MODELING OF DROP TESTS OF REACTOR SHUTDOWN SYSTEMS USING RELAP5

S. PARK, H. LEE, Y. YOO, Y. CHO
Korea Atomic Energy Research Institute
989-111, Daedeok-daero, Yuseong-gu, Daejeon, 34057, Rep. of Korea

A new reactor shutdown system is being developed for multipurpose research reactors with an upward flow in the reactor core. A RELAP5 modeling on drop tests of the reactor shutdown system has been developed to assess the effects of various design variables on the drop time of the control plate assembly. The force balance equation was established to calculate the drop speed and distance of the control plate assembly, and it was calculated using the control variables of RELAP5. The drop tests of the control plate assembly have been simulated in various design variables such as the weight of the control plate assembly and the flow area of return pipe. In addition, the drop tests have been simulated in normal forced flow conditions and pump trip events. This study shows that the RELAP5 modeling reasonably predicts the drop speed and distance of the control plate assembly and the effects of the design variables on the drop time.

1. Introduction

A new reactor shutdown system is being developed for research reactors with plate type fuels and an upward flow in the reactor core. The control plate absorbing neutrons regulates the reactor power in normal power operation and rapidly shuts down the reactor in emergency conditions. The speed of negative reactivity insertion depends on the weight of the control plate assembly (CPA) and on the hydraulic load due to an upward flow in the reactor core and due to the return flow from the guide tube assembly to the lower plenum. A test facility to verify the performance of the reactor shutdown system has been installed and a RELAP5 modeling on drop tests of the CPA has been developed to assess the effects of various design variables on the drop speed and time. The drop tests of the CPA were simulated in various design variables such as the weight of the CPA and the flow area of the return pipe from the guide tube assembly to the lower plenum.

2. Description of Test Facility and Reactor Shutdown System

2.1. Test Facility

The test facility for the reactor shutdown system, as shown in Figure 1, consists of a test section simulating the reactor core, the reactor shutdown system, and fluid systems to provide test conditions. The test section has a lower plenum, an upper plenum, four fuel assemblies, and a control plate including a guide channel for the control plate. The coupling rod, extension shaft, and armature of the reactor shutdown system are arranged in and below the lower plenum. The motor drive mechanism to move the CPA up and down is located below the lower plenum. The return pipe is a flow path from the guide tube assembly to the lower plenum. The water pushed out from the guide tube assembly is returned to the lower plenum as the CPA moves down.

The fluid systems has two pumps, a filter, an ion-exchanger, a heater, a heat exchanger, a tank and a cooling system. The elevation of water surface in the tank simulates the water depth of a reactor pool. The rated flow and head of the circulation pump are 380 m^3/hr and 25 m, respectively. The direction of flow is upward in the test section. The bypass pump provides flow to purify the water and to control the water temperature.

