

Numerical Analysis on the Free Fall Motion of the Control Rod Assembly for the Sodium Cooled Fast Reactor

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1. Introduction

In a sodium-cooled fast reactor(SFR), the control rod assembly is used to control the reactor power. If any of the operating limits are exceeded, the control rod assemblies are inserted into the core within a stipulated time to shut down the reactor power as soon as possible. On receiving the scram signal, the control rod assemblies are released to fall into the reactor core by its weight. Thus drop time and falling velocity of the control rod assembly must be estimated for the safety evaluation. However, because of its complex shape, it is difficult to estimate the drop time by theoretical method.

In this study, numerical analysis has been carried out in order to estimate drop time and falling velocity of the control rod assembly to provide the underlying data for the design optimization.

2. The Control Rod Assembly Model

The calculation domain consists of two main parts: control rod assembly and its guide duct. The guide duct is composed of handling socket, nose piece, hexagonal duct and damper. Hexagonal duct serves to restrict the falling path of the control rod assembly. And the damper is located at the bottom of the hexagonal duct to reduce the falling velocity of the control rod assembly. The control rod assembly consists of control rods, lower and upper adapter, mounting rail, clamping head, piston head(Shown in Fig.1). On the verge of falling termination, the piston head is inserted into the damper to reduce the falling velocity.

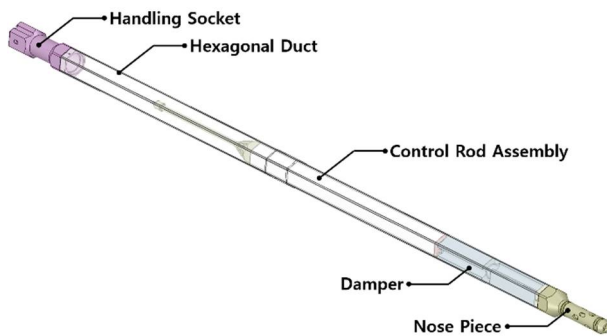


Fig. 1 Configuration of the control rod assembly and the guide duct

3. Numerical Analysis Method

To calculate the rigid body motion of the falling control rod assembly, buoyancy force and drag force must be considered with gravity force. The equation of motion of a falling rigid body can be expressed as Eq.1.

$$m \frac{dV}{dt} = mg \left(1 - \frac{\rho_f}{\rho_s}\right) - \frac{1}{2} \rho_f V^2 A C_D \quad \text{Eq.1}$$

But it is not easy to estimate the drag coefficient(C_D) of the falling body having a complicated shape. Furthermore, it is more difficult to estimate the drag coefficient of the moving object in theoretical way. Therefore, experiment or numerical analysis must be performed to estimate the drag coefficient of a falling object having a complicated shape.

In this study, 3D unsteady CFD(computational fluid dynamics) analysis has been conducted to calculate the drag term wherein the Eq.1. In the process of the analysis, external force term of the Eq.1 is calculated by CFD solver, and effect of falling object on the flow field is considered at the same time. To calculate the flow field, continuity equation(Eq.2) and momentum equation(Eq.3) have been used. And K- ϵ turbulence model is also adopted to consider turbulent effect.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \quad \text{Eq.2}$$

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) + \rho \vec{g} + \vec{F} \quad \text{Eq.3}$$

About 750,000 grids are used in the entire calculation domain for the CFD analysis(Shown in Fig. 2). Mesh deformation method and sliding mesh method are used to deal with the mesh deformation during the falling of the control rod assembly.

The guide duct is completely filled with coolant, and it is assumed that there are no coolant flow. In this study, the coolant is regarded as water(Table 1). Weight of the control rod assembly is 48.0 kg.

