Feasibility study of using permanent magnets as indirect temperature monitor in irradiation capsule of nuclear research reactor

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Abstract. In sodium cooled nuclear fast reactors, materials used for fuel cladding and structural components can undergo significant physical and dimensional changes due to exposure to high energy neutrons. At high temperature and radiation conditions prevailing in the nuclear reactor, material properties change considerably. Information about the temperature of exposure during specimen irradiation in a nuclear reactor is important since the temperature is having a strong influence on the mechanical and physical properties of materials. A proper evaluation of the effects due to radiation on materials needs a precise knowledge of the irradiation temperature. Many times, standard techniques for measuring temperature are not practicable in reactors due to the availability of limited instrumented positions. Therefore, the use of small-sized indirect temperature monitors such as melt wires, permanent magnets, etc. which can be incorporated along with the samples and examined after the irradiation are preferred. In the present study, permanent magnets of neodymium grade N38 and N38SHX of different sizes have been studied for their possible use as an indirect temperature monitor. The study was carried out first for their compatibility with sodium since the monitor will be exposed to sodium during irradiation experiments in fast reactors, and then by exposing to different temperatures in an electrical furnace for the determination of Curie point to study the feasibility of using these materials as indirect temperature monitors. Since the material loses its magnetic properties when the temperature of exposure exceeds the Curie point, by using a series of magnets having progressively increasing curie points, the temperature of exposure can be determined by testing these magnets for the retention of their magnetic properties. Specifically, since there is variation in the Curie temperature as reported in the literature, the experimental method was developed to determine the Curie temperature accurately. This paper discusses the details of the experiments carried out in our laboratory and the results obtained from these studies.

Keywords: Neodymium magnet, Irradiation device, Temperature detector, Demagnetization, Curie point

1. Introduction

Fast Breeder Test Reactor (FBTR) at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India offers good facilities for irradiation of structural material specimens to determine the change in the properties due to irradiation [1, 2]. In the reactor, the irradiation performance of the materials will be influenced by the neutron flux level and temperature [3, 4]. It is essential that the temperature of specimens during irradiation is determined accurately for correct interpretation of results obtained in the irradiation experiments. However, many times the standard techniques for measuring temperature such as the use of thermocouple [5] are not practicable in the experimental facilities of nuclear reactor core,
due to the non-availability of instrumented irradiation locations. The general practice is the use of small size indirect temperature indicators in the irradiation capsule along with the sample and to examine it after the irradiation experiment. Some indirect techniques available for measuring temperature include the use of melt wire [6], Silicon Carbide (SiC) temperature monitor [7], and thermal expansion difference (TED) monitor [8]. Melt wire method is used to measure the peak temperature attained using wires of known composition and melting temperature. The multiple wires are encapsulated into a single compact unit. This method requires the identification of the melting of wire unambiguously after the irradiation experiment. TED method is used to measure the peak temperature by a change in the dimension of the tube (fully filled with liquid such as sodium) when exposed to high temperatures. In the TED method, there is a chance for improper filling of sodium, so it can give an inaccurate measurement of the temperature.

In the present work, a magnetic method (Curie point technique) for peak temperature monitoring has been explored. In this technique, the temperature can be measured using magnetic materials. In theory, if the temperature of the magnet exceeds its Curie point ($T_C$), the magnet loses its magnetic property [9]. The phenomenon of the loss of magnetic property concerning Curie temperature has been studied using an in-house experimental setup to explore this phenomenon and to identify the peak temperature attained. It is based on the principle that when the temperature of the magnet exceeds the Curie temperature the magnet loses the magnetic properties. Conversely, if it is not so, it can be inferred that the maximum temperature remained below the Curie point. It is reported in the literature [10] that a similar work has been carried out by Marth et al. [11] in Karlsruhe Germany but not much detail is available in the open literature. Using a succession of the magnets with different Curie points it is possible to attain sufficient data to determine the maximum temperature of specimens at various partitions of an irradiation capsule in the reactor during irradiation.

