MEANS FOR MEASURING THE THERMAL QUANTITIES

ACOUSTIC THERMOMETRY OF TEMPERATURE DISTRIBUTION IN FUEL RODS AT THE DESIGN STAGE

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Abstract. At the stage of design and testing of fuel rods for reactors that must operate in complex temperature and mechanical conditions, it is important to establish the maximum allowable temperature regimes, in particular the temperature distribution along the fuel rods. An ultrasonic control seems to be one of the possible non-destructive methods for assessing product quality. We consider the ultrasonic devices to monitor operational temperature modes of fuel rods and can propose the pulsed multi-zone thermometers as the optimal type.

Keywords: Nuclear reactor, Fuel rod, Ultrasonic measurements, Acoustic thermometer

1. Introduction

The transition of nuclear energy to the status of "green", 2021, requires an in-depth study of the processes occurring in the core of the reactor, where the assemblies with fuel rods containing nuclear fuel are located.

Structurally, a fuel rod is a hollow tube made of zirconium alloys, in which uranium dioxide fuel tablets are installed. In the USA, Canada, and Western Europe for the shells of fuel rods, casings, and reactor channels are used [1] zirconium alloys tsirkaloy-4 and tsirkaloy-2; the first is used mainly for fuel rods of PWR reactors, the second - for BWR reactors. In the USSR, the E-110 is Zr – 1 % Nb alloy was developed and used for fuel rods in "BBEP" and "RBMK" shells, and E-125 (Zr - 2.5 % Nb) was recommended for fuel assemblies and technological channels. Important prerequisites for reliable utilization in reactors of fuel rods and core elements made of zirconium alloys are their long-term corrosion resistance and preservation of plastic properties [2].

Here is a brief description of typical fuel rods with the particular contents inside. Length - 3.8 m, outer diameter - 9.1 mm. In the middle - uranium dioxide tablets with an outer diameter of 7.57 mm and a height of 20 mm, in the center of each tablet is a hole of a 1.2 mm diameter. The tablet does not touch the walls of the fuel shell. The gap and the hole inside the tablets are designed to hold radioactive gases formed during nuclear disintegration. The tablets are fixed inside the fuel rod with bushings. The total length of the column is 3.53 meters increasing by 30 mm while disintegrating. During nuclear fission, the temperature in the central part of the tablet reaches 1500-1600 ^{0}C (Fig. 1), and on the outer surface - only 470 ^{0}C, i.e. a difference of about one thousand degrees at a distance of 3-4 mm [3].

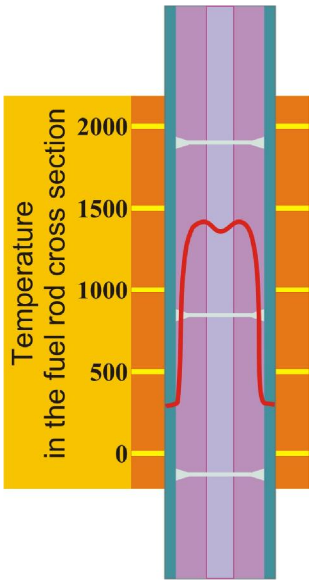

Fig. 1. Temperature distribution by fuel rod's cross-section

2. Drawbacks

Unfortunately, for a long time there exist still unresolved problems of metrological reliability of temperature-measuring instruments in the "hot" zone of the reactor. Used thermoelectric thermometers in these conditions have a guaranteed period of metrological reliability, within which changes in metrological characteristics do not exceed the allowable values in some degrees, that's 1-2 years. While the resource work of fuel rods is much higher up to tens of the years. At the same time, the design of the fuel rods does not provide the possibility to replace the thermometer, because significant thermo structural stresses, as a consequence of operation, lead to deformation of the rods and jamming of the thermometer. Therefore, it is important to study other types of thermometers that can be operated for a long time in reactors with high metrological reliability. It seems that for this purpose appropriate would be the acoustic thermometers [1, 6]. The impact of transmutation effects on these thermometers' reliability is substantially less due to their sensitive elements production of pure refractory metals. Additionally, the influence of nuclear flow-related effects is much weaker on the mentioned thermometers, because the passage of the acoustic signal in their elements is determined by mechanical rather than electrical properties, as in thermoelectric thermometers.

3. The Aim of the Article

The work aims to study the capabilities of ultrasonic temperature-measuring instruments to control the temperature regimes of fuel rods at the design and experimental operation stage, to optimize their design for long-term application.