Table 1. Material properties of the coolant

	Water (25°C)
Density	997.0 kg/m ³
Viscosity	8.899 × 10 ⁻⁴ Pa·s

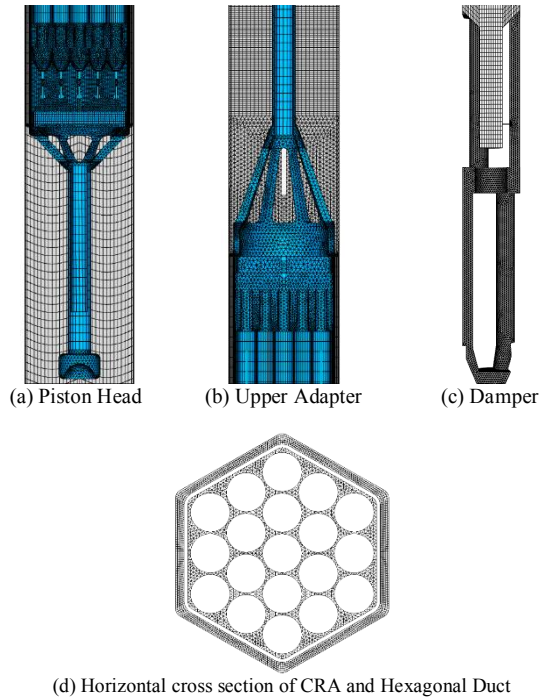


Fig. 2 Grid System

4. Methodology Verification

To validate the CFD methodology, experiment on underwater steel sphere drop has been carried out. And a numerical analysis has been conducted under the same conditions as the experiment. Weight of the steel sphere is 110.2g and its diameter is 30mm. The steel sphere is released to fall at 1.45m height. Fig.3 shows the schematic diagram of the experiment on the steel sphere drop in water.

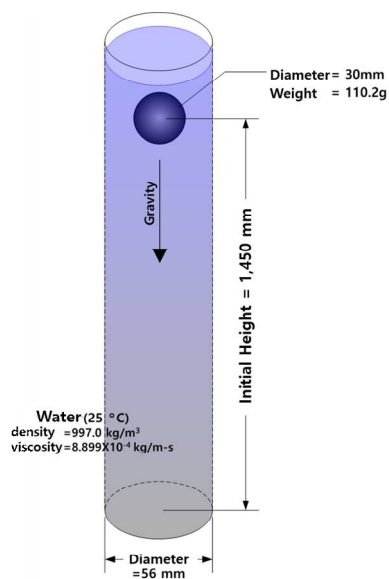


Fig. 3 Schematic diagram of the experiment on the steel sphere drop in water

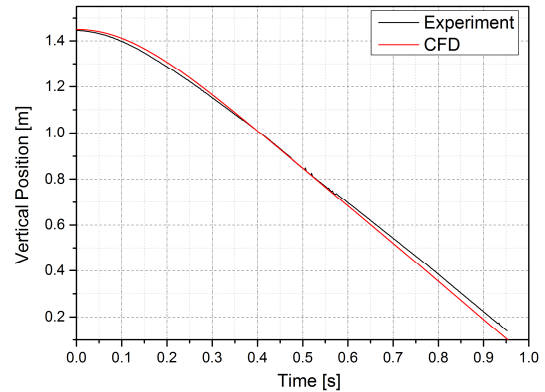


Fig. 4 Traveling distance of the steel sphere

Fig 4 shows the traveling distance of the steel sphere while falling. The experiment result and CFD results are assessed to be similar. In experiment, drop time(from 1.45m to 0.2m) of the steel sphere is measured to be about 0.914 s. In CFD analysis, drop time(from 1.45m to 0.2m) is estimated to be about 0.893 s. The relative Error in the CFD analysis for the experiment is only about 2.3 %.

5. Analysis Results

Velocity and pressure contour in the calculation domain while falling are shown in Fig. 5 and Fig. 6 respectively. The fastest flow velocity is observed in the control rod assembly. Because the gap among control rods is relatively narrower than any other regions. During the control rod assembly is dropping, relatively higher pressure is formed in the lower region of the control rod assembly.

Graphs of falling distance and velocity of the control rod assembly are shown in Fig. 7 and Fig. 8. In the beginning of the drop, falling velocity of the control rod assembly is rapidly increased. Thereafter, increasing rate of the falling velocity decreases, and then the falling velocity reaches the terminal velocity. When the piston head of the control rod assembly is inserted into the damper, falling velocity decreases quickly. Maximum falling velocity is 0.78 m/s, and the terminal velocity (impact velocity) is 0.65 m/s, which is reduced by damper effect(The falling velocity is reduced about 14 %). The drop time of the control rod assembly is about 1.47s.

