MEANS FOR MEASURING THE THERMAL QUANTITIES

DIAGNOSTICS OF RESISTANCE TEMPERATURE DETECTORS UNDER OPERATING CONDITIONS

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Abstract. Among all sectors of human economic activity, the energy industry exerts the most significant influence on our lives. Errors in this field may lead to severe consequences. The provision of heat and lighting in households, the movement of transport flows, and the functioning of industry all require substantial energy resources. As the global community seeks to meet the steadily increasing demand for energy, the development of nuclear power plants (NPPs) as one of its reliable sources is gaining ever greater importance.

Modern nuclear power plants are equipped with complex automated control systems that monitor the reactor unit's condition and ensure its safe operation. These systems include numerous sensors, controllers, and other devices operating in real-time, providing high reliability for NPPs.

The problem of reliably determining the primary circuit coolant temperature in nuclear power engineering is one of the most crucial, as its successful resolution determines the reliability, efficiency, and service life of the nuclear reactor [1]. This article analyzes methods for determining the static characteristics of resistance temperature detectors (RTDs) under operational conditions when measuring temperature.

Key words: resistance temperature detector (RTD); test method; property identification; diagnostics

Introduction

The safety of nuclear power plants (NPPs) is one of the most important issues associated with the use of nuclear energy. NPPs have enormous potential for providing additional energy resources and delivering vital services, but if operated incorrectly, they can pose serious threats to human life and health, the environment, and socio-economic stability.

Most critical temperature processes at nuclear power plants are measured using resistance temperature detectors (RTDs) and thermocouples. In pressurized water reactor (PWR) installations, the primary circuit coolant temperature and the process water temperature are measured using RTDs, while the temperature of water exiting the reactor core is measured with thermocouples. These thermocouples are mainly used for temperature monitoring, so high accuracy and fast response are not critical. In contrast, RTDs in the primary coolant circuit provide signals for the plant’s control and safety systems, and must therefore be accurate and have good dynamic characteristics. The main advantages of RTDs compared to other types of temperature sensors include their high accuracy, wide operating temperature range, compact size, vibration resistance, linear nominal static characteristic, and relatively high temperature coefficient of resistance.

The methods used to assess the condition of RTDs in nuclear reactors typically rely on immersion testing. These methods are inconvenient, as the sensor must be removed from the reactor’s coolant pipeline and transported to a laboratory for testing. Reproducing the operational conditions of a nuclear reactor—150 bar and 300°C—is extremely challenging in a laboratory setting. Therefore, all laboratory tests are conducted under much milder conditions, and the results are extrapolated to actual operational conditions. This leads to significant measurement errors in temperature readings.

This paper presents a study of a methodology for verifying RTDs without removing them from service, using an in situ approach based on heating the sensing element with an electric current.

1 Disadvantages

Existing methods for determining the metrological characteristics of a temperature transducer require its removal from the technological process, which is not feasible, as it would disrupt the reactor's operating conditions.

2 Objective

The aim of this work is to investigate the LCSR method for diagnosing the static characteristics of resistance temperature detectors (RTDs).

3 Specifics of RTD Application

Temperature measurement in industrial processes is essential in many applications. Temperature sensors, such as resistance temperature detectors (RTDs) used in nuclear power plants, are critical components of measurement, control, and safety systems. For this reason, they must be accurate and have good dynamic characteristics. Temperature measurement is one of the most common types of monitoring in reactor systems.

The task of a resistance thermometer is not to display the temperature directly but to convert it into an electrical resistance, making it easier to measure. Thus, an RTD is not a measuring device per se, but participates in the primary stage of temperature measurement.

There are many standards for industrial RTDs with either local or international status. Among the most common are the European IEC 60751 (DIN/IEC EN 60 751) and the North American ASTM 1137. IEC 60751 is one of the most widely used and regulates the characteristics of platinum PRTs with a nominal resistance of 100 ohms at 0°C and a temperature coefficient of resistance $\alpha = 0.00385$ °C^{-1}.

The temperature coefficient of resistance characterizes the change in resistance with temperature:

$$\alpha = (R_{100} – R_0)/(R_{100} \times 100°C), \quad (1)$$

where R_{100} and R_0 are the PRT resistance values at 100°C and 0°C, respectively, based on the nominal static characteristic (NSC).

