Performance Analysis of Oil Dashpot in Control and Safety Rod Drive Mechanism of Prototype Fast Breeder Reactor

L. Suresh, R. Vijayashree, V. Rajan Babu, S. Raghupathy, P. Chellapandi
Indira Gandhi Centre for Atomic Research
Kalpakkam, Tamilnadu, India
suresh_l@igcar.gov.in

***Abstract*— In Prototype Fast Breeder Reactor, there are two independent, fast acting, diverse shutdown systems each comprising of sensors, logic, circuit, Drive Mechanisms and neutron absorber rods having B_4C pellets. The absorber rod of the first system is known as Control &Safety Rod (CSR) and its drive mechanism is known as Control & Safety Rod Drive Mechanism (CSRDM). The functions of CSRDM are to facilitate start-up, reactor control, controlled shutdown and emergency shutdown by scram (Safety Control Rod Accelerated Movement) action. During normal operation of the reactor the CSRs are all partially inserted in the core. During emergency shutdown the scram release electromagnet gets de-energised and the Mobile Assembly (MA) of CSRDM along with CSR drops under gravity into the active core. The maximum drop height is 1085 mm. At the end of free fall there is an oil dashpot which acts as a damper to absorb the kinetic energy of the falling mass. Proper functioning and performance of the oil dashpot is critical for the healthiness of the shutdown system. In the present study, Characterisation of flow parameters in the oil dashpot using a commercial Computational Fluid Dynamics (CFD) code to obtain a relation between velocity and pressure drop in the dashpot and implementation of the flow characteristics in the performance analysis code to obtain the performance characteristics of the dashpot has been done. The performance analysis is performed by mathematical modeling of the dashpot system as spring-mass-damper two degree of freedom system. This paper gives a brief description of Control and Safety Rod Drive Mechanism and oil dashpot, the methodology of modeling, flow characterisation in dashpot and presents the results of performance analysis of oil dashpot.**

Keywords—shutdown system; CSRDM; Oil dashpot; PFBR

I. INTRODUCTION

Prototype Fast Breeder Reactor (PFBR) a (U-Pu)O_2 fuelled, sodium cooled fast reactor with a power capacity of 500 MWe. The reactor is under construction at Kalpakkam, India. The reactor is equipped with two independent diverse shutdown systems. Each shutdown system consists of sensors, logic circuit, Drive Mechanisms and neutron absorber rods having B_4C pellets. The absorber rod of the first system is called as Control & Safety Rod (CSR). The respective drive mechanism of CSR is Control & Safety Rod Drive Mechanism (CSRDM). The schematic of the same is shown in Fig. 1. There are nine CSR & CSRDM in the reactor. Safety of the reactor depends on the reliable operation of CSR and their mechanism. This demands a very detailed design, analysis, technology development in manufacturing and testing of the entire system under simulated reactor-operating conditions to check and ensure the intended functions in the reactor. An extensive qualification programme was envisaged from the onset of the design of CSR and CSRDM. Critical components of the system were identified, developed and qualified by testing the full-scale models. Later, integrated assembly of full-scale prototype CSRDM and CSR was manufactured indigenously and qualified by elaborate performance testing and endurance testing under simulated reactor-operating conditions.

A. *The functions of CSRDM are to facilitate*

- Start-up & controlled shutdown of the reactor and control of reactor power by raising and lowering of CSR and
- Shutdown of the reactor at off-normal conditions by rapid insertion of CSR into the core (i.e., by scram action) under gravitational force.

For emergency shutdown, absorber rods of CSRDM are dropped under gravity.. CSR fall height varies from 0-1085 mm as CSRs are partially inserted in the core during normal operation. At the end of free fall travel CSRs are decelerated by dashpots. In CSRDM oil dashpot located above the control plug top is used for decelerating.

When CSRDM Electromagnet is switched off, the mobile assembly along with CSR falls under gravity for 835 mm and it is decelerated for 250 mm by oil dashpot. The dashpot dissipates a total energy of 3.8 kJ of the falling mobile assembly along with CSR. Since dashpot experiences a huge impact load it is a critical component of CSRDM which controls the performance and life of the mechanism.

