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RESEARCH OF THE ROD DROP TIME BASED ON THE CONTROL ROD SYSTEM OF TMSR - SF1

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ABSTRACT

The reactor scram function realized by the rapidly dropping of control rods ensures safety when the reactor accidents (loss of electricity and earthquake, etc.) happen. In the thorium base molten salt reactor (TMSR - SF1), the rod drop time is obviously affected by the resistance which produced in the molten salt as its high density and viscosity. In this paper, the drop time of the control rod is obtained by the theoretical and experimental methods for comparison. Firstly, the drop time is analyzed both in air and water condition with calculation and experiment. And the method used for the resistance calculation of the rod during dropping is verified. Secondly, the similarity criterion is adopted to calculate the drop time in molten salt condition. The study shows that: 1) In air and water condition, the calculation is coincidence with the experimental results within the maximum error less than 2 %. 2) The drop time of the rod in molten salt is 2.8 s with a dropping height 2.4m in reactor, which satisfy the safety requirement of the control system. 3) It is necessary to use another buffer beside the disc spring to protect the driving mechanism of the rod during the rod dropping.

Key word: thorium base molten salt reactor; driving mechanism of control rod; scram; control rod drop time.

INTRODUCTION

Safety of the reactor during normal and abnormal condition is achieved with controlling the reactivity by using engineering safeguard shutdown system, which consists of neutron absorber rods and their driving mechanism operating in fail-safe mode to ensure high reliability. There were many research progresses for the subject of control rod dropping in the past(1~12). Nevertheless, it is still indispensable to carry out the research for control rod dropping of TMSR - SF1, in which the control rod dropping is designed to work in a special liquid environment, the molten salt. As the high density and viscosity of the molten salt, the hydraulic resistance will affect the control rod drop time. For the demand of the reactivity control and shutdown of the core, a series of studies are projected to make sure the control system working in order in the molten salt. And in all of these projects, solving out the fast drop time of control rod in the molten salt is the foundation.

As shown in fig.1, the driving system of the control rod in TMSR – SF1 is consist of stepping motor, reducer, chain, limiting stopper, disc spring and so on. Fast dropping of the rod happens after blackout of the stepping motor in an accident or other emergency situations. In the case of safe shutdown, the rod drops into the guide tube by its own weight, and receives resistances from the driving mechanism and the molten salt in the tube, simultaneously. In this paper, the transmission theory and classic hydromechanics theory are adopted to solve the resistances from the driving mechanism and the molten salt. Dropping experiment in air was carried out to prove the transmission calculation of the driving mechanism, and another dropping experiment was processed in water for the comparison with the calculation result in the same condition. With the demonstration of the calculation method, the similarity criterion is adopted to calculate the drop time in the molten salt condition.

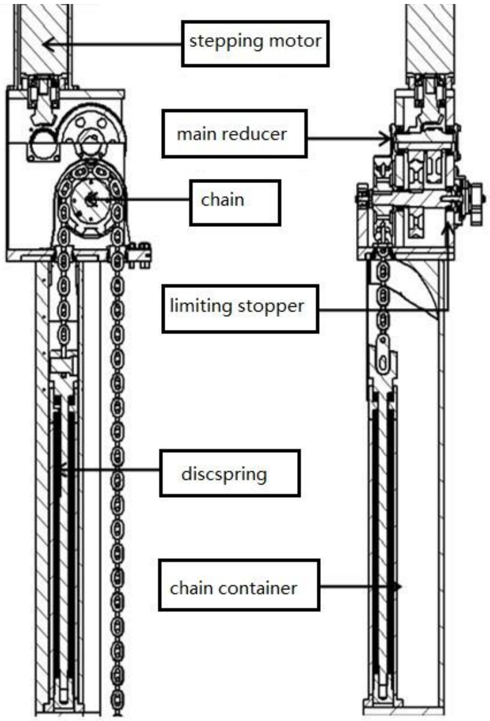

Fig.1 Geometry structure of the CRDM

THEORETICAL DESCRIPTION

In the case of control rod fast drop in liquid, the kinematical equation of the rod dropping is presented as Eq.(1).

$$m\ddot{z} = mg - F_{CRDM} - F_{FLUID} \quad (1)$$

where m is mass of the rod. z is displacement of the rod in z direction. g is the acceleration of gravity. F_{CRDM} is resistance of the driving mechanism and F_{FLUID} is the resistance from molten salt.

