

Investigation of the elastic modulus and internal friction temperature dependences for the fuel rods by the resonance method tested by the modernized high-temperature device in hot cell

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Abstract: using the modernized high-temperature installation, the elastic characteristics and internal friction of the fuel rod shells were investigated in hot cell in order to update computer codes for WWER-1000 fuel rods. The elastic characteristics of the shell are analytically described and obtained a numerical shape factor of the first longitudinal frequency is calculated. There is description of new measuring units that provide data gathering by automatic or half-automatic mode. The elastic modulus and internal friction temperature dependences are determined by application of high-temperature modernized device that provides carrying out experiments at a temperature of 1160 K. Obtained effect could be interpreted by the crushing of the structure of the material.

1. Introduction

The engineering of new types of nuclear fuel rods involves the investigation of their physical and mechanical properties [1]. One of the major characteristics demanded for calculation codes for fuel rods is the temperature dependence of elastic characteristics (Young's and shear modules, Poisson's ratio) of the shell material in the temperature range up to the melting point. This article describes the resonance method [2,3], ultrasonic installation and experimental results on temperature dependences of young modules, shear and internal friction of aluminum and steel. All measurements were carried out using a unique measuring device developed and produced at NRNU MEPhI. A characteristic specificity of the device is uniform amplitude-frequency response of the measuring path for the frequency range 20-200 kHz combining with its high sensitivity and noise immunity, which enables to obtain the elastic characteristics and internal friction of samples for vast range of their quality factor. Due to the structure of device, the sample is sandwiched between two waveguides. There are sensors with converters at the ends of both waveguides, providing the conversion of electrical signals into mechanical vibrations and vice versa.

The modernized device enables to measure temperature dependences of elasticity and internal friction characteristics of different items, such as fuel rods, composites, components made by powder metallurgy, etc., up to their temperature of melting point, as well as to study the specificity of structural and phase transformations of them, the kinetics of frittage of metallic powders, non-destructive testing of mass production goods, evaluation of composites structure, etc.



The structure of our paper: the main theoretical states are represented in Section 2; the structure and functionality of modernized device are described in Section 3; there are the received results in section 4; we analyze the main achievements in Section 5.

The specific characteristic of the modernized device is the possibility to carry out measurements in the hot cell.

2. Theoretical basis of measurements

The principle of operation of the facility is based on the relationship of the resonance characteristics of the samples (resonance frequencies f_i and Q_i , where i is the number of the resonance peak) with their elastic and inelastic characteristics.

The elasticity characteristics of isotropic materials are: Young's modulus E , shear modulus G , bulk modulus of elasticity B , Poisson's ratio ν . Of these four characteristics for isotropic materials, two are independent, since there are coupling equations:

$$G = \frac{E}{2(1+\nu)} \quad (1)$$

$$B = \frac{E}{3(1-2\nu)} \quad (2)$$

In general, the resonance spectrum of an arbitrary shape product is a function of several parameters. The frequencies f_i of natural oscillations of any isotropic defect-free body with characteristic size d can be represented as:

$$f_i = P_i(d, \nu) C_L \quad (3)$$

where $P_i(d, \nu)$ is the coefficient of the form of oscillations at the i -th frequency, which depends on the geometry of the product and its Poisson's ratio ν . C_L — is compressional velocity in the product:

$$C_L = (E/\rho)^{1/2} \quad (4)$$

where E — Young's modulus, ρ — density of material.

For products of the cylindrical form made of one material (for example, segments of claddings of fuel elements), the coefficient of the form can be represented as:

$$P_i(d, \nu) = 1/2 h k_i \quad (5)$$

where h is the height of the sample; k_i is the coefficient of the i -th mode of oscillations, depending on the ratio of height to the diameter of the segment.

For standard segments of claddings 30 mm long, the Young's modulus E is:

$$E = 4h^2 f_{com}^2 k_{com} \rho \quad (6)$$

and shear modulus

$$G = 4h^2 f_{tor}^2 \rho \quad (7)$$

where f_{com} — the resonant frequency of the first longitudinal form of vibrations of the segment, k_{com} — the coefficient of the form of the first longitudinal frequency, close to one, f_{tor} — the resonant frequency of the first torsional form of vibrations of the fuel element segment.