RTDs are classified by accuracy according to standards such as DIN EN 60751 and IEC 60751, with classes typically being AA, A, B, and C. Class AA is the most precise, while class C has the broadest tolerance. Industrial RTDs such as Pt100 typically offer accuracy ranging from 0.15°C to 0.6°C.

3.1 Determination of Metrological Characteristics of RTDs Under Operating Conditions

The ability to test resistance temperature detectors (RTDs) at the point of installation offers significant advantages, as the conditions of the technological process greatly influence the characteristics of temperature sensors. This is particularly relevant to methods for determining the dynamic characteristics of RTDs.

Reviews of experimental methods for testing temperature sensor parameters, as presented in [2], include the determination of dynamic characteristics. The dynamic properties of a resistive temperature sensor can be determined using the immersion method or the self-heating method. Immersion involves exposing the sensor to an external step change in the temperature of the surrounding fluid or air. Heat is then transferred through the internal structure of the sensor to the sensing element (or in the opposite direction if the temperature step change is from higher to lower). During self-heating testing, the sensor is excited by an internal step change in heat generation rate within the sensing element, which occurs due to an increase in the electric current passing through it (Joule heating). The temperature of the sensing element rises, and heat is transferred through the sensor layers to the surrounding fluid. The self-heating step-change excitation test method is known as the Loop Current Step Response (LCSR) method [3].

In general, all these methods have been applied exclusively to the study of the dynamic characteristics of primary temperature transducers.

Today, to assess the static characteristics of primary temperature transducers under operating conditions, so-called embedded calibrator methods have seen certain development.

Publication [4] reports on the use of chemically pure elements (or eutectic alloys) as reference temperature markers built into the structure of RTDs. The concept is based on the fact that certain chemical elements or alloys exhibit well-defined phase transition temperatures (melting, freezing, polymorphic transitions, etc.), which can be used as reference points for calibration or stability monitoring of RTD characteristics directly under operating conditions.

In [5], a design is described in which small containers of pure metals are embedded in the RTD housing. Upon reaching their melting/freezing temperatures, these containers cause abrupt changes in heat dissipation or other physical effects, which can be registered to verify sensor readings.

Research by scientific institutions (e.g., NIST, PTB, VNIIM) [5] describes the use of "sealed metal cells" as integrated temperature markers within designs intended for field operation.

Thus, there are numerous publications and patents describing the idea of embedding chemically pure elements or their alloys inside RTDs to create reference temperature points required for determining or monitoring the sensor's static characteristics during operation. This is especially relevant in fields where temperature measurement accuracy is critically important (metrology, energy, chemical industry, etc.).

Therefore, in these methods, when the environmental temperature reaches the temperature of the embedded element, a certain stabilization of the sensing element's temperature occurs. The registration of a phase transition allows the identification of the magnitude of the input disturbance. This approach to diagnosing the static characteristic of an RTD can ensure high accuracy, but it has several drawbacks. First, it significantly complicates the design of the RTD. Second, it greatly increases the time constant of the RTD. Third, the phase transition temperatures of the embedded elements are subject to some of the same destabilizing factors as the static characteristic of the sensing element (e.g., diffusion processes).

3.2 Method for Stimulus Testing of RTDs Under Operating Conditions

In the mid-1970s, an in situ testing method called LCSR — Loop Current Step Response test — was developed for remote measurement of RTD response time. References [6,7,8] describe the Loop Current Step Response (LCSR) method for analyzing thermocouples and resistance temperature detectors (RTDs). The LCSR method was validated by comparing its results with those obtained from traditional immersion tests in a controlled environment. In the LCSR method, the sensing element is heated by an electric current; this current induces Joule heating in the sensor and causes a transient thermal process within the sensor. This transient temperature response is recorded, and based on this process, the sensor's response time to changes in external temperature is determined using the LCSR transformation.

In the general, the heating process of the RTD sensing element is described by the following expression:

$$E\,(t) = Q_{че}\,(t) + Q\,(t), \qquad (2)$$

where E(t) is the electrical energy supplied to the sensing element: $E(t) = P{\cdot}t$ (assuming P = const);

$Q_{че}(t)$ is the heat accumulated by the sensing element (used to heat it up): $Q_{че}(t) = C{\cdot}T(t)$; Q(t) is the heat dissipated to the surrounding environment (via conduction, convection, etc.). C is the heat capacity of the sensing element during heating (C = const).

