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Control rod position measurement with helix-electrode capacitance sensor in nuclear heating reactor

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ABSTRACT

Capacitance sensors are frequently applied for dielectric objects measurements. However, the study on the ungrounded/grounded control rod position measurements with capacitance sensor is limited. In this connection, a system based on the helix-electrode capacitance sensor is applied to measure the rod position in NHR. Based on the variations of equivalent electrical permittivity with different control rod positions in NHR, the helix-electrode capacitance sensor has been successfully used for the ungrounded/grounded control rod position measurement due to its advantages of non-invasion, low-cost, high reliability and non-radiation. The finite element method is used to calculate the sensor capacitance and the sensor sensitivity is also presented. Then, the ungrounded/grounded control rod position experiment is carried out to measure the response of the helix-electrode capacitance sensor, in which a novel method is proposed to calibrate the helix-electrode capacitance sensor based on the grating linear displacement measuring probe. The capacitances obtained by simulations were compared with experiment results to verify the proposed models. The subsequent quantitative analyses on the data indicate the reliability and accuracy of the apparatus for monitoring control rod position. It is demonstrated that such a system shows promising applications for measurements of the control rod position in NHR.

Control rod position directly affects the safety and efficiency of reactor operations. As one of the key process parameters in nuclear heating reactor (NHR), the control rod position measurement is of great importance, especially for the reliable and real-time automatic monitoring of control rod. 5 MW NHR was built in Institute of Nuclear and New Energy Technology, Tsinghua University.

The exploration of control rod position measurement has attracted much attention from theoretical and experimental research fields on account of its significance. In recent studies, three methods are mainly employed in control rod position observation. These are, magnetostrictive measurements, sonar measurements, and electrically-induced measurements (Maurio et al., 2015; Zhu et al., 2016; Wang et al., 1996). Maurio Joseph et al. have developed a magnetostrictive control rod position measurement device (Maurio et al., 2015). Unfortunately, due to certain factors, such as low reliability, the device is still at present in a state of improvement. In sonar measurement, a high frequency transducer is used to emit different forms of signals and the time-delay between the two interfaces detected (Zhu et al., 2016). The rod position can be calculated from the time difference between the echo signals from the two interfaces and the sound velocity in the measurement area. However, it is unable to avoid the influence of interface properties. Electrically-induced measurements began to be used in control rod position in the 1970s (Wang et al., 1996). Electrically-induced measurement is commonly used in commercial nuclear power plants. In this method, the control rod position is obtained by analyzing induced signals. The method can be directly applied in jamming environment and produce high-quality output signals. Despite the research results, there exist significant challenges in the control rod measurement in NHR. For example, the low measuring accuracy on the measurement response is still a problem.

Therefore, a new device is designed to measure the ungrounded/grounded control rod positions in NHR. It aims to monitor the control rod position in time with a high accuracy (Lin et al., 2016). Moreover, the reliability is high. In addition, the whole device set has a low cost and is suitable for a critical working condition (Kerpel et al., 2014; Shin et al., 2015; Pengmin, 2016; Lee et al., 2016). This study first introduces the capacitance sensor involved, as well as the finite element method (FEM) used to calculate the helix-electrode capacitance sensor response for the ungrounded/grounded control rod. Then, it discusses the validity of this apparatus in the detection tests carried out on the ungrounded/grounded control rod. The calibration of the apparatus

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is also analyzed. Finally, the problems encountered with it are discussed and solutions and improvement measures for these problems presented.

1. Sensor theory

1.1. Sensor structure

The structure of the helix-electrode capacitance sensor is schematically shown in Fig. 1. Helical electrodes are mounted on a dielectric pipe to form a capacitor. They are covered in a metal shield to isolate external electromagnetic interferences. R_1 is the inner radius of the control rod. R_2 and R_3 denote the inner and outer radius of the dielectric pipe, respectively. α is the angle of the helical electrode. L is the length of the helical surface-plate electrode. Moreover, the number of the electrode twisting turns along the pipe surface is denoted by n. In this paper, the helical electrodes and shield are made of red copper and stainless steel, respectively. The material of the dielectric pipe is ceramic. Other structural parameters are as follows: R_1 = 7 mm, R_2 = 8 mm, R_3 = 11 mm, α = 170°, L = 990 mm, n = 16.5. It is worth noting that the surface of the two-electrode sensor is sealed using insulating materials to prevent direct contact of the capacitance electrodes with the control rod or earthed screen. The central angle of the electrode is 170 degrees. The selected central angle is an optimal result based on my previous research (Hu and Bo, 2017).