4. Design and Operation of Fuel Rods

For all the variety of designs of nuclear reactors, they all have the same type of functional elements and process units. The main element of the reactor is the core - a structurally allocated volume, where nuclear fuel is loaded and where the controlled chain reaction takes place. During the chain reaction, a large amount of heat is released, which is removed from the core by a coolant - a liquid or gaseous substance that passes through the core. In thermal neutron reactors, water is most often used as a heat carrier, and in fast neutron reactors, metal melts (for example, Li, Na, K, and mixtures thereof) are used.

Mandatory systems for any reactor are control and protection systems that allow the implementation of the selected mode of the controlled chain reaction of fission, as well as emergency protection systems - to quickly stop the reaction in the event of an emergency. The action of both systems involves the introduction into the core of rods made of materials that efficiently absorb neutrons (for instance, boron carbide). All modern nuclear reactors are equipped with multi-barrier radiation protection systems that prevent exposure of personnel and the release of radioactive substances into the environment.

Rod operates in difficult conditions. It is affected by powerful streams of fast and thermal neutrons, characterized by unevenness; during the passage of heat fluxes in the shell there are significant thermal stresses; water has a corrosive and erosive effect on the shell: salts are deposited on the shells of fuel rods, which increase the temperature and accelerate corrosion; in liquid metals and alloys there is a transfer of mass (deposition of metals and their compounds in cold areas); organic heat carriers, polymerizing, form sediments on the shells of fuel rods; when the fuel rod swells, additional tangential stresses occur in the shell. In such a way the complexity of the mentioned factors affects the long-term operation of the fuel rods. Prolonged irradiation of zirconium alloys increases their strength characteristics but significantly impairs ductility. At temperatures above 350–360 °C, zirconium alloys corrode rapidly and hydration of zirconium increases under irradiation. Studies of E-110 alloy corrosion in water at 350 °C and under a pressure of 16.8 MPa demonstrate that the increase in sample weight in the first 4000 h was 2 mg / cm^2, after 13000 h (1.5 years) - 3 mg / cm^2, after 22000 h - 4 mg / cm^2. Zirconium alloys can be successfully used in reactors up to a shell temperature of 350 °C. Therefore, at the stage of design and tests of fuel rods, it is important to establish acceptable temperature regimes, in particular the actual temperature distribution along the length of fuel elements.

The efficiency of the fuel rods in the reactor is determined by three factors: design and quality of manufacture, mode of operation of the core. The main parameters of the whole variety of forms of fuel rods and designs of fuel assemblies are the active volume occupied by the fuel and the total surface of the fuel rods, which characterize the level of reactor loading with nuclear fuel and heat-dissipating characteristics. The ratio of these values is probably the best criterion for comparing different types of structures of fuel rods and assemblies. In the design process, taking into account the experience of known structures, roughly determine the approximate to real conditions operating temperatures of fuel rods, thermal stresses in them, strength reserves of structural materials, thermophysical and hydraulic characteristics of fuel assemblies, and maximum heat productivity. The obtained data are used for further detailed computation, which is verified by a physical experiment for the final selection of the characteristics of fuel rods, refinement of their design, and manufacturing technology.

The greatest difficulty in designing fuel assemblies is the need for an arrangement of fuel rods, in which the fuel assemblies simultaneously meet the mechanical (structural strength), hydrodynamic (low resistance and uniform cooling of fuel rods), thermal, and other requirements [3]. Free movement of fuel rods in fuel assemblies should be ensured to compensate for thermal expansion, and mechanical impact on fuel rods from the casing and fasteners of fuel assemblies should be prevented (Fig. 2).

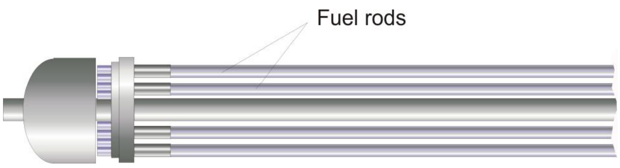

Fig. 2. Fragment of the design of the fuel assembly

Considering the requirements for fuel rods, it is necessary to determine two of them: first, the fuel rods must contain as much nuclear fuel as needed for the entire life cycle, and second, the fuel rods must reliably work this time and withstand the estimated fuel burnout without breaking the shell.