The internal friction is determined by the formula:

$$Q_i^{-1} = \Delta f_i^{0.7} / f_i \quad (8)$$

where $\Delta f_i^{0.7}$ is the width of the resonance peak at the height of 0.7 of the maximum amplitude.

The coefficient k_{com} is calculated using the finite element method (FEM) in ANSYS for different lengths of fuel cladding segments. The calculation results are shown in figure 1.

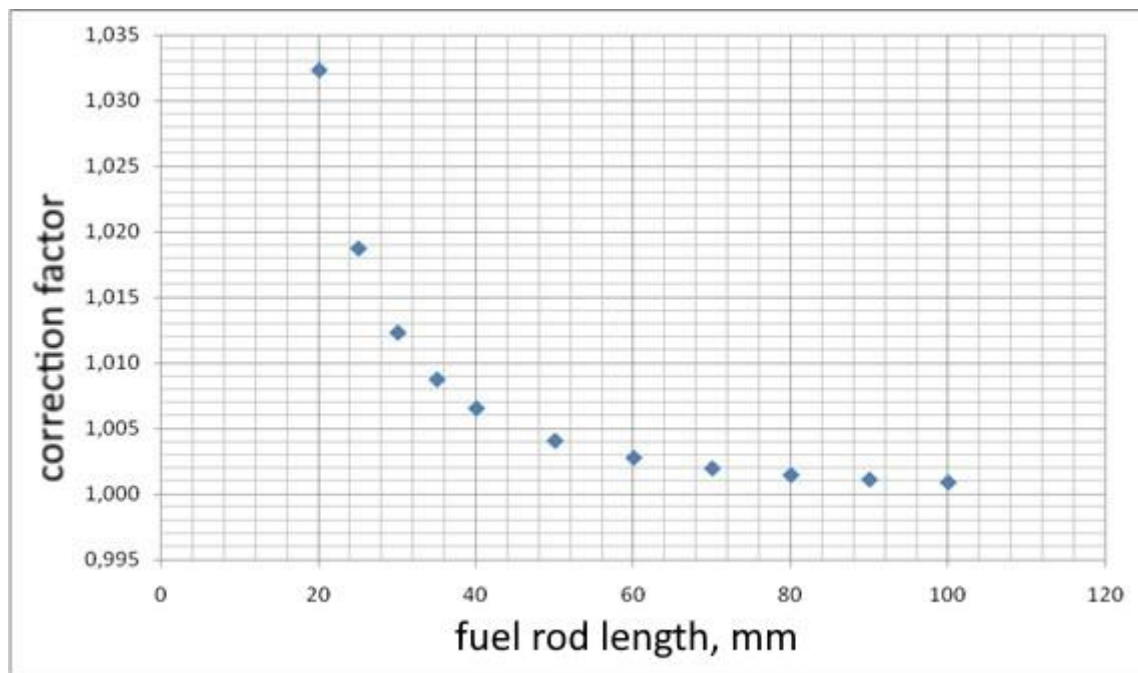


Figure 1. The dependence of the correction coefficient k_{com} on the length of the fuel cladding segment

3. Experimental facility

A block diagram of an experimental sample of a spectroscopic high-temperature device for obtaining the elastic characteristics and internal friction of samples is demonstrated in figure 2. The device is combined by two main sections: a measuring apparatus placed in a hot chamber 25 and auxiliary equipment located outside it. In turn, the measuring part also contains two main units - an ultrasonic unit and a high-temperature chamber with a heater. The body of the ultrasonic unit 1 is stationary, and the body of the high-temperature chamber 2 can move in the horizontal direction. Both nodes are mounted coaxially with the help of special racks 3. In this case, the racks of the ultrasonic unit are mounted on the base 4, and the racks of the high-temperature chamber are attached to the movable carriage 5, which can be moved with the help of the stepper motor 24. This design makes it possible to simplify the measurement procedure in hot conditions cameras. Before taking measurements, the heater moves in the horizontal direction, freeing up access to the sound ducts, one of which (movable) 7 serves to excite oscillations of the sample, and the second (fixed) 8 serves to register them. The sample is hold by two sharp tips of the sound ducts. After that, the high-temperature chamber 2 with a nichrome heater 9 is moved all the way to the housing 1 and sealed using a special silicone seal (sleeve) 10. Both sound ducts pass through the guide sleeve 11 with sound insulators 12. The movable sound duct is connected to the spring 13, which creates a small force pressing it against the test sample [4, 5].