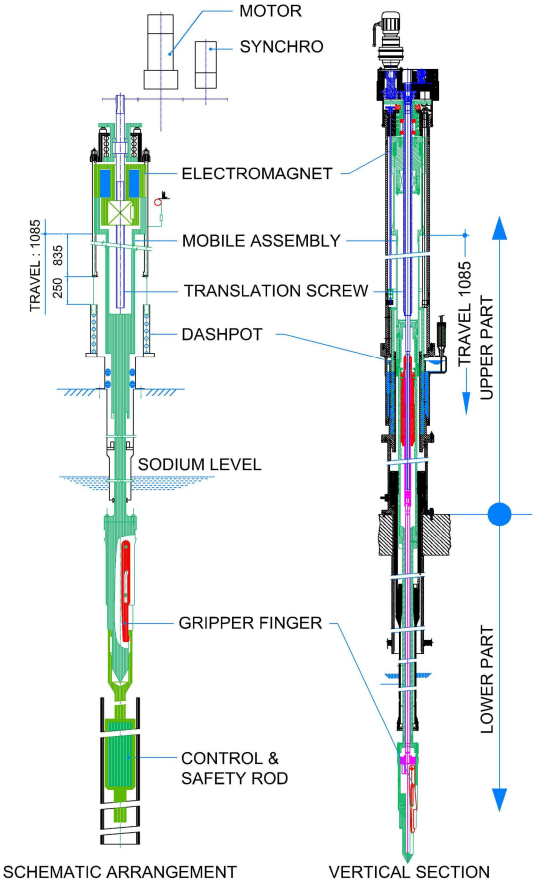


Fig. 1 Schematic of Control and Safety Rod Drive Mechanism

The oil dashpot in CSRDM is a variable flow area type dashpot with annular piston arrangement. On the course of downward movement the piston closes the orifices in the outer cylinder walls and thus the flow area across cylinders are reduced which in turn increases the pressure in inner cylinder. This increase in pressure gives the deceleration to the piston and the mobile assembly. The deceleration continues and brings the mobile assembly velocity to near zero before reaching the bottom limit. The aim of this study is to characterise the performance of the oil dashpot theoretically. In this study the pressure drop in the orifice was studied with the help of CFD tool Star-CD. This paper briefs the design aspect of Oil dashpot of CSRDM, details out the methodology to analyse the system and discusses the parameters affecting the performance.

II. SYSTEM DESCRIPTION

Typical components of CSRDM and its functions are explained in the following section [1]

A. *Control and Safety Rod Drive Mechanism*

Schematic of CSRDM along with CSR and vertical section of CSRDM is show in Fig.1. The CSRDM consists of two main parts viz upper part and lower part. The overall Length of CSRDM is 12 m. Lower part of CSRDM is partially immersed in hot pool sodium and the upper part is in argon/air atmosphere. CSR consists of B$_4$C(Boron carbide) as absorber material which is used to control the reactor power by raising/lowering the CSR. Raising/lowering of CSR is achieved with the help of CSRDM. The CSRDM holds CSR mechanically by gripper fingers. The raising lowering is achieved by screw nut mechanism. An electromagnet is housed in the nut of translation screw. The electromagnet magnetically holds the mobile assembly. The mobile assembly consists of guide tube, translation tube and gripper sub-assembly and CSR. Motor drive assembly rotates the translation screw to raise or lower the electromagnet and hence the mobile assembly. On receiving the scram signal, the electromagnet is de-energised and the mobile assembly of CSRDM along with CSR is released to fall under gravity. At the end of free fall travel (835 mm), the mobile assembly is decelerated by an oil dashpot for the remaining 250 mm travel. In life time of the reactor that is 40 years CSRDM will experience 752 scrams. CSRDM and dashpot shall perform consistently throughout their life time.

Dashpot Sub assembly

The oil dashpot is a hydraulic impact shock absorber. The schematic of the dashpot cylinder, piston and the rearming spring is shown in the Fig. 2. The dashpot cylinder has two annuli, the inner one for piston movement and the outer one for oil collection. The piston slides with close fit in inner annulus. Leak-tightness between cylinder and piston is achieved by means of 'O' ring seals and nickel impregnated Teflon rings. During scram, the mobile assembly falls on the piston which moves down in the annular cylinder displacing out the oil through the orifices to the outer cylinder. While the piston is moving down and losing its kinetic energy, it closes the orifices at different elevations on the wall of the cylinder one by one and the oil flow area is reduced gradually. The orifices are positioned in such a way that the oil pressure developed in the cylinder and hence the deceleration experienced by the piston and the mobile assembly are almost uniform. There