A force equilibrium equation is established for the control rod, chain, reduction gears and the electric motor to solve the resistance of the driving mechanism. The free-body diagram of the control rod driving mechanics is shown in Fig.2. Without the resistance of the fluid, the kinematical equation is presented as follow

$$m\ddot{z} = mg - F_{CRDM} \quad (2)$$

The kinematic equations of the No.1 ~ No.4 axes of rotation systems are presented as follow

$$F_7 r_7 \eta - F_6 r_6 = (J_6 + J_7)\alpha_7 = (J_6 + J_7)\left(\frac{1}{r_7}\right)\frac{dv}{dt} \quad (3)$$

$$F_5 r_5 - F_4 r_4 = (J_5 + J_4)\alpha_5 = (J_5 + J_4)\left(\frac{r_6}{r_5 r_7}\right)\frac{dv}{dt} \quad (4)$$

$$F_3 r_3 - F_2 r_2 = (J_3 + J_2)\alpha_3 = (J_3 + J_2)\left(\frac{r_4 r_6}{r_3 r_5 r_7}\right)\frac{dv}{dt} \quad (5)$$

$$F_1 r_1 - M_f - M_e = J_1\alpha_1 = (J_0 + J_1)\left(\frac{r_2 r_4 r_6}{r_1 r_3 r_5 r_7}\right)\frac{dv}{dt} \quad (6)$$

where $F_1 = F_2$, $F_3 = F_4$, $F_5 = F_6$, $F_{CRDM} = F_7$. F_1 ~ F_7 are the forces on the revolute pairs. J_0 is the rotational inertia of the motor. J_1 ~ J_7 are the rotational inertias of the revolute pairs. $\alpha_1 \alpha_3 \alpha_5$ and α_7 are the angular acceleration of No. 1 ~ No. 4. η is the transmission efficiency of whole driving mechanism, which is simplified from the transmission efficiencies of the four gear pairs and a sprocket drive. M_e is the oriented torque of the stepping motor. And M_f is the damping torque(10), which is ignored in the calculation within a small value.

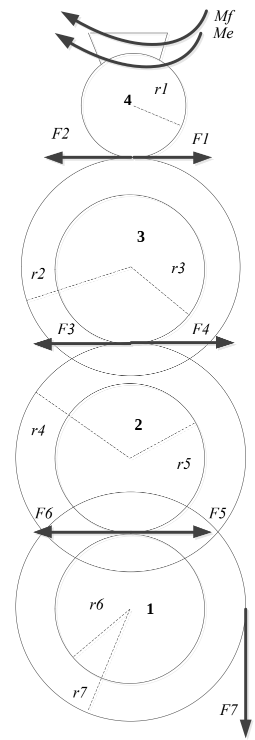

Fig.2 The free-body diagram of the CRDM

With solving the Eq.(2) ~ (6), the control rod drop time in air is calculated to compare with the expriment result which is processed in the same condition, and the total transmission efficiency of whole driving mechanism, η will be fixed with a constant for the system in the next calculation.

In calculation of the resistance of the fluid, the viscous friction and the pressure drag are supposed as the major contribution of the resistance(11). And the kinematical equation is presented as follow

$$F_{FLUID} = \int F_L dz + \Delta P A_{cr} \quad (7)$$

where ΔP is the differential pressure and A_{cr} is the cross sectional area of the control rod. F_L is the viscous friction per unit length in cylinder, and its formula is presented as follow

$$F_L = \frac{1}{2}\rho U^2 \pi d \frac{\lambda}{4} \quad (8)$$

where ρ is the density of the fluid. U is the equivalent relative velocity between the rod and the fluid. λ is the coefficient of viscous friction in the fluid, which is calculated from the Eq.(12). And d is the wetted perimeter, the same as external diameter of the control rod.