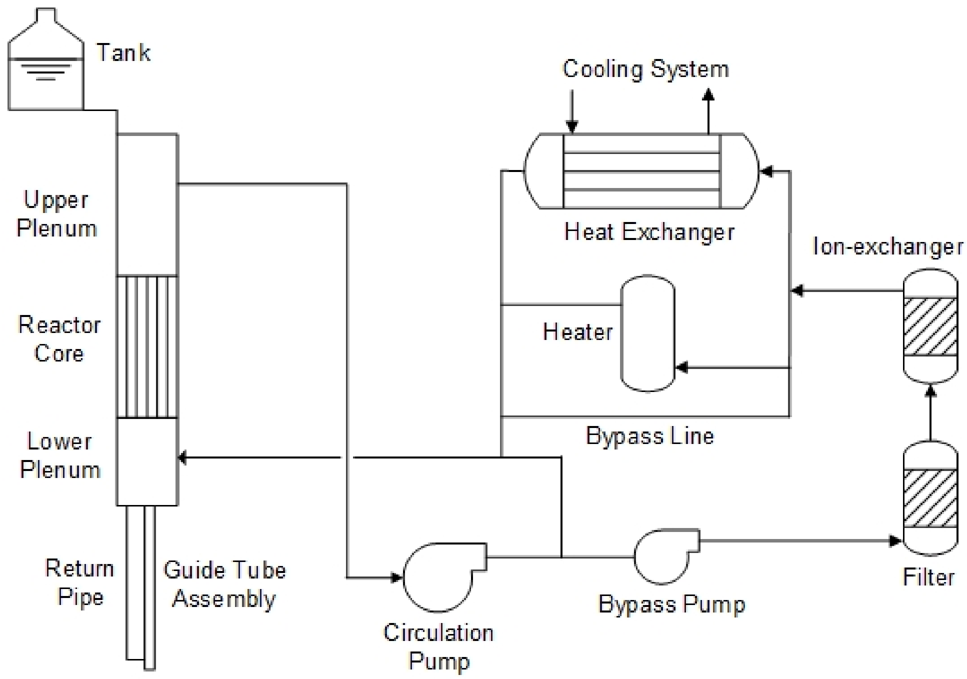

Figure 1: Schematic diagram of test facility

2.2. Reactor Shutdown System

The reactor shutdown system consists of a CPA, a guide tube assembly, an electromagnet assembly, and a control drive assembly. The CPA consists of a control plate, a coupling rod, an extension shaft, and an armature, as shown in Figure 2, and moves up and down in the guide tube assembly. The electromagnet assembly outside the armature guide tube holds the armature, which moves up and down with the electromagnet assembly by the step motor drive assembly during normal power operation. On the other hand, the CPA drops when the electromagnetic force holding the armature is released by shutting off the electricity. The length of the control plate is around 770 mm. The length and weight of the CPA are around 6.5 m and 37 kg, respectively.

Figure 2: Control plate assembly

3. Modeling of Test Facility and Drop of Control Plate Assembly

3.1. Test Facility

Figure 3 shows a node diagram of RELAP5 modeling on the fluid system of the test facility. The nodes colored pink simulate the test section consisting of four fuel assemblies, a fuel assembly gap, a lower plenum, and an upper plenum. The nodes colored dark blue indicate a flow path between the CPA and the guide tube assembly. The nodes colored light blue show the primary fluid system consisting of a circulation pump, a tank, and pipes. The fluid system, which controls the water chemistry and temperature, is not included in this modeling because it is not supposed to affect drop tests of the CPA.

Table 1 describes what each node simulates. The nodes of 414 to 444 indicate fuel assemblies. The node of 454 considers the flow path through the gap between the fuel assemblies. The node of 810 indicates the water tank, and the water level simulates the water depth of reactor pool. The node of 310 is the circulation pump. The nodes of 114 and 140 simulate the water volume below the bottom of the CPA, which is pushed out as the CPA drops. The nodes of 713 and 715 are time dependent junctions. The calculated speed of the CPA is used as an input velocity of the time dependent junctions. A flow path indicated as the node of 710 is added to maintain mass balance in the fluid system. The node of 141, a solenoid valve of RELAP5 valve components, simulates the hydraulic damping of the reactor shutdown system by reducing the area of the flow path that the water gets pushed out of the guide tube assembly. The flow area of 141 decreases as the CPA reaches the damping cylinder. The nodes of 126 and 128 represent the flow path through which the water pushed out from the guide tube assembly is returned to the lower plenum as the CPA moves down abruptly.