2. Selection of magnetic materials for temperature monitor

For the measurement of the peak temperature in the irradiation capsule the magnets can be selected based on following properties: (a) They should have Curie point near to the temperature of interest, (b) They should have good resistance to radiation and, (c) It is preferred that they are compatible with liquid sodium, the coolant of the fast reactor. There are various types of permanent magnets available having different Curie points. By varying the composition of the magnetic material, different Curie point temperatures can be achieved [12-14]. Radiation effect on the permanent magnet is well studied and permanent magnets, such as neodymium magnet, Sm-Co, Alnico, have been reported for higher tolerance to radiation [15-17]. As part of the feasibility study as the temperature monitor in this work, neodymium magnets of grade N38 and grade N38SHX have been selected in different sizes and shapes (Figure 1) for the experiment. The neodymium magnet has a Curie point near to our temperature of interest for the irradiation experiment, and these magnets are also easily available. Compositions of these magnets are shown in Table 1.

| Magnet          | Composition (percent by weight) |
|-----------------|--------------------------------|
| Neodymium magnets | Neodymium 29-32 | Iron 64-68.5 | Boron 1.0-1.2 | Aluminium 0.2 - 0.4 | Niobium 0.5 - 1 | Dysprosium 0.8 - 1.2 |

Table 1: Composition of magnets used in the study
Figure 1: Grade N38 Neodymium magnet (a) 15mm diameter X 5mm width (b) 5mm diameter X 3mm width; Grade N38SHX Neodymium magnet (c) 10mm X 4mm X 2mm (d) 8mm diameter X 1mm width

3. Sodium compatibility test of magnet samples

For the measurement of exposure temperature of the specimens in the non-instrumented irradiation capsules, the magnet samples are being studied for their use as the indirect temperature monitor. The irradiation capsule, where the specimens are kept, is normally filled with the sodium for providing the near-uniform temperature distribution within the capsule. Hence, the magnet which is to be used as the temperature monitor should be compatible with the sodium environment. Therefore, it is necessary to check the compatibility of the neodymium magnet with sodium. The compatibility test experiment of the magnet sample in sodium has been carried out in the glove box with an argon environment. The magnet samples were kept in the sodium container as shown in Figure 2 for the duration of about 150 hours at the temperature of 150 °C.

Figure 2: Magnet samples are kept in quartz tube which in turn is placed in sodium container
The magnet samples before and after exposure to the sodium are shown in Figure 3(a) and 3(b) respectively. The weight and the dimensions were measured for the magnet samples before and after exposure to the sodium, and are shown in Table 2.

![Magnet samples](image)

**Figure 3**: Magnet samples (grade N38, disk type, and grade N38SHX, plate type) (a) before sodium exposure, and (b) after sodium exposure

| Sl. No. | Type of magnet | Weight of magnet (g) | Dimensions before exposure to sodium | Dimensions after exposure to sodium |
|---------|----------------|----------------------|-------------------------------------|-----------------------------------|
|         |                | before exposure to sodium | after exposure to sodium | before exposure to sodium | after exposure to sodium |
| 1.      | Grade N38 (Disk type) | 0.556 | 0.556 | 5 mm diameter x 3 mm width | 5 mm diameter x 3 mm width |
| 2.      | Grade N38SHX (Plate type) | 0.530 | 0.530 | 10 mm x 4 mm x 2 mm | 10 mm x 4 mm x 2 mm |

The sodium compatibility test results show that there is no significant effect on the magnet due to exposure to sodium and they can be used as temperature monitors in the irradiation capsule in the sodium environment.

**4. Determination of Curie point of the magnet samples**

Compounds of neodymium magnets contain iron and it is reported that the variation in the iron weight percentage influences Curie temperature. The neodymium magnets (Grade N38 and Grade N38SHX) used in this study contains 64% to 68.5% of iron (by weight) as shown in table 1 and due to this, Curie temperatures of the samples are not known precisely. A similar observation is reported in the literature [18] on the influence of the material composition of cobalt ferrite on curie points while working for stress sensor applications. Hence it is important that before using these magnets as a temperature sensor, the Curie temperature should be determined for each type of magnet.
monitor, an experiment is to be carried out for estimating the Curie point accurately. In this experiment, the Curie temperature of the permanent magnets which can be used as indirect temperature monitors has been determined. An experimental setup (Figure 4) was designed to determine the Curie point of a permanent magnet sample by heating it above the Curie point. A magnetic probe is made by using two ceramic tubes, which are of 0.6m long and two magnetic bases which have higher Curie point is attached at the bottom of the ceramic tubes as shown in Figure 4. These magnetic bases are connected with a battery using conducting wire. The magnetic bases of the probe are also attached with two numbers of K-type thermocouples. The sample magnet material is placed on the same plane in contact with the two magnetic bases, and as a result of which a closed electrical circuit is made. The whole setup is placed in the electric furnace to determine the temperature at which the sample magnet become demagnetized. The data (temperature and voltage) were recorded using a data logger (Yokogawa make) at the rate of 2 data per second. The furnace was started at 30 °C with a step increase in temperature of 5 °C per minute. In this arrangement, the sample magnet functions as a switch in the electrical circuit. When the sample magnet becomes demagnetized due to furnace temperature crossing the Curie point of sample magnet, the circuit would break, and the output voltage would become zero.