In calculation of the pressure drag, solving the differential pressure is the most important. An equivalent motion model of a cylinder moving in a fluid tube is adopted (12), and the Navier-Stokes equation of fluid is established as follow

$$\frac{\partial(\rho U)}{\partial t}+U\frac{\partial(\rho U)}{\partial z}=\rho g-\frac{\partial P}{\partial z}-F_{vis} \qquad (9)$$

where P is the pressure and F_{vis} is the differential pressure per unit length from the viscous force.

A transformation of Eq.(9) by integration is presented as follow

$$\Delta P=\Delta P_{vis}+\rho g\left(Z_b-Z_a\right)+\int_{Z_a}^{Z_b}\frac{\partial(\rho U)}{\partial t}\mathrm{dz} +\frac{1}{2}\rho\left(U_{Z_b}{}^2-U_{Z_a}{}^2\right) \qquad (10)$$

$$\Delta P_{vis}=\frac{1}{2}\rho\lambda U^2\frac{\left(Z_b-Z_a\right)}{d_e} \qquad (11)$$

$$\frac{1}{\sqrt{\lambda}}=-2\lg\left(\frac{\Delta}{3.7d_e}+\frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \qquad (12)$$

$$R_e=\frac{\rho d_e U}{\mu} \qquad (13)$$

where ΔP_{vis} is the differential pressure caused by the viscous force. $Z_a \sim Z_b$ is the path of integration. U_{Z_a} and U_{Z_b} are the equivalent relative velocities between the rod and the fluid at position Z_a and Z_b, respectively. d_e is the hydraulic diameter. Δ is the wall roughness of the tube. R_e is the Reynolds number and μ is the coefficient of kinetic viscosity.

EXPERIMENT

The experimental equipment is shown in fig. 3. The left one shows the control rod driving mechanism. And in the right one, there are control rod, tube and outer container. The fast dropping experiments of the control rod were processed with the same equipment in air and in water, respectively.

In the experiment, there are mainly four steps. Firstly, the rod is raised at certain height and held there. Secondly, the power supply of the motor of the driving system is cut off, and the rod drops with its gravity. And during the dropping it is also received the resistances from driving mechanism and fluid in the tube. Thirdly, the displacement of control rod and the acceleration speed is collected and recorded by the sensor on the rod during the dropping. Fourthly, the disc buffer works at the end of the dropping to protect the driving mechanism from the dropping shock of the rod.

(Left) Driving mechanism **(Right) Rod and container**

Fig.3 Experimental equipment

To calculate the resistance of the driving mechanism, the dropping experiment is firstly processed in air for comparison, and the resistance from the air is ignored in the calculation. After the experiment in air, the container is filled with water, and then the control rod drops in water. The control rod is hold at 1.42 m height in the both experiments. The rod mass is 120 kg, and the mass of the chain is ignored at the calculation. The other concerned parameters of the experiment are shown in tab.1.

Table.1 The calculating parameters

parameter	value	parameter	value
m(kg)	120	g(m/s^2)	9.81
ρ_w(kg/m^3)	1000	ρ_m(kg/m^3)	1940
μ_w(cPa.s)	0.8937	μ_m(cPa.s)	5.6
d(m)	0.11	M_e (N.m)	2.32
D_h(m)	0.126	J_0 (kg.m^2)	0.0035
r_7(m)	0.0771	J_7(kg.m^2)	0.0250
r_6 (m)	0.0935	J_6 (kg.m^2)	0.0294
r_5 (m)	0.0460	J_5 (kg.m^2)	0.0022
r_4 (m)	0.0975	J_4 (kg.m^2)	0.03
r_3(m)	0.0329	J_3 (kg.m^2)	0.001
r_2 (m)	0.068	J_2 (kg.m^2)	0.0040
r_1 (m)	0.034	J_1 (kg.m^2)	0.0004