Variation of the drag force acting on the control rod assembly is shown in Fig. 9. In common with the falling velocity, drag force acting on the control rod assembly increases rapidly in the beginning. And then stable drag force is acting on the falling body. When the piston head of the control rod assembly is inserted into the damper, the drag force increases instantaneously. At that moment, the maximum drag force occurs, and its amount is about 270 N.

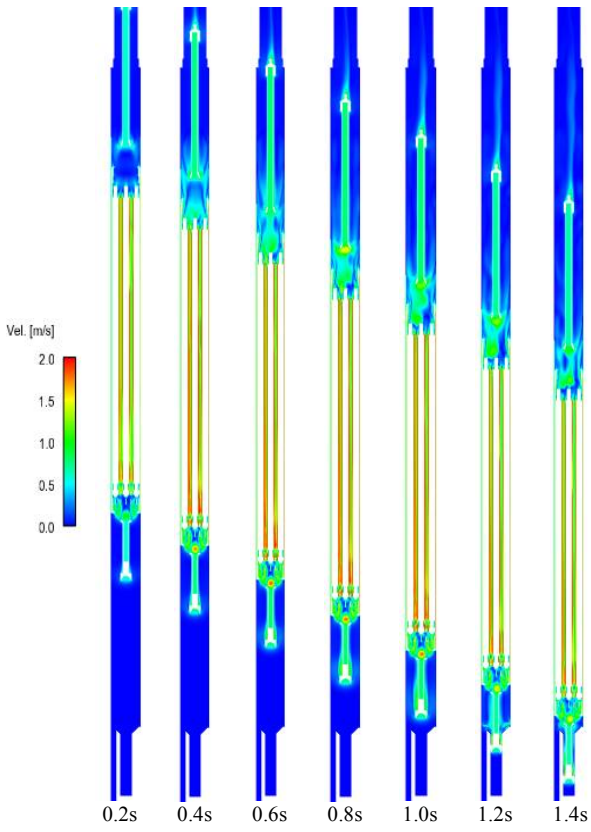


Fig. 5 Velocity contour

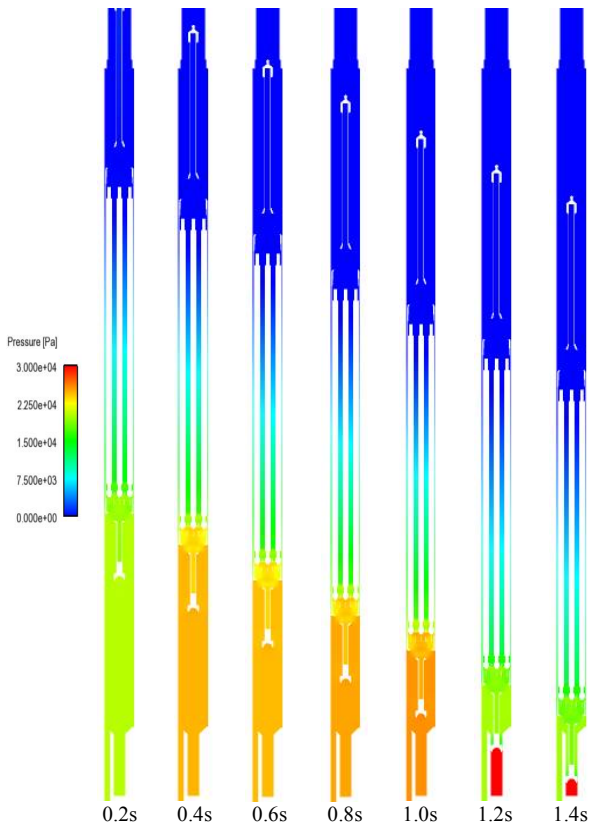


Fig. 6 Pressure contour

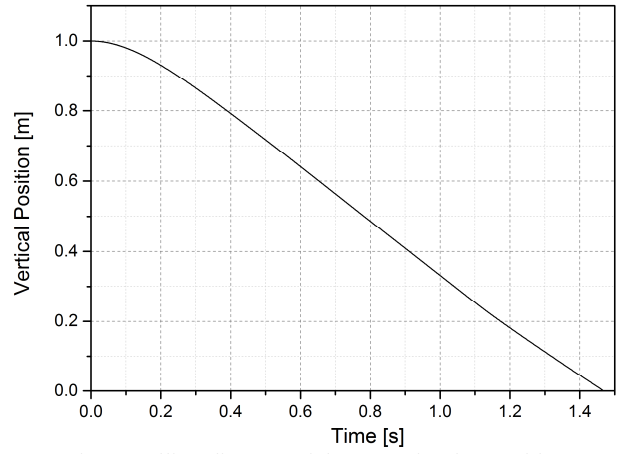


Fig. 7 Falling distance of the control rod assembly

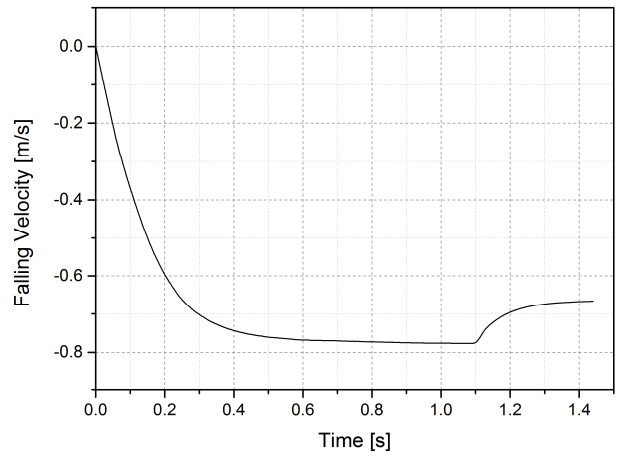


Fig. 8 Falling velocity of the control rod assembly

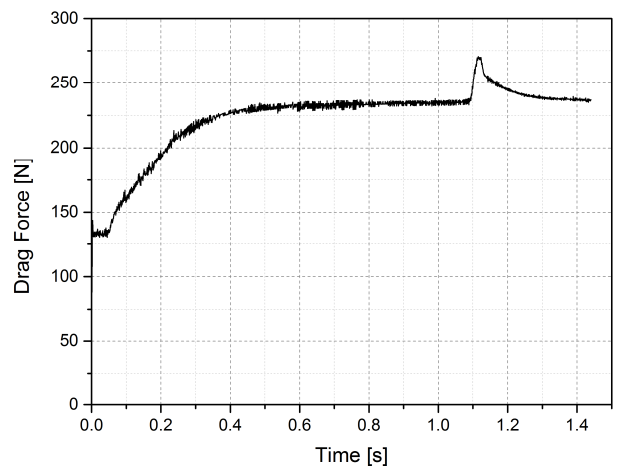


Fig. 9 Variation of the drag force acting on the CRA

6. Conclusions

Numerical analysis has been carried out to estimate the drop time and falling velocity of the control rod assembly for sodium-cooled fast reactor. Before performing the numerical analysis for the control rod assembly, sphere dropping experiment has been carried out for verification of the CFD methodology. The result of the numerical analysis for the method verification is almost same as the result of the experiment. The relative Error in the CFD analysis for the experiment is only about 2.3 %.

The results of CFD analysis for the control rod assembly are as follows. Falling velocity and drag force increase rapidly in the beginning. And then it goes to the stable state. When the piston head of the control rod assembly is inserted into the damper, the drag force increases instantaneously and the falling velocity decreases quickly. The falling velocity is reduced about 14 % by damper. The total drop time of the control rod assembly is about 1.47s.

In the next study, the experiment for the control rod assembly will be carried out, and its result is going to be compared with the CFD analysis result. Moreover, numerical study on the effect of geometric parameters on drop time and velocity is planned to be carried out.

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