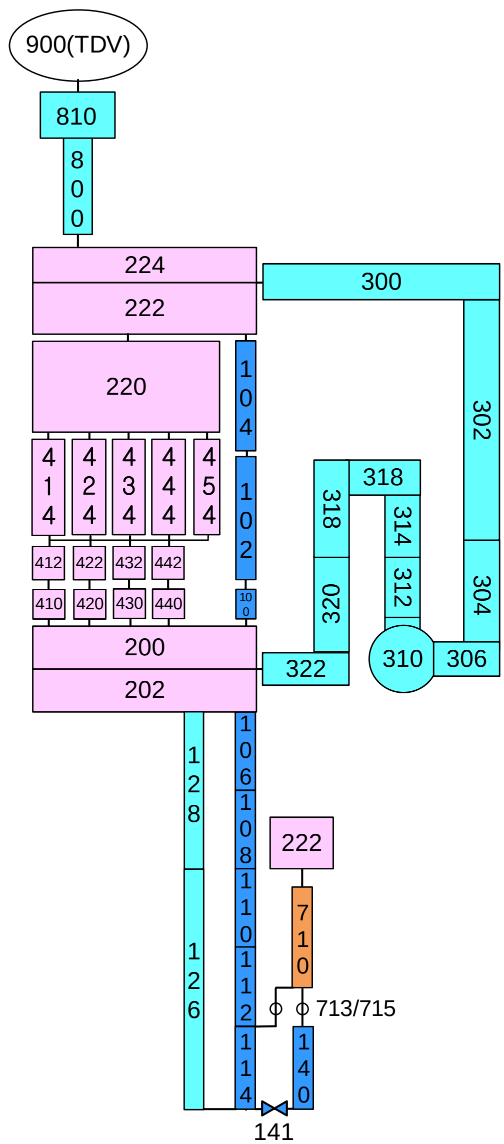

Figure 3: Node Diagram of RELAP5

Table 1: Description of nodes of RELAP5 modeling

Nodes	Hydraulic components of RELAP5	Descriptions
200, 202	Branch	Lower plenum
410~444	Single volume, Pipe	Grid plate, Fuel assembly
454	Pipe	Gap flow path
220~224	Branch	Upper plenum
300~322	Pipe, Pump	Primary fluid system
800, 810	Pipe, Branch	Water tank, pipe
100~114, 140	Single volume, Pipe	Flow path between the control plate assembly and guide tube assembly
713, 715	Time dependent junction	Drop speed of control plate assembly
141	Solenoid valve	Variable flow area to simulate the hydraulic damping
126, 128	Pipe	Flow path to simulate the return flow

3.2. Drop of Control Plate Assembly

During the drop of CPA, the force balance equation can be expressed as follows:

$$M_s \frac{dv(t)}{dt} = M_s g + \sum P_i(t)A_i - \sum P_j(t)A_j \quad (1)$$

where M_s, v, and g are the mass and speed of CPA, and gravity acceleration, respectively. $\sum P_i(t)A_i$ is hydraulic force in the same direction of gravity, and $\sum P_j(t)A_j$ in the opposite direction of gravity. The pressures at the nodes modeling the flow path between the CPA and the guide tube assembly are calculated from RELAP5.

The speed of CPA is obtained by integrating Equation (1) as follows:

$$v(t) = \frac{1}{M_s}\int_0^t M_s g + \sum P_i(t)A_i - \sum P_j(t)A_j \, dt \quad (2)$$

Equation 2 is calculated based on the control variables of RELAP5. The drop distance of CPA is expressed by integrating Equation (2) as follows:

$$l(t) = \int_0^t v(t)dt \quad (3)$$

Figure 4 shows the simplified CPA, the guide tube assembly, and the node diagram modeling the flow path in the guide tube assembly, in order to predict the drop speed of CPA. The CPA is all out before it starts to drop. As the CPA drops, it can affect the flow in the flow path. In turn, the flow can affect the moving of CPA. This study does not consider the interaction between the flow and the moving of CPA because a lot of modification of RELAP5 are needed. However, the hydraulic force reacted from the water pushed out of the guide tube assembly by the moving down of CPA is taken into consideration using the time dependent junctions of 713 and 715 described in Table 1. The speed calculated from Equation (2) is used as the velocity inputs of 713 and 715 time dependent junctions.

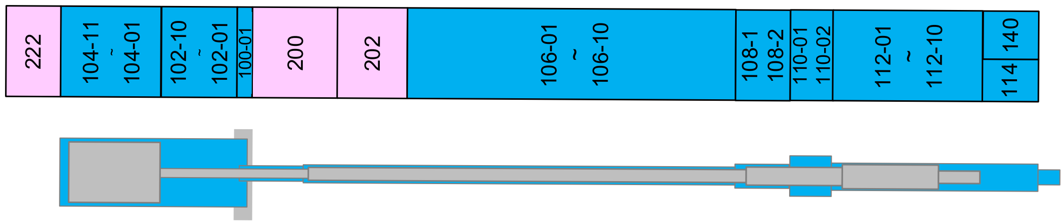

Figure 4: Node diagram modeling flow path between CPA and guide tube assembly

The hydraulic damping is simulated by reducing the flow area of 141 node in Figure 3. The flow area decreases steeply to around 28.3 mm^2 when the bottom of CPA reaches the top of the damping cylinder, and then decreases gradually until the bottom of CPA moves down to the bottom of the damping cylinder. The water in the node of 140 is returned to the lower plenum via the nodes of 114, 126 and 128.

4. Simulation of Drop Tests of Control Plate Assembly

4.1. Normal Forced Flow Conditions

Figure 5 shows the flowrates during the drop test of CPA in normal forced flow conditions. The total flow is around 113 kg/sec, and the differential pressure between the lower plenum and the fuel assembly top is around 198 kPa. The flowrates per fuel assembly is 26.5 kg/sec. The weight of the CPA is around 37 kg and the inner diameter of the return pipe from the guide tube assembly to the lower plenum is 16.52 mm. The flowrate at the test section remains nearly constant for the drop tests of CPA.