THEORETICAL RESULTS DISCUSSION

An inner computing code is developed, which uses the difference equation model to solve the dropping kinetic equations (1) ~ (13) based on MATLAB computing workbench. As we can see in Fig.2, the whole driving system includes four gear pairs and a sprocket drive, it is impossible to solve out the efficiency each of them. Therefore, it is simplified into a total efficiency of the driving system, as shown in Eq.(3) ~ (6). In fact, the efficiency of the transmission is related to the dropping velocity of the control rod, as the efficiencies of the gear pairs and sprocket drive are related to their rotational frequencies. Since the total transmission efficiency of the whole driving system is assumed to be a fixed value η in this paper, it can be reckoned from the experiment result of dropping in air. With the experiment result in air and the initial calculating parameters shown in tab.1, the total efficiency of the whole driving system is fixed and the mechanic friction and hydraulic resistances are all solved out by the inner code.

Before the dropping experiment in water, the friction of driving mechanic system must be solved out from an experiment of dropping in air. After comparing with the dropping experimental result in air, the total efficiency of the driving system (η) is identified as 0.75 in calculation. It means that the total friction from the whole driving mechanic system is assumed to be a certain value in the calculation. The time displacement curve of experiment result shows that it is a proximate parabola, which means the dropping motion is approximated as a uniformly accelerated motion and makes the assumption of η with a fixed value credible. With this assumption, the error is within 1.5 % between the calculated drop time and the experimental one as shown in Fig.4.

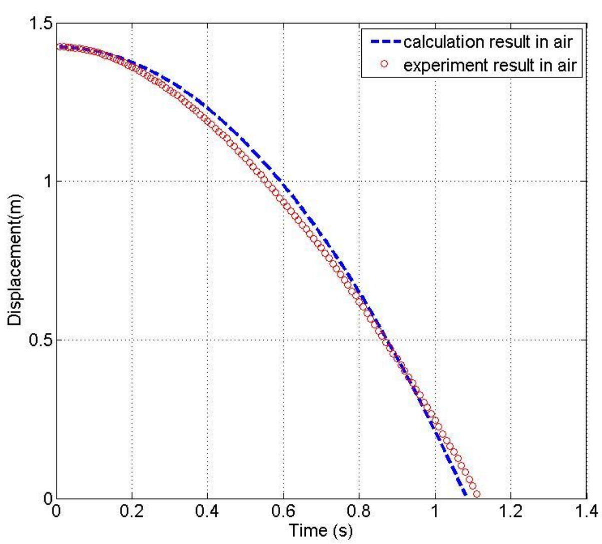

Fig.4 Comparison between calculation and experiment results in air

After the dropping experiment in air, the same equipment is used in the experiment under water condition. And in the calculation, the same transmission efficiency of the driving mechanism is used. The Comparison between calculation and experimental results in water is shown in Fig. 5. The error of drop time between the calculation and experiment is about 1.6 %. The standard deviation of displacement of the two curves is 0.025 m, which means the theoretic result from the calculation is proved well by comparison with the experimental result.

