MEANS FOR MEASURING THE THERMAL QUANTITIES

ENHANCEMENT OF TEMPERATURE MEASUREMENT IN NUCLEAR POWER PLANTS

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Abstract. One of the most critical challenges in nuclear power is reliably determining the temperature state of fuel assemblies. Successful resolution of this problem affects the possibilities for enhancing a nuclear reactor's reliability, efficiency, and service life.

This paper analyzes methods for detecting the contact of the thermocouple in the reactor cassette head for temperature measurement.

Key words: Thermocouple with a protective shell, time constant, measurement accuracy, and optimization of placement.

1. Introduction

Among the challenges for the nuclear power industry today are the problems of efficient and safe usage of nuclear facilities. Nuclear power plants (NPPs) provide the economy with additional energy resources and essential services. Their improper operation can cause serious threats to human life and health, the environment, and stability.

A reactor is a complex system with the primary function of generating nuclear energy changing in thermal. This thermal energy is employed to elevate the temperature of a coolant, which subsequently conveys the heat to a steam generator. It is essential to ensure efficient heat removal from the reactor core to prevent overheating. This is achieved with the help of a cooling system that circulates the coolant through the core.

Energy release is measured in 64 fuel assemblies located across the core, and the coolant temperature is measured by thermocouples at the outlet of 95 fuel assemblies (FAs) [1]. The sensitive element of the thermocouple is placed in the cavity of the cylindrical part of the cassette head. Since the efficient and safe functioning of the reactor is largely determined by the reliability of control over the fuel assemblies, and the placement of thermocouples in the outlet of each fuel assembly is complicated, the question arises whether it is possible to control the state of the thermocouple installation in the cassette head during its replacement.

Thus, temperature measurement, especially in the reactor, is vital. Keeping the reactor temperature within a safe range is a key factor in preventing emergencies, such as reactor core meltdowns, while also contributing to the efficiency of the reactor Overheating can lead to severe failures, including the release of radioactive materials. Heat release in a reactor is directly related to the nuclear fission process. Measuring the temperature is the major instrument in controlling and regulating the rate of nuclear reaction, ensuring the stable performance of the reactor. High temperatures can damage critical reactor components and other equipment, so continuous monitoring of temperature parameters helps prevent such damage. In an emergency, temperature measurements are important for analysis of the accidents to avoid them. So, the temperature measurement in nuclear reactors becomes a part of their safe, reliable, and efficient power plant exploitation.

2 Shortcomings

Existing methods for determining the parameters of a temperature transducer require its deployment from the manufacturing facilities, which is impossible because it disrupts the reactor's workflow.

3 Goal

Study of methods for ensuring the correct location of the temperature transducer in the cavity of the cylindrical part of the reactor cassette head that contributes to the needed parameters of measurement of operation.

4 Specifics of using temperature transducers in a nuclear power plant reactor

The temperature measurement and control system include up to a hundred temperature transducers. The most common are thermocouples (TCs) [2]. When repeatedly exposed to high temperatures and ionizing radiation, thermocouples are prone to drift and recalibration. The problems of detecting a thermocouple malfunction include uncertainty inherent in the physics of measurements and passing the transient processes in fluids.

Here, the Seebeck effect is used. It describes the conversion of temperature difference into electrical voltage. The output voltage U of the temperature transducer is proportional to the temperature difference: $T_2 - T_1$:

$$U = \int_{T_1}^{T_2} \varepsilon_{AB}\left(T\right)dt, \qquad (1)$$

T_1 i T_2 are the temperatures (°C) and ε_{AB} (T) is the Seebeck coefficient (V/°C). The thermocouple conductors are embedded in a ceramic insulating compound (magnesium oxide or aluminum oxide). A metal shell surrounds the insulating compound and the sensing element (Fig. 1).

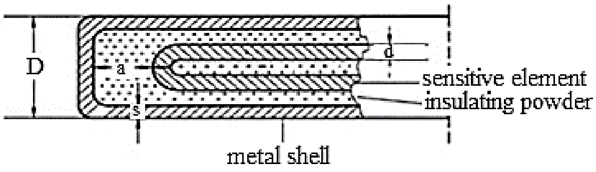

Fig. 1 Cross-section of an insulated thermocouple with a shell

There are three types of connections between the sensing element and the shell (Fig. 2):

- thermocouple with a grounded connection (a);
- ungrounded thermocouple (b);
- open thermocouple (c).