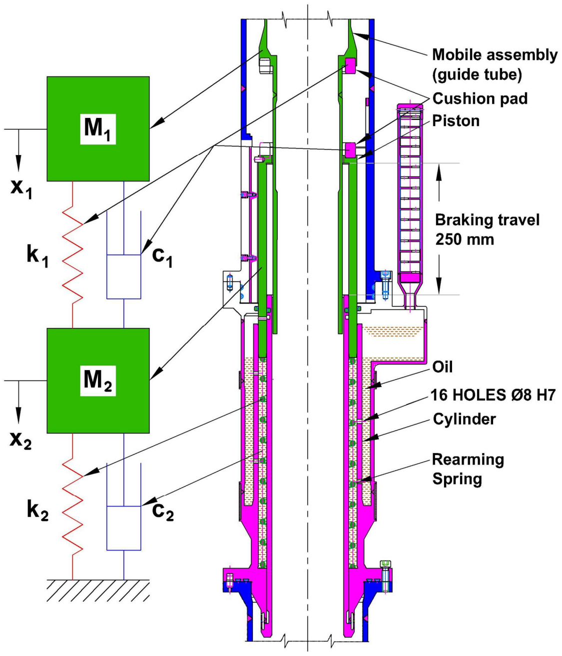


Fig. 2 Spring-mass-damper system and CSRDM dashpot

is a pre-compressed coil spring inside the cylinder to keep the piston at its top most position (so that the dashpot is ready for the next drop of the mobile assembly), when the mobile assembly is held and raised up by the electromagnet. When the piston is moving down, oil is displaced from the inner cylinder and collected in the outer cylinder. Dip-stick arrangement and an oil level sensor are available to check the oil level in the dashpot. Breather housing provides communication to the atmosphere for air and at the same time prevents spill of oil. The mobile assembly establishes contact with dashpot piston only when it reaches 250 mm position and the contact is maintained by net downward force acting on the mobile assembly. Because there is no contact between the falling mass (mobile assembly) and the piston which is at rest in 250 mm position at the time of contact both the colliding components experience an impact load. This impact load is instantaneous and will die down as the momentum is transferred to the piston.

To avoid damage of the contacting surfaces cushion pad made of 6 % graphite impregnated Teflon has been fixed on both mobile assembly and the piston. The pad is designed to bear the shock load and to transfer the momentum in either direction.

III. PROBLEM DESCRIPTION

The physical system of dashpot is equivalent to a two degree of freedom spring- mass-damper system as shown in Fig. 2.

The mathematical model of the spring-mass-damper two degree of freedom system yields the following equation. Descriptions of the variables are given in Table 1. Numerical values of the parameters with reference to actual system are given in Table 2.

$$M_1\ddot{x}_1 + c_1(\dot{x}_1 - \dot{x}_2) + k_1(x_1 - x_2) = 0 \qquad (1)$$

$$M_2\ddot{x}_2 + c_2\dot{x}_2 - c_1(\dot{x}_1 - \dot{x}_2) + k_2x_2 - k_1(x_1 - x_2) = 0 \qquad (2)$$

The performance characteristics of oil dashpot are determined by the pressure drop characteristics of the dashpot. Correlations are available in open literature for estimation of pressure drops in orifice plates fitted in pipes as show in Fig.3 [2]. The Ward Smith correlation [3] gives good prediction for perforated plates with multiple orifices as shown in Fig.3. But there was difficulty in use of the above correlations for the purpose at hand. Fiureg. 4 shows the schematic of the oil dashpot of CSRDM with oil flow path.

$$K = \left[\frac{1}{\beta\left(0.872 - 0.015\frac{t}{d} - 0.08\frac{d}{t}\right)\left(1 - \beta^{3.3}\right) + \beta^{4.3}\left(1 + 0.134\left(\frac{t}{d}\right)^{0.5}\right)^{-1}} - 1\right]^2 \qquad (3)$$

