of magnetic field from the magnet pole cap relative to the size of the bath container were included in the uncertainty budget. In addition, the spatial distance from the center of the gap to the sensor could be the reason for the temperature difference

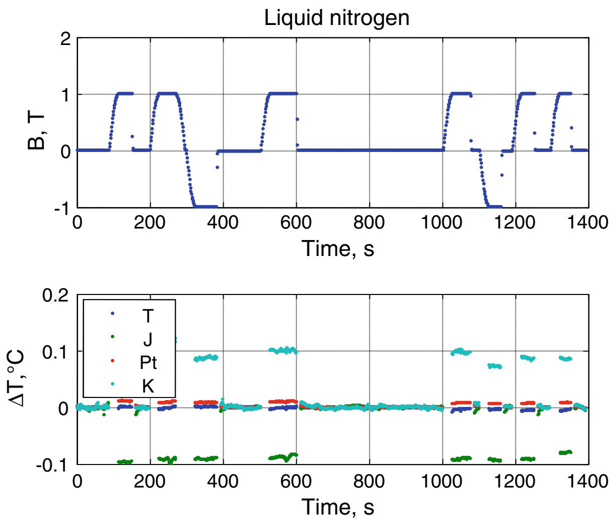

Fig. 4 Temperature change due to the magnetic field effect for nitrogen boiling point. Upper graph shows magnetic flux density in the gap. T, J, and K stand for thermocouples and Pt for platinum resistance thermometers. Lower graph shows the temperature difference ΔT. NTC thermistors were not used in liquid-nitrogen bath

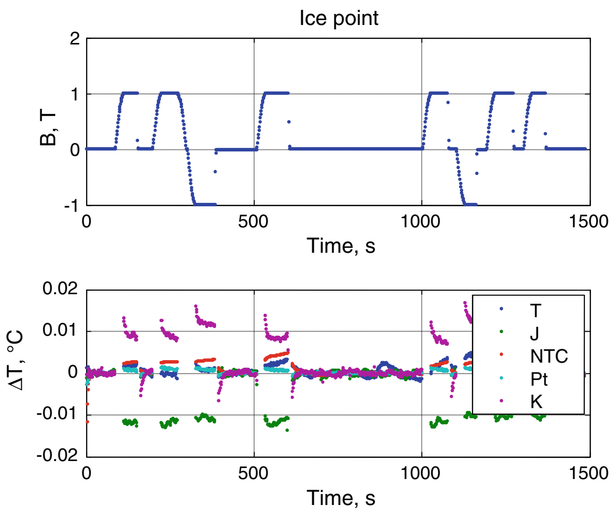

Fig. 5 Temperature change due to the magnetic field effect for ice-point bath. Upper graph shows magnetic flux density in the gap. T, J, and K stand for thermocouples, NTC for thermistors, and Pt for platinum resistance thermometers. Lower graph shows temperature difference ΔT

of the two measuring points due to a limited media volume of the temperature baths. The sensor's short-term time drift was evaluated and corrected to ensure the absolute change in temperature to be predominantly magnetic field dependent.

For a better presentation, temperatures in Figs. 4 and 5 were normalized, i.e., the difference between temperature values was zeroed at the beginning of the measurement

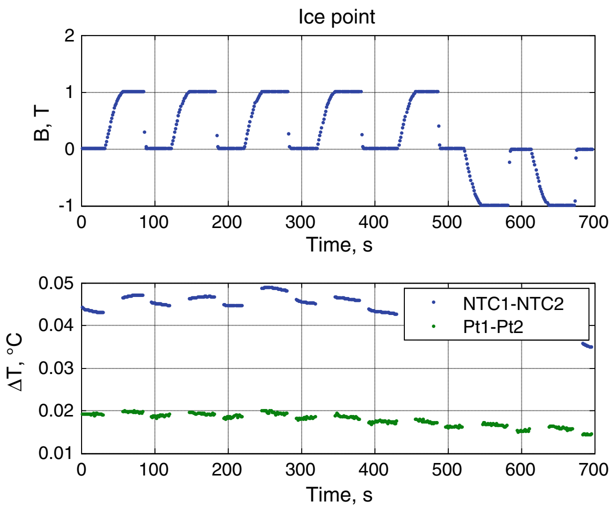

Fig. 6 Temperature difference ΔT of two thermometers in the ice-point bath, one in the magnetic field (NTC1 and Pt1) and the other outside the magnetic field (NTC2 and Pt2)

sequence, whereas the type T thermocouple's reading was kept as a reference. For better clarity, the sections during magnetic field commutation were omitted, since they exhibit predominantly artifacts due to electrical induction.

To evaluate the effect of different magnetic flux densities, an experiment with thermometers being fixed at different spatial points, one in the center (magnetic flux density of 1 T) and the other well outside with a magnetic flux density lower than 50 mT), was performed (Fig. 6).

In Fig. 7, the temperature difference in various temperature ranges for different types of thermometers at 1 T magnetic flux density is shown. Measured points were interpolated by means of linear regression.

4 Conclusions

Our results indicate an observable effect of a low field DC magnetic field of 1 T to resistance thermometers, thermocouples, and thermistors, which is in agreement with [6].