Figure 6 shows the hydraulic force and total force in Equation (1). The total force is the sum of the hydraulic force and the weight of CPA. The positive value represents a direction of gravitation, while the negative value represents the opposite direction. The hydraulic force acts to the opposite direction of gravitation due to an upward flow in the test section. The total force abruptly decreases right after the start of CPA drop, and gradually decreases. Finally, the total force steeply decreases due to the increase of hydraulic force reacted from the water in the damping cylinder when the bottom of CPA reaches the top of the damping cylinder. After then, the total force gradually increases as the hydraulic force decreases because the water in the damper is slowly released to the return pipe. The hydraulic and total forces oscillate when the CPA starts to drop and approaches to the top of damping cylinder, respectively. The oscillation is supposed to be caused by numerical errors of RELAP5 in the abrupt transient calculation.

Figure 7 and Figure 8 are the drop speed and distance of CPA, respectively. The CPA starts to move down at zero seconds. The drop speed increases up to around 0.89 m/sec and rapidly decreases as the bottom of CPA gets close to the top of the damping cylinder. After then, the speed gradually decreases and finally becomes zero when the bottom of CPA reaches the bottom of the damping cylinder. Figure 8 shows the drop distance with time. The CPA rapidly drops as it reaches the top of the damping cylinder, and slowly drops after then. The drop time of the CPA is predicted as around 0.83 seconds. It seems that the trend of the drop speed and distance of the CPA with time is reasonable. However, the quantitative prediction should be verified experimentally.

Figure 9 and Figure 10 show the drop times with the weight of CPA and the size of the return pipe, respectively. The drop time of the CPA decreases obviously as the weight of CPA and the flow area of the return pipe increase. This prediction will be compared with the experimental data to be obtained this year. Some modification of the present RELAP5 model will be followed.