Construction materials must have a minimum neutron capture cross-section, must be corrosion and erosion resistant; corrosion products should be evaluated based on their nuclear activity and safety during reactor operation. For example, the presence of cobalt and other highly active elements with a long half-life is undesirable. The design and selected materials must be mechanically strong to maintain the shape, size, and tightness throughout the operation of the fuel rod. It is necessary to remember about the regeneration of spent fuel rods to return nuclear fuel, so the materials of the fuel rods must meet the technological conditions of reprocessing processes.

Creating reliable, efficient fuel rods with high energy density at high temperatures and efficient use of nuclear fuel is a difficult task. On the one hand, the active fuel material must have the maximum possible concentration per unit volume, on the other - the fuel core must maintain the stability of size and chemical content under irradiation, and the maximum operating temperature must be below the melting temperature and phase transformations if any are fixed.

Prevention of large temperature differences in the cross-section of the fuel rod can be achieved by using materials with high thermal conductivity, but some other requirements lead to the need for a material with opposite, lower thermal conductivity. Chemical resistance to air, water vapor, shell materials, coolant are the main requirements for fuels, as the lack of noticeable interaction determines the efficiency of fuel rods in reactors. Recently, attention has been paid to fuels based on carbides and nitrides. For example, UC contains uranium per unit volume by 30 % more than UO_2, and its thermal conductivity is an order of magnitude higher. Uranium nitride (UN) contains even more uranium, and its thermal conductivity increases with temperature and reaches 21-26 W / (m×K) at 800–1000 °C. In the process of development, tests of fuel rods are performed outside the reactor, and although these tests do not provide a full guarantee of performance in the reactor conditions during the planned operation time, they still permit to identify weaknesses in the structure and fulfill the necessary adjustments.

5. Design and Manufacture of Means for Measuring the Temperature of Fuel Rods

During operation in fuel rods, significant temperature drops occur, which cause thermal stresses due to the difference in the coefficients of thermal expansion of the components of the fuel rods' material. Therefore, at the previous stage, various thermal tests of fuel rods are performed. One of these is the heat-shock test: fuel rods are heated to a certain temperature and then rapidly cooled in water. In such a test, repeated several times, the high-mentioned stresses occur in the fuel rods. Such stresses can cause cracking, distortion, violation of diffusion adhesion, peeling off the shell, swelling, and so on.

To assess the efficiency of fuel rods, it is necessary to know the temperature distribution along the cross-section and length of the fuel rods under operating conditions, because the value of the maximum temperature has a decisive influence on the thermal stresses and compatibility of fuel elements. Since it is almost impossible to perform direct measurements of the temperature in the middle of the fuel rod, to determine the temperature distribution over the cross-section of the fuel rod, modeling is usually used, in particular by the method of electrical analogies.

The distribution of temperature along the length of the fuel rod can be measured by known means, but the analysis of methods and means for multi-zone measurement showed that the thermoelectric and resistive thermometers are ineffective since for the case of measurements in several zones, the dimensions of such thermometers are significant and they substantially distort the temperature field around the fuel rod.

In this regard, several advantages over traditional devices are inherent to the ultrasonic thermometers, in particular pulse type of them [3-6]. These are thermometers, the action of which is based on the temperature dependence of the speed of propagation of ultrasound in thermosensitive elements. The measuring range is determined by the high-temperature creep and the characteristics of the propagation of the acoustic signal. It can be in practice within the range of cryogenic temperatures up to the melting point of tungsten.

For example, a pulsed multi-zone thermometer (Fig. 3) due to the small transverse dimensions and mass of the sensitive element (option in Fig.3c) minimally affects the heat transfer around the fuel rod or inside the fuel assembly, which ensures the adequacy of the mentioned rod's and assembly's temperature. If you create several reflective planes in the sensitive element by introducing acoustic inhomogeneities (grooves, holes, bends, etc., Fig. 3b-e), the ultrasonic pulse thermometer can determine the temperature distribution.