Fig. 2 The connection of the sensing element of the thermocouple with the shell

A major problem in temperature measurement by thermocouples is the complexity of installing them at the measurement sites. Two methods are known for installing the working element of a thermocouple on the shell of an irradiated fuel element (IFE) by spot welding, in a protective chamber, and by a special clamp [2-3], performed remotely. The first method was applied in experiments in the Halden reactor vessel channel, and the second method of fuel rod mounting was implemented in experiments conducted in the containment chamber.

The above methods of attaching thermocouples to the irradiated fuel element shell are performed remotely and are therefore difficult to implement. In addition, they are not technically possible for every reactor, and a reactor shutdown is required. Certain problems arise when installing thermocouple communication lines to a secondary device, sometimes due to design features, it is technically impossible.

It is more rational to install the thermocouple in a special guiding tube. The cross-section of the end of the guiding tube and the thermocouple is shown in Fig. 3. When placing a new thermocouple, it is pushed through this guide tube until it reaches the end, which is the correct place to install the thermocouple. In this case, the thermocouple is in close contact with the wall of the guide tube, which is rinsed from the outside by the flow of coolant. It is assumed that in this way the thermocouple measures the average temperature of the coolant.

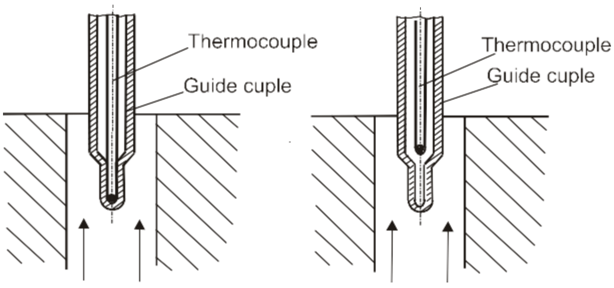

Fig. 3 Correct position of the TP in the guide tube (a), incorrect position of the TP in the guide tube (b).

If the thermocouple does not reach the end of the guide tube, the contact with the tube wall is absent, the thermocouple can't measure the temperature of the coolant exactly. One method for determining the contact between the hot junction of a thermocouple (TP) and the guide tube is to measure the time constant (τ) of the thermocouple by heating the sensing element and analyzing the transient response under operating conditions.

1.1 Methods for determining the dynamic characteristics of the thermocouple

Time series analysis methods

Time series analysis methods can be used to determine the dynamic characteristics of thermocouples [4]. Time series spectrum analysis is the one method, to examine which frequencies of the process components are reflected in the time series. It becomes possible to identify periodic components, oscillation amplitudes, and other dynamic characteristics of the signal that can be useful for analyzing temperature changes measured by thermocouples.

Another approach is the analysis of auto-correlation functions. This method is based on studies of the correlations between signal values at different time points. The nature of the signal's time changes, its delays, and periodicity can be determined by analyzing the autocorrelation function.

Yet another method is time series modeling by ARIMA models (a statistical model which applies to analyze time series and predict future values based on past observations). In such a way we create a mathematical model that describes the signal dynamics over time and predicts future temperature values.

Spectral analysis method

The spectral analysis method is an effective tool for analyzing the dynamic characteristics of thermo-couples [5]. This method is based on the decomposition of the signal into a spectral composition, with the next detection of frequencies and analysis of particular frequency components in the signal. A time series of temperature measurements must first be obtained to apply the spectral analysis method to a thermocouple. This time series is then analyzed with the help of spectral analysis techniques such as the Discrete Fourier Transform (DFT) or Fast Fourier Transform (FFT). Once the spectral representation of the signal is obtained, various characteristics can be analyzed.

Amplitude spectrum: determination of the amp-litude of the signal's frequency components, including the fundamental and distinctive harmonics.

Phase spectrum: determination of the phase shift between different components of the signal.

Power spectral density: determination of the power distribution by frequency.

This method can help identify various dynamic characteristics of thermocouples, such as periodic oscillations, response time to temperature changes, and detection of any anomalies in the signal.

