Experimental analysis of liquid-metal reactor scram rod kinematic characteristics

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Abstract. This article represents the results of computational and experimental research of liquid-metal research reactor control rod kinematics. In this research liquid-metal coolant (sodium) was simulated by water. Investigation of control rod scram-mode movement duration and investigation of velocity of movable parts near the bump of damper are the purposes of this research. Also mathematic simulation of control rod movement in scram mode was performed. Computational results for some modes of water circulation comply with experimental results well. Results of this work will be used for tests of scram rod drive of above-named research reactor. It will significantly simplify the scram rod drive testing stand construction.

1. Introduction
In this work the results of experimental evaluation and mathematical simulation of kinematics of scram rod of research liquid-metal nuclear reactor are presented. In this research reactor control and scram rods are moved in guiding pipes. Liquid-metal coolant flows through these pipes in bottom-upwards direction. The scram rod is moved by rod drive. In case of scram signal or zeroing of rod drive scram rod moves into the core by gravity or by scram springs force.

The definition of scram rod model movement time in case of opposite liquid flow and discovering the hydraulic damper characteristics were the purposes of this work. Received data will be used for scram rod drive testing. In this testing scram rod mass simulator will be moved in slack water. Therefore testing stand construction can be simplified.

Also the mathematical simulation of scram rod movement and comparison simulation and experimental results were provided.

Depending on construction, technical characteristics and work conditions rod drives can include different damping devices [1]. On the one hand, damper must provide smooth scram rod slowdown to prevent it breakdown. On the other hand, scram rod movement time is important parameter, which influence on nuclear safety. Hydraulic damper was chosen for this research nuclear reactor. The main advantage of hydraulic damper is no rebound after the scram rod slowdown. Similar researches (without damper characteristics discovering) were provided in India [2].

2. Testing object
The object of experimental research was a scram rod model and a hydraulic damper model. Scram rod model was mounted in guiding pipe and can be moved axially over a distance of (650 ± 5) mm. Geometric parameters of scram rod model, guiding pipe and hydraulic damper model consist with geometric parameters of real scram rod, pipe and hydraulic damper. Scram rod model mass and real
scram rod mass are equal.

During the experiments the liquid-metal coolant (sodium) was substituted by water. Scram rod movement time depends on hydraulic drag force from the flow. Hydraulic drag force is proportional to pressure fall. Water friction coefficient is more than sodium friction coefficient for about 14% in case of same water and sodium velocities. Hence, we may suppose, that friction pressure fall is independent of Reynolds criteria [3].

Pressure fall at local hydraulic resistances depends on geometrical characteristics, fluid density and fluid velocity. Therefore pressure falls on scram rod for water and sodium will be equal under the following conditions:

$$\frac{\rho_{\text{H}_2\text{O}}v_{\text{H}_2\text{O}}^2}{2} = \frac{\rho_{\text{Na}}v_{\text{Na}}^2}{2}$$

(1)

where $\rho_{\text{H}_2\text{O}}$ – water density, kg/m$^3$;
$\rho_{\text{Na}}$ – sodium density, kg/m$^3$;
$v_{\text{H}_2\text{O}}$ – water velocity, m/s;
$v_{\text{Na}}$ – sodium velocity, m/s.

The necessary water velocity for correct sodium velocity simulation can be found from this equation.

Testing stand consists of flowing circuit and testing devices: pipe, scram rod model and hydraulic damper. In different testing modes water flow varies from 0 to 12 m$^3$/h.

Initially hydraulic damper plunger leans on hydraulic damper shank. Scram rod model is moved upwards over a distance (650 ± 5) mm and is fixed in the top position. Scram rod model falling is provided by gravity. For measuring scram rod model coordinate and falling time is used wire displacement sensor WDS-3000-SR-I.

The wire of the displacement sensor is fixed to the scram rod model. The wire is coiled on the drum of the sensor. Rotation angle of the drum is transduced into current. Output signal of the sensor is given to oscilloscope through the current-to-voltage converter. Scram rod model displacement and displacement time can be measured by the oscillogramm. The scheme of the testing stand is presented on figure 1.

3. Testing methods

In [1, 5] the following method is described: the pressure fall on the scram rod is measured and the scram rod velocity is calculated. In our tests scram rod coordinate is measured directly, and scram rod velocity could be calculated as the first time derivative of the scram rod coordinate.