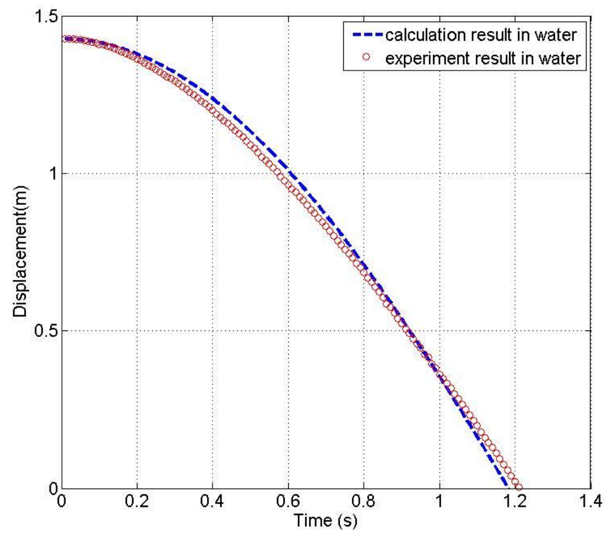

Fig.5 Comparison between calculation and experiment results in water

With the confidence of the theoretical calculation, the drop time in molten salt is calculated, which is shown as Fig. 6. It shows three curves which present the time displacement in three different conditions, in air, in water and in molten salt, respectively. The drop time in air is the least, since the resistance only contains the friction from the driving mechanism. The drop time in molten salt, 1.36 s is longer than 1.19 s in water, which is mainly due to the different density and viscosity between water and molten salt making the hydraulic resistance different according to Eq. (7) ~ (13).

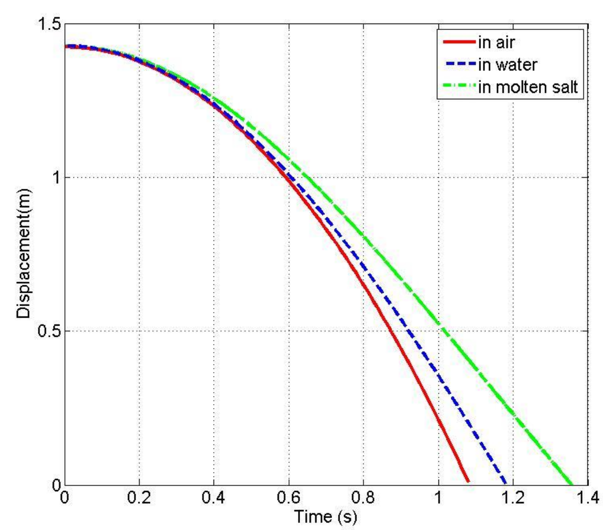

Fig.6 The time displacement curve of the dropping in air, in water and in molten salt

At the beginning of the dropping, the gravity is larger than the resistance from driving mechanism and hydraulic, and the control rod drops at an accelerating state. As the rod drops into the liquid, the hydraulic resistance grows from viscous drag and pressure drag. And finally, it almost comes into an equilibrium condition between gravity and other resistances, which makes the dropping velocity almost constant at this stage. In fact, the drop height of the control rod is designed with a height 2.4 m, and the drop time is about 2.8 s in calculation, which is satisfied with the safe command of the control rod in the molten salt reactor.

Besides, it is found that the velocity is about 1.7 m/s at uniform motion phase of the dropping in water experiment. And the driving mechanism suffers an impact from the dropping shock of the rod while it enters into the buffer phase. The destruction of the sprocket shaft is obvious, which cannot be ignored in the experiment, as the system only contains the disc spring buffer for alleviating the dropping shock.

CONCLUSION

An inner computing code is developed to solve out the drop time of the control rod in molten salt reactor. With the experimental and theoretic analysis, the motion of control rod dropping is simulated in this study. The total transmission efficiency of the driving mechanism (η) is identified as 0.75 in the system. The theoretic result from the calculation is proved well by comparison with the experimental result. The drop time is about 2.8 s in molten salt with a drop height of 2.4 m, which is satisfied with the safe command of the control rod in the molten salt reactor. Besides, as the control rod drops into the buffer phase, the dropping velocity will give a contribution to the impact of the structure of the control rod system from the dropping shock. And the shock may cause a destruction of the driving mechanism. A further investigation will be focused on the hydraulic buffer design to alleviate the impact in the buffer phase, and the total transmission efficiency is expecting to be solved as a precise function relationship with the dropping velocity of the control rod to make the calculation correspond to reality.

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