**Figure 4:** (a) Schematic view of the experimental setup and (b) The actual setup of the experiment

The experimental results for estimating the Curie points of neodymium magnets are shown in Figure 5. It can be seen from Figure 5 that as the temperature increases the magnets lose the magnetic properties and at a particular temperature complete loss in permanent magnetism results in drop down of magnets from the electrical circuit. Eventually, this leads to zero voltage. The Curie point for the tested grade N38 magnets are shown in Figure 5 (a) and (b). It was found to be 255 ± 5 °C (n=10, where n being independent trials) for both the sizes i.e.,15mm diameter x 5mm width (Figure 1(a)) and 5mm diameter x 3mm width (Figure 1(b)). The experimental results of neodymium magnet N38SHX are shown in Figure 5(c) and (d). The N38SHX grade magnet lost its permanent magnetic property at the temperature of 270 ± 5 °C (n=10), for the sizes of 10mm x 4mm x 2mm (Figure 1(c)) and 8mm diameter x 1mm width (Figure 1(d)). It has been observed that both grades of magnets have different curie points and interestingly it has been also observed that the size of the magnet has little influence on the Curie point. The possible reason would be the overall magnetization of the magnet is coupled ferromagnetically to the lattices of the transition metal irrespective of the size of the magnet. The Curie temperature of the magnet samples exposed in the sodium environment was also found to be the same as that of unexposed magnet samples.
It can be noted here that the Curie temperatures reported in the literature for N38 and N38SHX magnets are 310 °C and 330 °C respectively [19] which are widely different from the results obtained from this experimental work (255 °C and 270 °C respectively).

**Figure 5:** Voltage versus temperature graph for magnet (a) grade N38 size 15mm diameter x 5mm width (b) grade N38 size 5mm diameter x 3mm width (c) grade N38SHX size 10mm x 4mm x 2mm (d) grade N38SHX size 8mm diameter x 1mm width

The current study is towards exploring the feasibility of temperature measurement under reactor operating conditions of specimens during irradiation experiments, where such measurements are complex. This study can further be extended to determine the effect of irradiation on the magnets during the measurement of temperature by the use of a similar experimental setup.

5. Conclusion

This work demonstrates a possible method of using permanent magnets to determine the temperature indirectly during irradiation experiments. The experimental results show that magnets samples selected for the study (N38, N38SHX) are compatible with sodium and it is also found that exposure to sodium environment does not have any effect on Curie temperature of the magnet samples. It was found that the shape and size of the magnet do not affect the Curie temperature of the magnets. The peak temperature can be determined within ±5 °C. The advantages of this method are their small size, easy measurement, no need for encapsulation, and reliability of the indicated temperature to within a few degrees. It is also found that the Curie temperature reported in the literature is approximate since Curie temperature depends on many factors including the chemical composition of the specific magnet chosen. The peak temperature detection with permanent magnets depends on two factors: (1) the temperature profile should be guessed or calculated closely to enable the inclusion of many magnets with different Curie temperature, and (2) the availability of permanent magnets with a small difference in Curie temperature.
in the selected range of temperature among them. The best measurement of temperature occurs when one of the two adjacent magnets demagnetizes, and the other does not. If the temperature profile cannot be guessed closely, a wide range of magnet with different Curie points should be used. This work can further be extended to determine the effect of irradiation on the magnetic property of the material during the measurement of temperature.

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