Induced temperature disturbance method

The induced temperature disturbance method is an effective way to determine the dynamic characteristics of thermocouples. This method involves applying tempe-rature changes in a controlled manner and measuring the corresponding changes in the electrical signal of the thermocouple [6].

Here, it introduces the temperature disturbances induced in the system and measures the corresponding changes in the output signal. Changes in the electrical signal can be analyzed to determine dynamic charac-teristics such as response time, stability, and sensitivity. This method can be used to evaluate the response of a thermocouple to various temperature changes and to determine its dynamic properties. Mostly it measures parameters such as thermocouple response time to temperature changes and the degree of influence of external factors on the measurement.

Electrothermal Analogy Method

This method is applied to analyze and understand thermal systems by comparing them to analogous elect-rical systems [7]. The main purpose of the Electro-thermal Analogy Method is to use the knowledge and laws of electrical systems to solve problems in thermal systems. This can facilitate the analysis, modeling, and resolution of issues related to heat transfer, heat distribution, and other aspects of thermal systems.

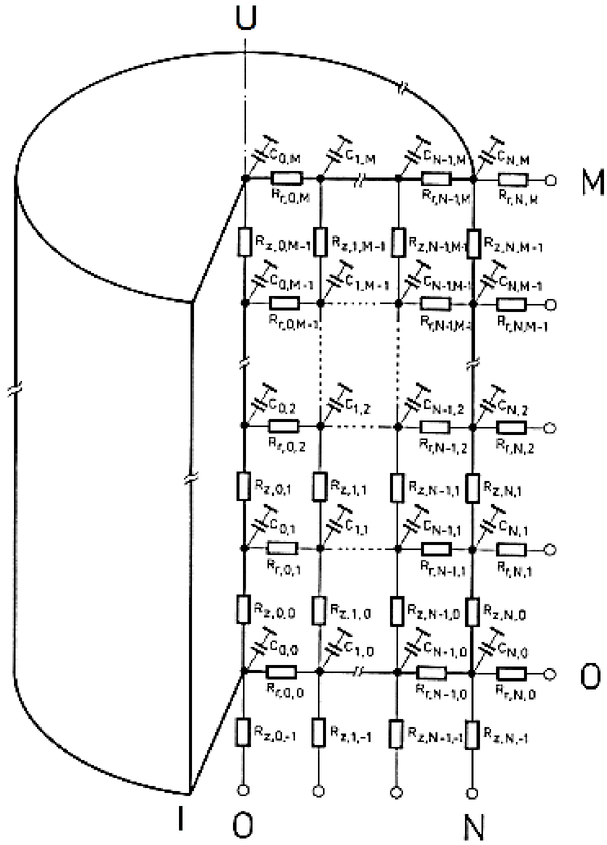

Fig. 4 Equivalent electrical circuit of a thermocouple with a protective shell

The goal of electrothermal analogies seems to simplify the analysis in the design and optimization of thermal systems by applying the tools and knowledge from the related field of electrical engineering. The temperature transducer is represented as an equivalent electrical circuit, where the elements of the thermocouple can be viewed analogously to electrical components like the resistor R and capacitor C (Fig. 4). The thermal conductivity resistance and heat transfer resistance are associated with electrical resistors. Thermal capacitance corresponds to electrical capacitance. Temperature cor-responds to voltage, and heat flow corresponds to electrical current.

LCSR Method

The LCSR method involves passing an electric current through the wires of the thermocouple's sensing element, causing the sensing element to heat up to a temperature several degrees above the ambient temperature [8]. The heating current is then turned off, and the output of the thermocouple is measured as it cools down. The total heating effect associated with the flow of electric current through the thermocouple wires consists of two components: Joule heating (proportional to the square of the current and distributed over the entire length of the wire) and the Peltier effect. The Peltier heating or cooling is proportional to the current and is concentrated at the measuring junction. The Peltier component can cause issues when using direct current (DC), as the temperature gradient along the wire accompanying the Peltier effect causes a transient process at the measuring junction when the current is stopped, unrelated to the radial heat exchange with the environment. To eliminate the Peltier effect an alternating current is applied to heat the thermocouple.