Assume a step power input of P = 1 W is applied to the sensing element at time t = 0. We consider a short timeinterval (e.g., up to 1 second), during which the temperature has not yet reached a steady-state value (see Fig. 1).

At the very beginning of the heating process, the entire supplied heat pulse is used to heat the sensing element, while heat losses to the surrounding environment are still minimal due to the thermal inertia of heat exchange. With a certain degree of approximation, the initial phase of the sensing element's heating can be considered adiabatic, meaning free from any external influences.It is precisely during this short interval that the heat capacity and the temperature coefficient of resistance α of the sensing element can be diagnosed, as there is no significant effect from heat transfer coefficients or environmental conditions.The duration of this initial phase of the thermal transient process is determined by the construction of the sensing element, its heat capacity, and the characteristics of heat transfer between the sensing element and the surrounding environment. Thus, for RTDs, it is possible to form an input disturbance with defined amplitude-time characteristics by applying an electrical heating current of a specific duration.

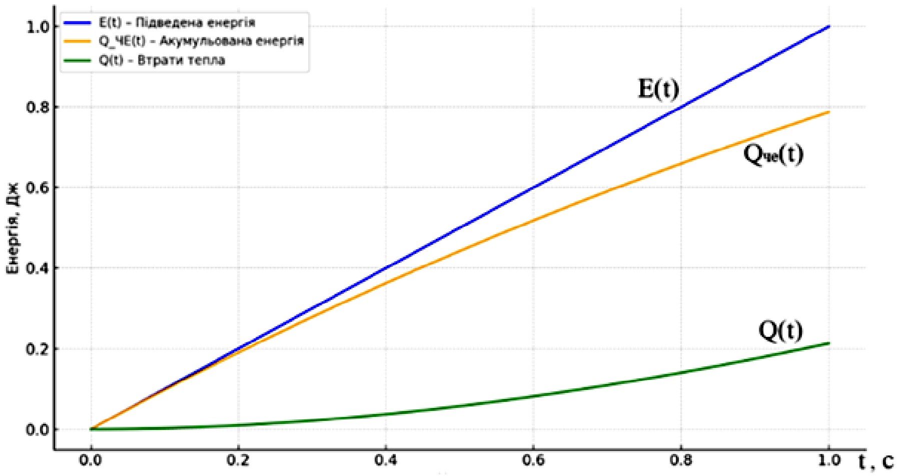

Fig. 1. Thermal Balance of the RTD Sensing Element (1 W Heating).

3.3 Structural Elements of the Sensing Element and Their Properties

To evaluate the parameters of the initial phase during the heating of the RTD sensing element by electric current, and to assess the influence of various destabilizing factors, let us consider the main structural components and analyze their properties. Platinum is the material commonly used in nuclear reactors. It exhibits high chemical stability, a sufficiently linear temperature dependence of electrical resistance, and resilience to environmental effects at high temperatures. In nuclear power applications, thermoresistive converters such as TSP-1390 and TSP-1790 are widely used. These RTDs utilize a sensing element design in which a platinum spiral is placed in the channels of a ceramic tube (see Fig. 2). The channels containing the spiral are filled with aluminum oxide (Al_2O_3) powder. This design ensures electrical insulation between the spiral coils and provides a minimal time constant.

The geometric dimensions of the sensing element are as follows:

— Length: 40 mm

— Frame diameter: 2.8 mm
— Platinum wire thickness: 0.03 mm

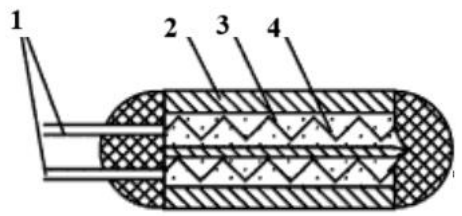

Fig. 2. 1 – Leads, 2 – Ceramic frame, 3 – Powder, 4 – Platinum spiral

Let us consider the initial stage of the transient process in the sensing element under a constant power current:

- The current through the sensing element is applied such that it ensures a constant heating power

$P = I^2R = 1$ W = const

- The heat capacity C of the sensing element is assumed to be constant in this region. For platinum, C ≈ 133 J/kg·K.
- There is no significant heat dissipation (i.e., the heating is considered adiabatic).

The initial heating dynamics are as follows.