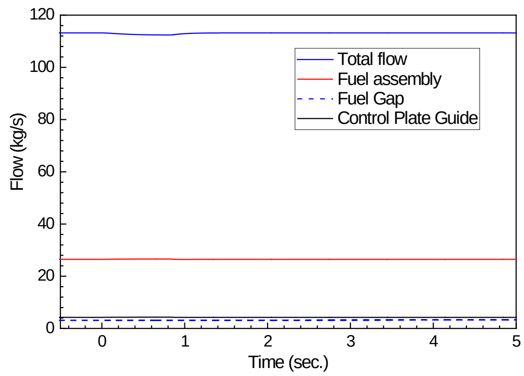

Figure 5: Flowrates at test section

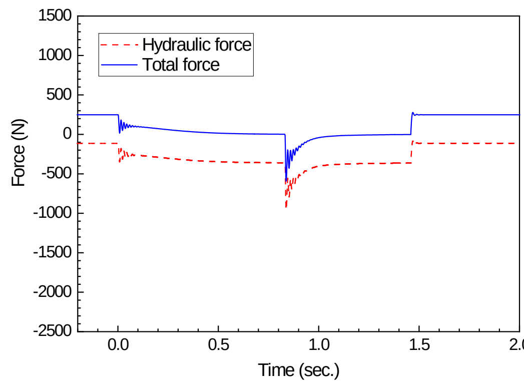

Figure 6: Hydraulic and total forces

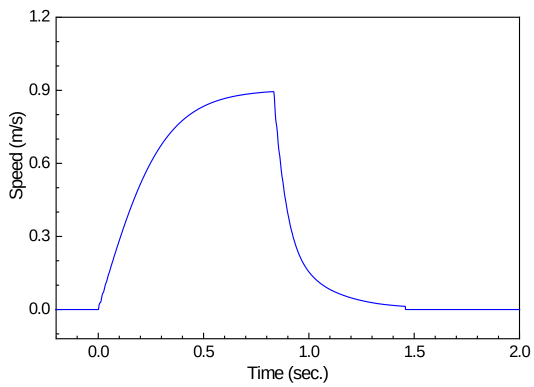

Figure 7: Drop speed of CPA

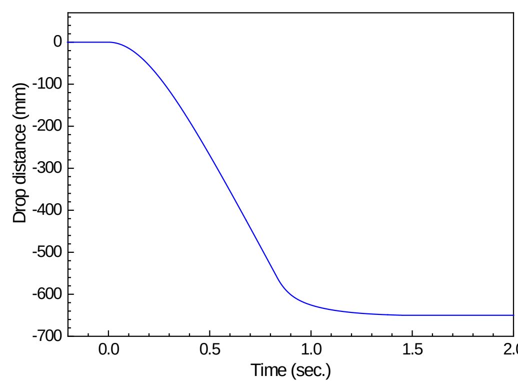

Figure 8: Drop distance of CPA

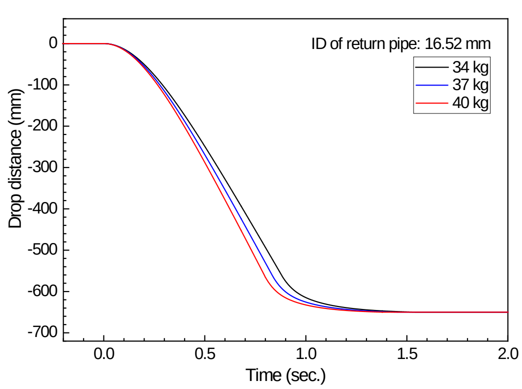

Figure 9: Drop time versus CPA weight

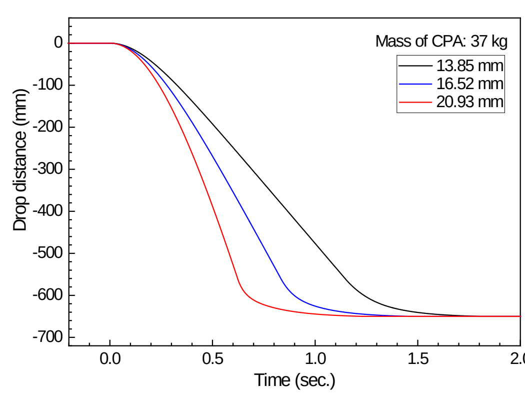

Figure 10: Drop time versus size of return pipe

4.2. Pump Trip Events

The flowrate coasts down after the pump trips as shown in Figure 11. It is assumed that the low flow trip signal occurs at 85% of normal flowrate and that the CPA starts to drop after the delay time of 0.55 seconds of the reactor protection system. Before the pump trips, the total flowrate, the differential pressure at the test section, the weight of CPA, and the inner diameter of the return pipe are the same as the simulation in Section 4.1. When the CPA starts to drop, the flowrate and the differential are around 84 kg/sec and 110 kPa.

Figure 12 shows the hydraulic force and total force in Equation (1). The hydraulic force decreases slightly and the total force increases as the flowrate and the differential pressure at the test section decrease by the pump trip. The CPA starts to drop at around 1.29 seconds. The total force rapidly decreases with the increase of hydraulic force due to the reaction of water pushed out of the guide tube assembly by the drop of CPA. The hydraulic force gradually increases and then the total force gradually decreases as the water in the guide tube assembly is released to the return pipe. The hydraulic and total forces oscillate when the CPA starts to drop and gets close to the top of the damping cylinder, respectively. This trend is similar to that in Figure 6.

Figure 13 and Figure 14 are the drop speed and distance of CPA, respectively. The CPA starts to drop at 1.29 seconds. The speed increases up to around 0.96 m/sec and then abruptly decreases. The maximum speed is slightly higher than that in the test of normal forced flow conditions due to the lower differential pressure between the lower plenum and the fuel assembly top. However, the overall trend is the same as compared with the prediction in Section 4.1. The CPA rapidly drops up to the top of the damping cylinder, and slowly moves down to the bottom of the damping cylinder. The drop time of CPA is predicted as around 0.78 seconds slightly shorter than that of Section 4.1 because of the lower hydraulic load.