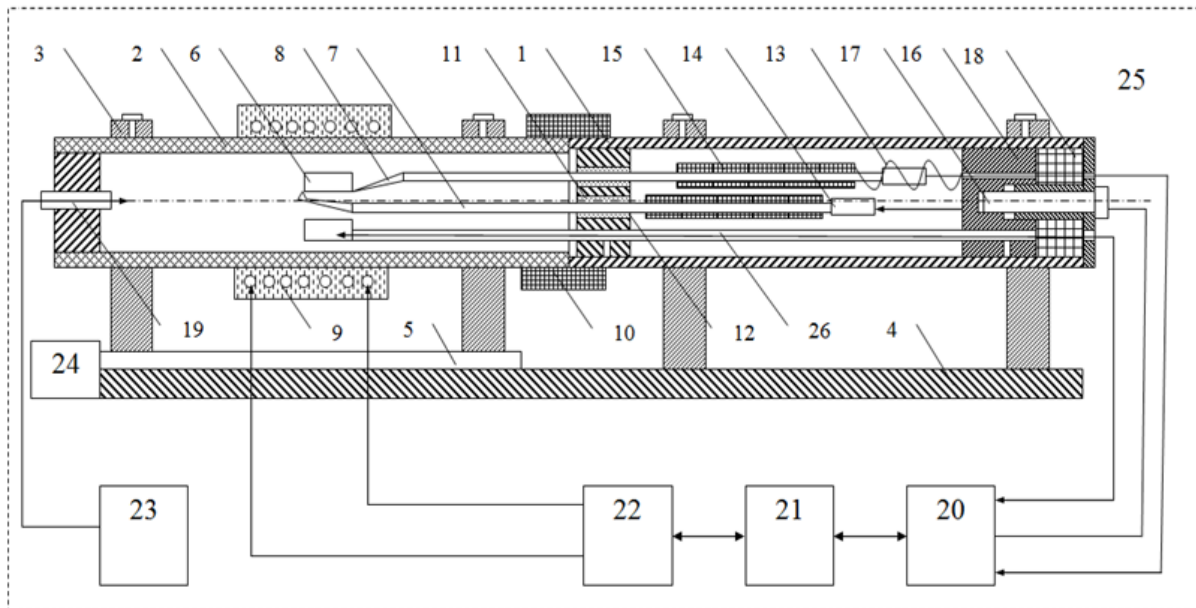


Figure 2. Block diagram of an experimental sample of an upgraded high-temperature plant for measuring the elastic characteristics and internal friction of samples in a hot cell:

1 - the body of the ultrasonic unit; 2 - heater body; 3 - racks; 4 - base; 5 - movable carriage; 6 - sample; 7 - exciting sound pipe; 8 - receiving sound duct; 9 - nichrome heater; 10 - silicone seal; 11 - guide sleeve; 12 - sound insulator; 13 - spring; 14 - piezoelectric holder; 15 - dampers; 16 - sealing sleeve; 17 - screw; 18 - rubber sleeve; 19 - pipe; 20 - electronic block pairing; 21 - personal computer; 22 - heater power supply; 23 - block vacuum and filling with inert gas; 24 - stepper motor; 25 - hot chamber; 26 - carrier tube with a thermocouple

Table 1. Main technical characteristics of the device

Temperature measurement range	300-1500K
Environment	vacuum, inert
Sample mounting method	point
Inaccuracy of measurement for elastic and shear modules, less than %	1
The range of internal friction of samples	$10^{-4} - 0,2$
Inaccuracy of measurement of internal friction, less than %	5
The operational range of frequencies, kHz	20-200
Irregularity of the frequency characteristic of the measuring path, dB	6
Material of acoustic waveguides	stainless steel
The material of the detector	PZT-19

4. Experimental results

Measurements of internal friction and Young's modules for aluminum and steel St5 were carried out on modernized device using half-automatic mode. Figure 1 shows the temperature dependence of the Young's modulus and the internal friction of an aluminum sample with a length of 25 mm at temperatures up to 0.99 of melting point temperature. The graphs show that the Young's modulus of aluminum (when sample is heated at the temperature range of 20-500°C) decreases almost linearly, and after 500°C starts to decrease rapidly tending to zero, when melting point temperature is 610°C. The internal friction reaches its maximum value, equal to $Q_{-1}=0.15$ at $T=575^{\circ}\text{C}$.