The magnetic effect is more expressed with the thermometers made from ferromagnetic materials. In addition, this is evident with thermometers in the cryogenic temperature range, but also observable at higher temperatures, e.g., ice-point, room-temperature, and water-bath temperatures. By means of the least-squares method, a linear regression function can be fitted to our results and the magnetic dependence of thermometers described (Table 2).

From our experiments we can conclude that a non-magnetic type T thermocouple had no significant magnetic dependency at any of the temperature points. This was expected, since both type T conductors are non-magnetic, and there is no Curie point and thus no abrupt change in characteristics. Magnetic thermocouples, type K

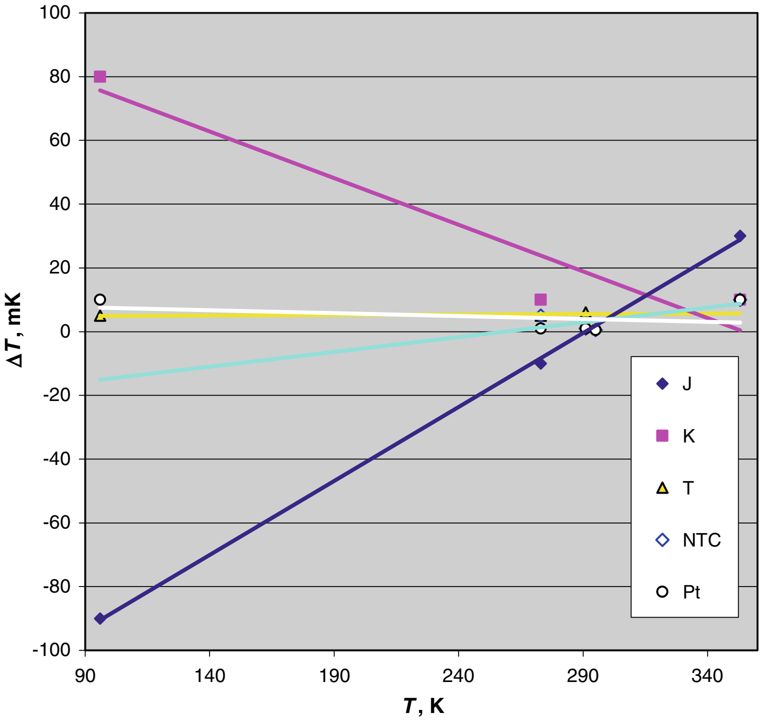

Fig. 7 Temperature change ΔT in different temperature ranges for different types of thermometers at 1 T magnetic flux density

Table 2 Magnetic dependence of thermometers at 1 T in various temperature ranges

Thermometer	Function $\Delta T = f(T)$ (ΔT, mK and T, K)	R^2
Non-encapsulated Pt resistance thermometer	$\Delta T = -0.0181T + 9.2263$	0.1224
Thermocouple type J	$\Delta T = 0.4645T - 135.11$	0.9994
Thermocouple type K	$\Delta T = -0.2927T + 103.79$	0.9075
Thermocouple type T	$\Delta T = 0.0031T - 4.6608$	0.3256
Thermistor	$\Delta T = 0.0926T - 23.924$	0.5314

with one of the constituent metals, nickel, being magnetic, and iron-containing type J, showed a magnetic effect from 10 mK to 100 mK (at the liquid nitrogen boiling point). This was expected due to the higher ferromagnetic content of the two sensors. The change in temperature at 77 K was approximately 80 mK for type K and approximately −90 mK for type J thermocouple. The negative values might be caused by the Ettingshausen–Nernst effect [20]. While experimenting with thermocouples, we noticed also a strong magnetic field direction dependency. Therefore, all of our measurements were performed with a magnetic field perpendicular to the junction. We found out that measurements were also dependent on the overall length of the wire inside the magnetic field. Resistance thermometers showed a small effect (non-encapsulated platinum resistance thermometers exhibited changes in temperature of 5 mK to 10 mK in 1 T magnetic field and NTC thermistors of 1 mK to 5 mK in 1 T magnetic field), which is consistent with [6].

Since our pilot experiments showed a noticeable magnetic effect of thermocouples and resistance thermometers, a detailed and more accurate further investigation is planned, especially because there could be some influence on final decisions in e.g. testing laboratories, when using CMC-s, as investigated in [21]. The room-temperature air container and water-bath experiments showed a lack of thermal stability; therefore, a more suitable bath is being designed for this temperature range. Currently, a setup for the investigations of the magnetic effect at temperatures up to 300 °C by means of a closed-loop high-temperature silicone oil bath is being built. Existing baths are also being improved combining more optimal thermal insulation with the limited volume requirement. Thus, we expect the temperature stability of the baths to be improved. Therefore, a series of experiments determining the change in the temperature reading due to different magnetic flux densities could be planned to determine the functional dependence of the magnetic effect from the intensity of the magnetic field. Because thermocouples exhibited the largest magnetic effect, we will try to investigate the similar influence on radiation thermometers and thermal imagers, which have a detector based not only on a series of thermocouples (thermopile), but also on other detectors (e.g., microbolometers) [22,23].

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