Noise Spectral Analysis Method

To determine the dynamic characteristics of thermocouples, the so-called "noise spectral analysis" method is developed in practice [9]. This method involves measuring the thermal noise generated by the thermocouple during temperature measurement and analyzing the spectrum of this noise to determine the characteristics of the thermocouple. Noise analysis is based on monitoring the natural fluctuations in the output of the thermocouple during the current technological process. These fluctuations (noise) are caused by turbulence due to water flow in the system, random heat transfer in the core, and other natural phenomena.

Peltier effect-based method

The method of determining the dynamic characteristics of thermocouples by heating the sensing element with the Peltier effect relies on the fact that when the temperature changes on the sensing element of the thermocouple, the Peltier potential changes [10]. The basic principle of the method for determining the dynamic characteristics of a thermocouple is to change the temperature of the sensing element with help of the Peltier effect.

1.2 Normalization of the dynamic characteristics of temperature transducers

In various regulatory documents (VDI/VDE 3522, DIN 43735, IEC 60584), the characteristics of contact thermometers (CT) are determined by different methods and do not always provide an accurate representation of these values, as they are based on laboratory studies when real-life conditions may vary [11].

The VDI/VDE 3522 standard is based on determining the response of a temperature transducer to sudden changes in temperature and assessing the behavior of a temperature transducer under periodic temperature changes. It describes the environmental impact on the characteristics of transducers, in particular the influence of heat transfer, thermal inertia, and mechanical characteristics of sensor materials. Similarly, DIN 43735 describes methods for measuring the dynamic characteristics of temperature transducers, in particular thermocouples and thermistors. It includes procedures for determining parameters such as the time constant and the transfer function.

The methods proposed in the IEC 60584 standard determines the primary time constant, which depends on the parameter $q=t_{90}/t_{50}$, and the secondary time constant as shown in (Fig. 5).

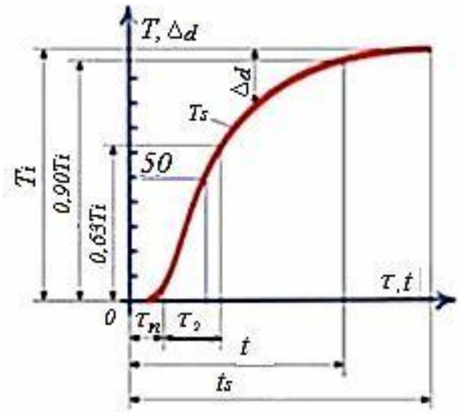

Fig. 5 Time characteristics of the transient process: τ_o (time from the start of the response, during which the thermocouple reading reaches 63 % of the change in the measured value), transient time t (time during which the thermocouple's output reaches 90% of the total change in the measured value), total settling time t_s (time during which the thermocouple's output reaches 100% of the total change in the measured value)

The standard specifies parameters for testing and measuring equipment to determine the dynamic characteristics of contact thermometers (CT), methods for experimentally determining these characteristics, methods for experiment results evaluation, and recommended formulas for describing the CT dynamic characteristics. The method for determining dynamic characteristics is based on measuring the output signal of the thermocouple (TP) during a sudden change in the surrounding temperature. The implementation of the method for determining the transient characteristic is a straightforward and internationally recognized practice.

These standards do not provide for the determination of the time constant under operating conditions [14].

According to DSTU 2389-94, the time constant is defined as the time required for the instantaneous value of the transient process in the system to change by a factor of e (e being the base of the natural logarithm, approximately 2.718), corresponding to a change in the output signal of the thermocouple by 63.2% of its total change during an exponential transient process [12-13].

5 Determining the thermocouple installation contact in the measurement channel of an NPP

The experiment for determining the thermocouple time constant based on the heating of the sensitive elements by the LCSR method under operating conditions is to determine the time required for the thermocouple to reach a certain proportion (usually 63.2%) after an intensive change in temperature that caused heating.

For internal excitation, the output terminals of the thermocouple are connected to a free-end temperature stabilizer and, through a signal switch, to a high-power AC voltage source to heat the sensitive element. LCSR parameters for thermocouples include AC voltage up to 40V and a current of up to 4 amps from the power supply. During the measurement of the thermo-EMF, the AC voltage source is switched off and the thermocouple output signal is switched to a measuring device that records the transient. The microcontroller calculates the time constant of the thermal conductor, and the results are displayed on the counting device (Fig. 6).