The energy balance equation at the initial moment (before any heat exchange occurs) is defined as:

$$P=C\cdot dT/dt \qquad (3)$$

where P is the heating power (constant current → constant power), C is the heat capacity of the sensing element, T is the temperature of the element.

Hence:

$$\frac{dT}{dt} = \frac{P}{c}\,. \qquad T(t) = T_0 + \frac{P*t}{C} \qquad (4)$$

That is, the temperature increases linearly over time as long as only internal heating is acting. The temperature dependence of resistance R(T) for platinum is given by:

$$R(T) = R_0(1 + \alpha T) \qquad (5)$$

From this, one can obtain:

$$R(t) = R_0\left[1 + \alpha\left(T_0 + \frac{P}{C}t\right)\right] = $$
$$= R_0\left(1 + \alpha T_0 + \alpha\frac{P}{C}t\right) \qquad (6)$$

Thus, in the initial phase of the transient process, the resistance increases linearly with time:

$$R(t) = A + B * t, \qquad B = \alpha\frac{P}{C}R_0 \qquad (7)$$

Thus, from the slope B, the product $\alpha \cdot R_0/C$ can be determined. If P is known, then:

$$\alpha = \frac{B*C}{P*R_0} \qquad (8)$$

It follows that changes in the static characteristics of the RTD can be diagnosed during the initial segment of the transient process.To determine the boundary of the adiabatic region (i.e., the time interval during which heat exchange with the surrounding environment is negligible), it is necessary to analyze the point at which heat losses Q(t) begin to constitute a significant portion of the supplied energy E(t).

The analysis of both theoretical considerations and experimental investigations has demonstrated that, for resistance temperature detectors (RTDs) of types TSP-1390 and TSP-1790, accuracy class C, the characteristic adiabatic heating time is approximately 170 ms at an applied heating power of 1 W.

Consequently, any variation in the temperature coefficient of resistance α (caused, for example, by alloy degradation, mechanical defects, or surface contamination) results in a modification of the resistance–temperature function R(T) and, accordingly, in a change of the slope of the transient response.

By comparing the measured slope in the adiabatic part of the transient response with the nominal slope, it becomes possible to assess whether the RTD maintains compliance with its specified accuracy class under actual operating conditions. Any experimental curve that falls within this band corresponds to the accuracy class (Fig. 3). When using the method, the following conditions must be met:

• coefficient α - must be stable in the desired range;
• heat capacity C - of the sensitive element does not change with temperature;
• heating power P - stable (excitation current does not change).

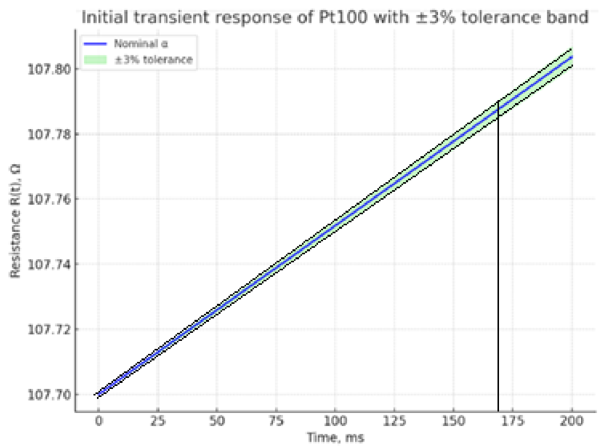

Fig. 3 Comparison of the experimentally measured slope B with its nominal value for class C.

4. Conclusion

Built-in calibrator methods for determining the static characteristics of RTDs have significant drawbacks, as they complicate the RTD design, increase the time constant, and undergo parameter changes due to diffusion processes.

The LCSR method is relatively simple to implement, as it does not require complex equipment to determine the static characteristics of an RTD under operating conditions. Under certain conditions, and by analyzing the initial phase of the transient process, it is possible to assess the static characteristics of a resistance thermometer without disassembly.

Therefore, comparison of the experimentally measured slope B with its nominal value provides a diagnostic criterion. If the deviation remains within the prescribed limits (±1 % for class A, ±3 % for class C), the RTD can be considered compliant with its accuracy class under operating conditions. Otherwise, degradation or malfunction is indicated.

The approach proposed in this paper can serve as a basis for determining the accuracy class of temperature sensors in operational environments. This has become possible due to advancements in measurement instruments and signal processing techniques.

Conflict of Interest

The authors declare that there are no financial or other potential conflicts of interest related to this work.

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