At the tests common mass of scram rod model and moving parts of the stand was equal to real masses (36±1) kg. Scram springs force has been ignored: it was assumed, that this force will be compensated by the friction force at the moving parts of the scram rod drive.

Oscillogramms of scram rod model falls were saved to graphics files, and then the scram rod model falling time and scram rod model velocity at the bottom mechanical stop were determined.
Experiments were provided with different damper plunger construction: with or without vertical slashes for liquid flow (figure 2).

Figure 1. Scheme of the testing stand.

Figure 2. Different damper plunger constructions.
4. Experiment results
As the result of the experiments the scram rod model falling time for different values of water flow was determined. Also the scram rod model velocity at the bottom can be determined by the oscillograms (figure 3).

![Figure 3](image)

**Figure 3.** Example of oscillogram (water flow – 2 m³/h, plunger without slashes).

Common graphics are presented on figure 4.

![Figure 4](image)

**Figure 4.** Scram rod model displacement for different values of water flow.

The test results analysis lead to the following conclusions:
- while water flow increasing the scram rod falling time is also increasing because of the hydraulic resistance force increases (but not more than 1 s);
- hydraulic damper without plunger slashes provides more smooth slowdown than the other one;
- the scram rod model displacement time is practically independent of the water flow value for water flow values lower than 4 m³/h.

The given results for models with real geometric parameters allow to determine the acceptable value of scram rod model falling time at scram rod drive tests in the slack water.

5. Analysis results
The approximate correlations for simple-formed bodies movement in viscous fluid calculations are presented in [1, 5]. These correlations are inapplicable because of complex form of the hydraulic damper plunger and short scram rod displacement time. Therefore the scram rod movement can be
calculated numerically. To simplify the mathematical model the following method was applied: the pressure falls on scram rod and on hydraulic damper plunger were calculated separately, and the common pressure fall was calculated as the sum of partial pressure falls.

For example, in work [6] pressure falls were calculated analytically, and the viscous friction was neglected. But in work [6] moving parts had simple form (cylinder). Therefore methods presented in [6] are unacceptable in our case. For example, the results of plunger movement calculation with the constant plunger velocity hypothesis are presented in work [7].

In our work the simulation was provided with SALOME-6.6 (grid generation and results representation) and Code-Saturne 4.0 [8] (flow calculation). The calculation was carried out for different plunger constructions: with and without slashes (figure 5). K-ε turbulence model [9] was used for the flow calculation. And the pressure falls were received as the result of the calculation.

![Figure 5. SALOME calculation result representation.](image)

For the simulation the following assumptions were accepted:

- fluid properties in the testing area are constant;
- the hydraulic resistance coefficient is constant for each part of plunger way (before and after hydraulic damper plunger pinch), therefore the pressure fall is proportional to velocity squared;
- some construction simplifications were setted.

The following calculation method was adopted: the pressure fall was calculated numerically for fluid velocity 1 m/s, then the resistance force was calculated for each value of fluid velocity, using the hydraulic resistance coefficient constance hypothesis. The resistance force was used in equation (2) to determine the scram rod speed and coordinate for each iteration.

$$x'' = \left( \frac{m \cdot g \cdot F_a - P \cdot (x' + u_0)}{s} \right) / m$$

(2)

where $x, x', x''$ – scram rod coordinate, m; velocity, m/s; acceleration, m/s$^2$, respectively;

- $m$ – moving parts mass, kg;
- $F_a$ – Archimedes force, N;
- $P$ – calculated pressure fall for fluid velocity $u_0$, Pa;
- $u_0$ – fluid velocity for simulation, 1 m/s;
- $S_{plunger}$ – plunger face area, m$^2$.

The received results have good agreement with the experimental results for low values (lower than
4 m$^3$/h) of water flow (figure 6).

![Plunger construction #2, slack water](image)

**Figure 6.** The comparison of experimental and calculation results (slack water).

For the water flow values more than 4 m$^3$/h the value of the scram rod movement velocity is overestimated. This fact can be explained with model geometrical construction simplifications.

6. Conclusions
The experimental and calculation investigation of liquid-metal research reactor scram rod kinematics were provided [10, 11]. The practical utility of this work consists in probability to simplify construction of scram rod drive testing stand: it is possible to test the drive in slack water using the results of the present work.

The results of the mathematical simulation have good agreement with the experimental results for low values of water flow. Hence, such calculation method can be used for estimation of hydraulic dampers kinematic characteristics only, but it is enough to solve the design problems.

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