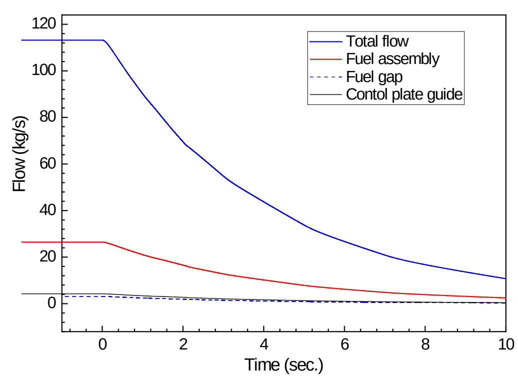

Figure 11: Flowrates at test section

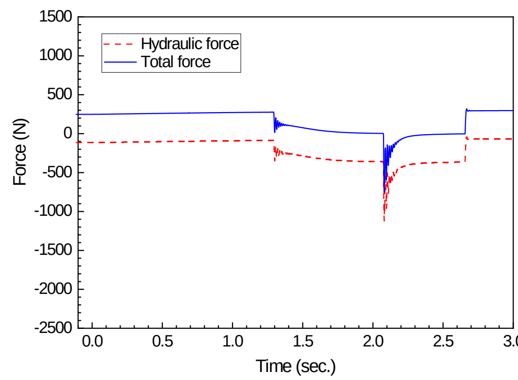

Figure 12: Hydraulic and total forces

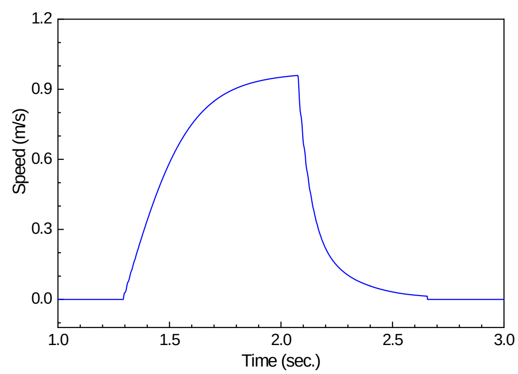

Figure 13: Drop speed of CPA

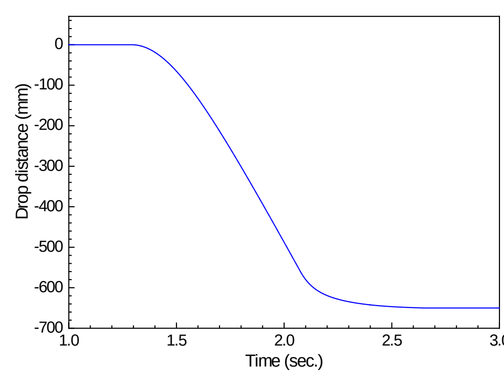

Figure 14: Drop distance of CPA

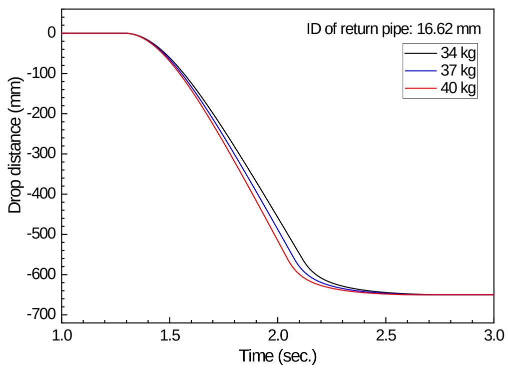

Figure 15: Drop time versus CPA weight

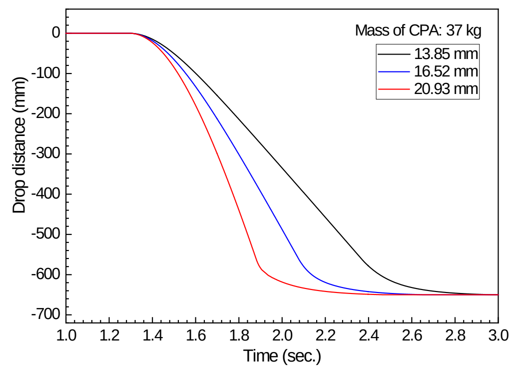

Figure 16: Drop time versus size of return pipe

Figure 15 and Figure 16 show the drop times with the weight of CPA and the size of return pipe, respectively. The drop time decreases obviously as the weight of CPA and the flow area of the return pipe increase. The drop time is predicted as around 0.59 seconds in case of the inner diameter of 20.93 mm and the weight of 37 kg.

5. Conclusions

A new reactor shutdown system is under development for multipurpose research reactors having an upward flow in the reactor core. In order to assess the effects of various design variables on the drop time of the control plate assembly, a RELAP5 modeling on drop tests of the reactor shutdown system has been developed. The drop tests of control plate assembly have been simulated in normal forced flow conditions and pump trip events. The trend of drop speed and distance of control plate assembly with time is predicted reasonably. However, the quantitative prediction should be verified experimentally. The drop time decreases obviously as the weight of control plate assembly and the size of the return pipe increase. The drop time of the CPA during the pump trip events is slightly shorter than that during normal forced flow conditions.

Acknowledgements

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