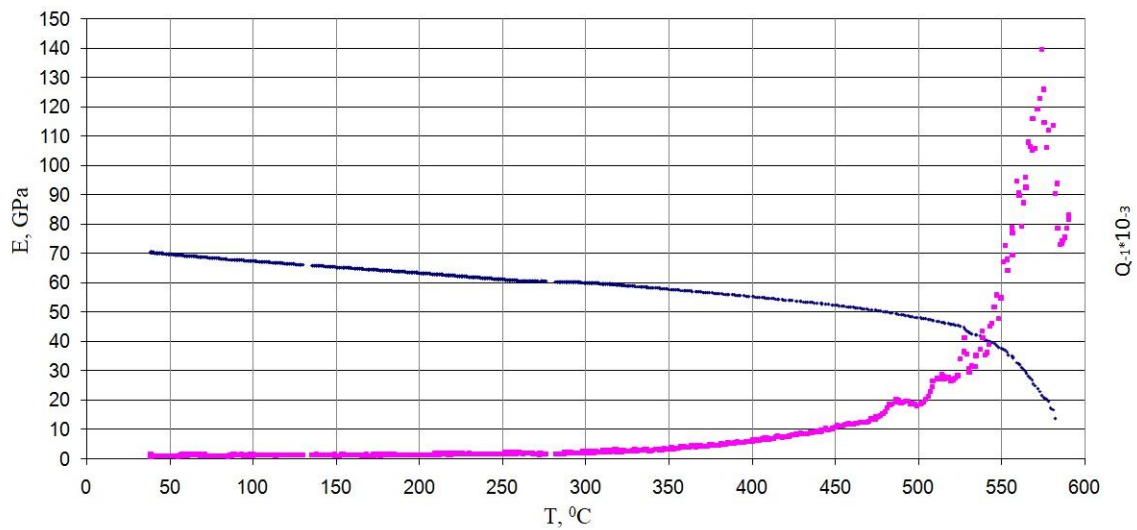


Figure 3. Dependence of Young's modulus and internal friction of aluminum on temperature

Figure 2 shows the temperature dependence of Young's modulus on the temperature for stick sample (length 20 mm, made of steel St5 GOST 380-2005). Due to Figure 2 the dependence of the Young's modulus of steel during heating does not corresponds with the dependence during cooling (the trends of temperature change is shown by arrows), which is typical for the phase transition of the first kind. In this individual case, it corresponds to the transition from body-centered cubic to face-centered cubic crystal system for steels. Meanwhile the hysteresis loop is located at the range of 600-900°C, and the phase transition maximum corresponds to melting point temperature (710°C) [6, 7].