The sample rate and the total number of selected points are determined based on the response behavior of the under-test thermocouple. The sample rate in the experiment ranged from 5 to 40 milliseconds for different thermocouples and testing conditions. The number of sampled data points ranged from 200 to 1000.

The data were processed using the least squares method to identify the thermocouple time constants.

For this experiment, 3 thermocouples of the TCA-1590 type with a diameter of 3.5 mm and a length of 4.5 m with a simulator of the guide pipe tip were used. The distance between the thermocouple and the guide pipe varied from 00 mm to 10 mm. The experiment was held in a non-stirred water bath. The results of the experiment are shown in Table 1.

The analysis of the experiment results shows that inserting the tip into the thermocouple (for ungrounded types) increases the time constant by 10 times. Increasing the distance between the tip and the thermocouple to 2 mm increases the time constant by 50%, while a distance of 10 mm increases the time constant by 220%. Similar results were obtained for grounded thermocouples. This indicates that increasing the distance between the guide tube tip and the thermocouple reduces the thermocouple's response speed to temperature changes. In other words, the thermocouple responds more slowly to temperature changes when it is positioned farther from the guide tube tip.

Table 2 shows the experimental data when measuring the time constant of thermocouples of different diameters when mixing water.

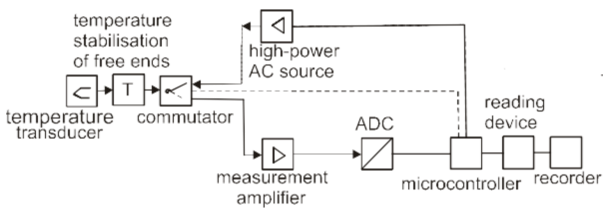

Fig. 6 Measurement system for internal excitation of the thermocouple and determination of the time constant of the thermocouple

Table 1. Time constant depending on the gap between the guide pipe and the thermocouple

Thermocouple number	Thermal inertia indicator, τ, s				
	Thermocouple without a tip	Thermocouple inserted into the tip, with a gap, mm			
		0	2	5	10
001ungrounded	0.5	5.6	8.4	9.0	18
002 ungrounded	0.5	5.8	8.5	10	20
003 grounded	0.3	3.2	4.8	5.1	7.6

Table 2. Response of shielded thermocouples to changes in heat transfer coefficient and their diameter

Water flow velocity, m/s	Thermocouple time constant, s	Construction type	Thermocouple diameter, mm		
			1.5	3.5	4.5
0.2	0.63%	ungrounded	0.2	0.6	1.2
0.2	0.63%	ungrounded	0.15	0.5	1.0
0.4	0.63%	ungrounded	0.15	0.45	0.7
0.4	0.63%	grounded	0.1	0.34	0.45

Analyzing Table 2, it is obvious that for optimal use of the dynamic characteristics of the thermocouple, it is important to consider its diameter and the environ- mental conditions where temperature measurements are made. To validate the LCSR method, the time constant of the thermocouple was measured directly under the same water flow conditions presented during the LCSR test. The direct measurement method (standard method) involved rapid immersion of the thermocouple from one temperature to another. The data were processed using the least squares method.

The results showed that the time constant determined by the LCSR method differed from the standard method by up to 3%. Such error is caused by the methodological component of the error, which arises due to the temperature gradient along the radius of the heating element.

The methodic error can be evaluated by modeling the thermal process, that describes the heat transfer from the sensitive to the protective element. This can be a differential equation considering the thermal conduc- tivity, heat capacity, and other characteristics of materials.

Conclusions

Methods for ensuring the correct location of the temperature transducer in the cavity of the cylindrical part of the reactor cassette head that contributes to the needed parameters of measurement of operation include a small line. So, the spectral analysis method requires sophisticated equipment and software for analysis and is time-consuming. The time-series- analysis method requ- ires complex data processing algorithms and significant computing resources. The Peltier method requires specialized equipment, which can be expensive.

The LCSR method is relatively easy to implement since it does not require sophisticated equipment to define the thermal constant of the thermocouple. The experiments performed using the LCSR method for thermocouples have shown that it is possible to achieve a test accuracy of approximately 10 percent for time- constant testing under operating conditions. This has become possible due to improvements in measuring instruments and signal-processing techniques.

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