1.2. Finite element model of the sensor

Fig. 1 shows the sketch of helix-electrode capacitance sensor, which consists of excitation electrode, measuring electrode, earthed screen, and an insulating pipeline. COMSOL Multiphysics software is used to draw the meshed finite element model of helix-electrode capacitance sensor with the earthed screen, as shown in Fig. 2.

If space charge does not exist inside the pipeline, the inner potential distribution can be described by the following poisson equation:

$$\nabla(\varepsilon_0\varepsilon(x,y,z)\nabla\varphi(x,y,z)) = 0 \qquad (1)$$

where ∇ is the divergence operator, $\varphi(x,y,z)$ is spatial potential distribution, ε_0 is permittivity of free space, $\varepsilon(x,y,z)$ is spatial permittivity distribution.

And the boundary conditions of this problem are the electric potential $\varphi(x,y,z)$ on the different surfaces of the sensors.

$$\varphi(x,y,z) = V_E \text{ on } \Gamma_{\text{excited}} \qquad (2)$$

$$\varphi(x,y,z) = 0 \text{ on } \Gamma_{\text{screening}} \text{ and } \Gamma_{\text{measured}} \qquad (3)$$

where the V_E is the excitation voltage, Γ_{excited} is the surface of the excited electrode, $\Gamma_{\text{screening}}$ is the surface of the screening and Γ_{measured} is the surface of the measured electrode. The charge (Q) induced on the surface of measured electrode (S) can be calculated by

$$Q = -\int_S \varepsilon_0\varepsilon(x,y,z)\nabla\varphi(x,y,z)\mathrm{d}\boldsymbol{S} \qquad (4)$$

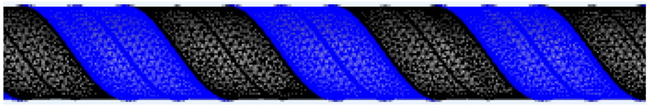
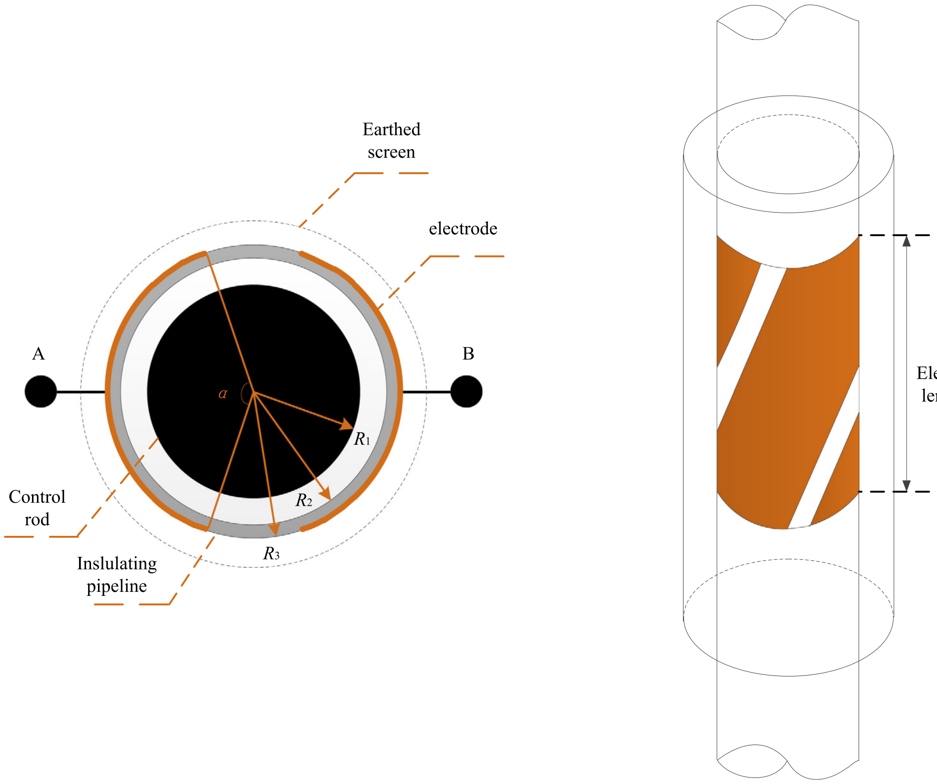


Fig. 2. FEM grid of the helix-electrode capacitance sensor.



(a) Cross-section view

(b) Three-dimensional view

Fig. 1. Sketch of the helix-electrode capacitance sensor.