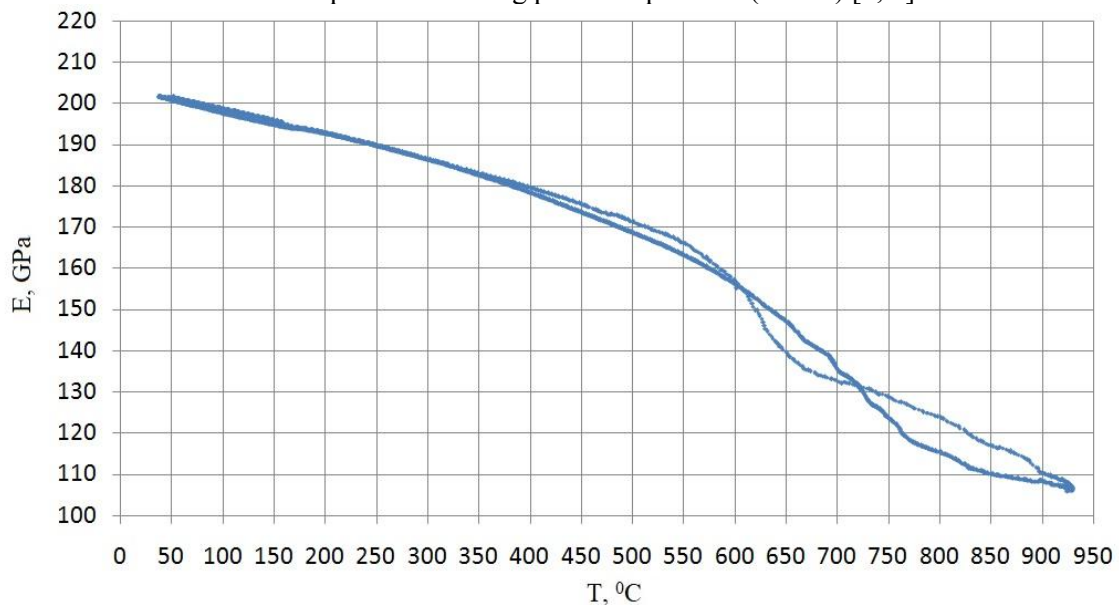


Figure 4. Dependence of Young's modulus of steel St5 on temperature

5. Conclusion

The developed ultrasonic device of high-temperature installation provides the ability to obtain temperature dependence of Young's, shear modules and internal friction of classic fuel rods. The

obtained characteristics are non-monotonic for a small temperature range of 1100-1200 K, and the peak of internal friction was obtained for temperature of 1160 K. This effect could be interpreted by the crushing of the structure of the material.

The correction coefficient of the form the first longitudinal frequency via finite element method was also obtained (see Figure 1). The results received by the experiments provided by modernized device will be fundamental for the development of a framework of integrated digital duplicates of fuel rods. The structure determines the correlation between thermophysical and neutron calculations according to the shifts of the technical condition of fuel rods determined by the presented methods

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References

- [1] Reshetnikov F G, Bibilashvili Y K, Golovnin I S, Gorsky V V, Kazennov Y I, Menshikova T S, Nikulina A V and Romaneev V V 1995 *Development, Production and Operation of Fuel Elements of Power Reactors* vol 1 (Moscow: Energoatomizdat) p 333
- [2] Baranov V M 1990 *Acoustic Measurements in Nuclear Energy* (Moscow: Energoatomizdat) p 319
- [3] Baranov V M, Karasevich A M, Kudryavtsev E M and et al 1999 *Diagnostics of Materials and Structures of the Fuel and Energy Complex* (Moscow: Energoatomizdat) p 360
- [4] Maximkin A I, Kryukov I S, Ableev A N, Berestov A V and Rodko I I Experimental research and development of safety analysis systems for advanced types of fuel rods *International 2018 Conference on Nuclear Engineering, Proceedings, ICONE, 2018* Vol. 3 (London, United Kingdom: American Society of Mechanical Engineers)
- [5] Martynenko S P, Martynenko S S, Ableev A N, Panasenko R A, Anufriev B F and Maksimkin A I Mock-up of experimental system for control of gas environment parameters in fuel elements during their production *2015 International Conference on Control Instrumentation Communication and Computational Technologies, ICCICCT 2015, 2015* pp. 668-67 (Kumaracoil, India: Institute of Electrical and Electronics Engineers)
- [6] Martynenko S S, Ableev A N, Martynenko S P, Panasenko R A, Berestov A V and Rodko I I High-precision information measurement systems for experimental control systems of gas environment parameters in fuel elements during their production and corrosive damage of fuel element shells *2015 International Conference on Control Instrumentation Communication and Computational Technologies, ICCICCT 2015, 2015* pp. 672-676 (Kumaracoil, India: Institute of Electrical and Electronics Engineers)
- [7] Panasenko R A, Martynenko S P, Martynenko A S, Ableev A N, Kudryavtsev E M, Frolov E S and Varyatchenko E P Experimental high-precision apparatus for control of corrosion damage of fuel element shells *2015 International Conference on Control Instrumentation Communication and Computational Technologies, ICCICCT 2015, 2015* pp. 677-681 (Kumaracoil, India: Institute of Electrical and Electronics Engineers)