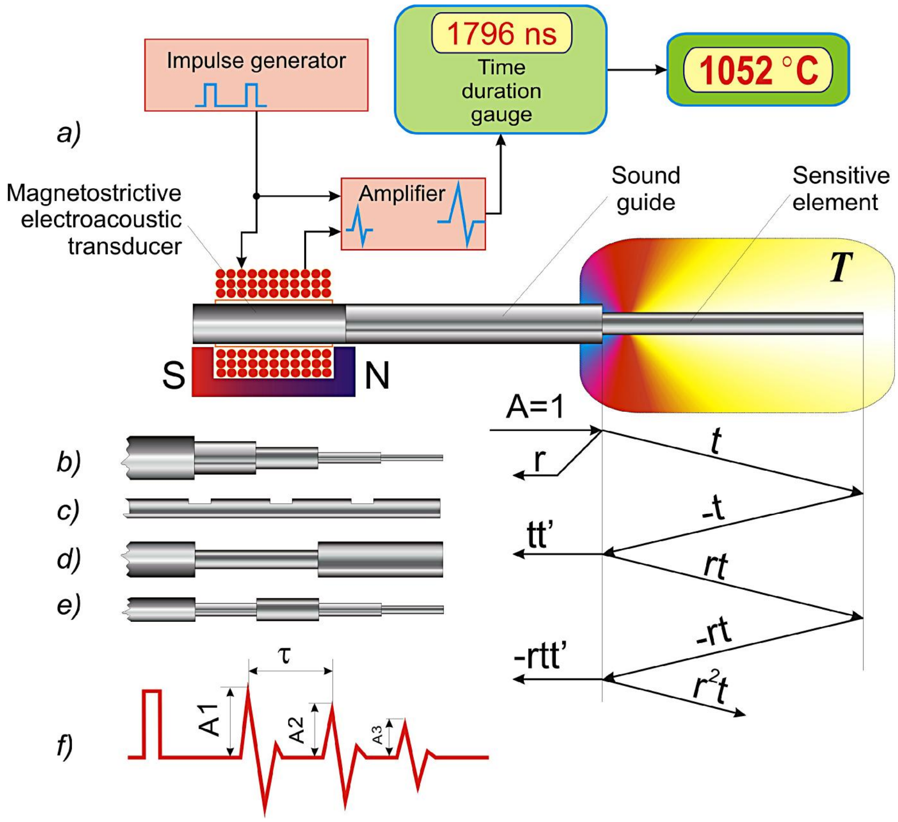

Fig. 3. Block diagram (a), the nature of the reflection of acoustic signal (f) in the single-zone sensitive element of the ultrasonic pulse thermometer and examples of implementation of multi-zone structures (b-e); r, t, t' are the coefficients of reflection and transmission of the acoustic signal

Here, time intervals are measured sequentially in pairs between echo pulses reflected from the respective planes (grooves), which corresponds to the average temperatures of the areas between these planes. Since the speed of propagation of ultrasonic waves in the thermosensitive material depends on the temperature, the measured time intervals give us information on the mean temperature of the appropriate area. The generation and reception of acoustic signals are realized by a magneto strictive electroacoustic transducer [5–6], which provides sufficient power for the acoustic signal at high temperatures. As for the sensitive elements of pulse thermometers, structurally they are performed in a large number of varieties (Fig. 4), due to the choice of oscillations (longitudinal, transverse, or torsional), the characteristics of the object, the number of zones, and more.

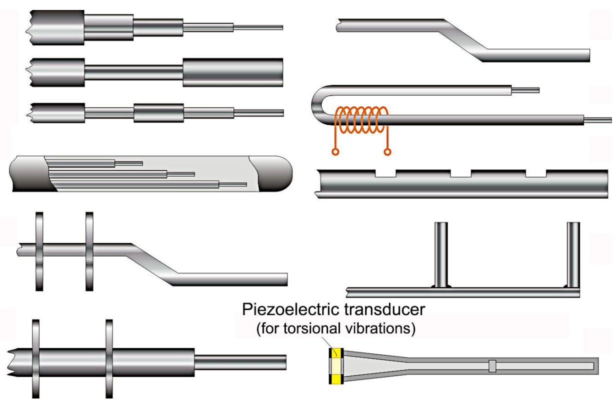

Fig. 4. The sensitive elements of ultrasonic pulse thermometer (examples)

To improve the stability of the characteristics and reduce signal distortion during the passage of ultrasonic signals through the sound guide and the sensitive element, it is recommended if it is possible to acoustically isolate the sensitive element and to perform the cap of the stick in a half-spherical shape.

6. Conclusions

At the stage of design, testing of fuel rods that operate in complex temperature and mechanical conditions, it is important to control in real-time the allowable temperature regimes, in particular the radial and longitudinal temperature distribution of the fuel rods. Analysis of the current R&Ds states that ultrasonic pulsed multi-zone thermometers are effective measuring instruments for controlling the temperature regimes of the fuel rod's long-term operation.

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8. Conflict of interest

The authors state that there are no financial or other potential conflicts regarding this work.

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