Where,

A - Cross sectional area of duct

β - Porosity = $\dfrac{\pi N d^2}{4A}$

t - Thickness of orifice plate

d - Diameter of orifice

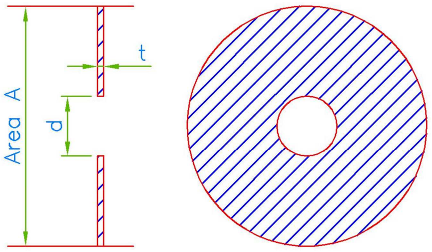
N - Number of orifice

TABLE I. VARIABLE DESCRIPTION

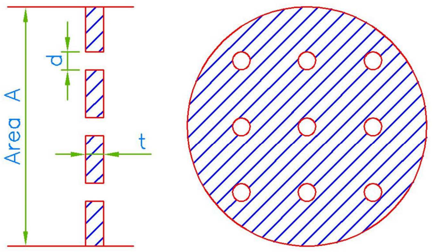
Variable	Description		
	Mathematical model	***Actual System***	***Units***
M_1	Mass of object 1	Mass of Mobile assembly	kg
k_1	Stiffness of spring element 1	Stiffness of cushion pad	N/m
C_1	Damping co-efficient of damper 2	Damping co –efficient of cushion pad	Nm/s
M_2	Mass of object 2	Mass of piston	kg
k_2	Stiffness of spring element 2	Stiffness of rearming spring	N/m
C_2	Damping co-efficient of damper 2	Damping coefficient of oil dashpot	Nm/s

TABLE II. PARAMETERS AND THEIR VARIABLES

S. No	**Parameter-Description**	**Status** ***Known*** - ✓ ***Unknown***- ✗	**Value /Expression of known parameter**
1	M_1-Mass of mobile assembly	✓	360 kg
2	k_1-Stiffness of cushion pad	✓	28988 N/mm
3	c_1-Damping co-efficient	✓	0.5[4]
4	M_2-Mass of piston	✓	27 kg
5	k_2-Stiffness of rearming spring	✓	1.84 N/mm
6	c_2-Damping coefficient of oil dashpot	✗	Dependends on flow characteristics of oil in dashpot



Orifice Plate



Perforated Plate

Fig. 3 Standard configuration of orifice plates

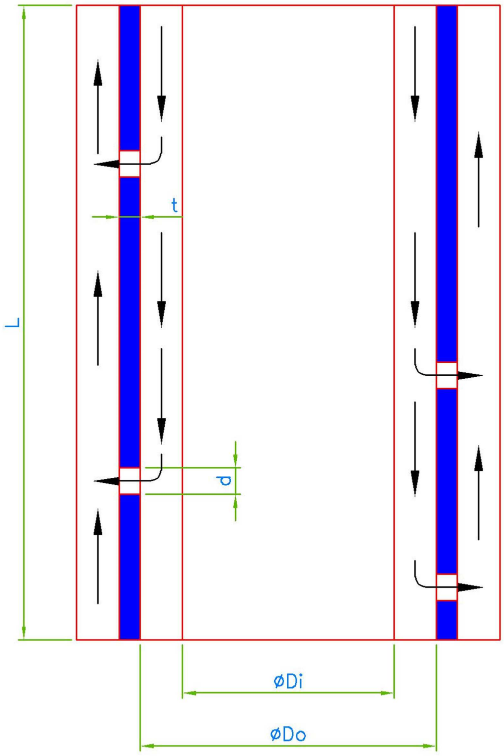


Fig. 4 Schematic of oil dashpot of CSRDM with oil flow path

For the above correlations orifice holes are parallel to the bulk fluid flow direction. In case of CSRDM dashpot the orifice holes are perpendicular to bulk fluid flow direction and so the fliud has to take turn and pass into the outer cylinder. The presence of outer cylinder wall also prevents the fully deveveloped flow. Hence it is understood that the standard correlations are not directly applicable for the case at hand. Hence CFD modelling and generating the flow vs pressure drop characteristics of the dashpot for variuos positions of piston was the option chosen for further analysis. The comparison of CFD results with Ward smith correlation is given in Fig. 5.

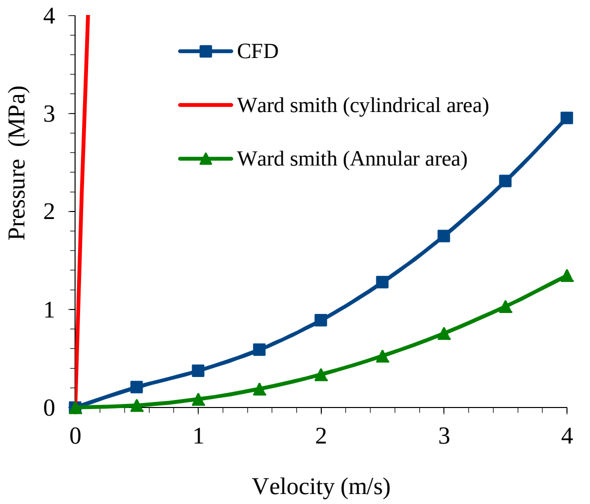


Fig. 5 Pressure Vs Velocity plot with Ward Smith correlation and CFD results

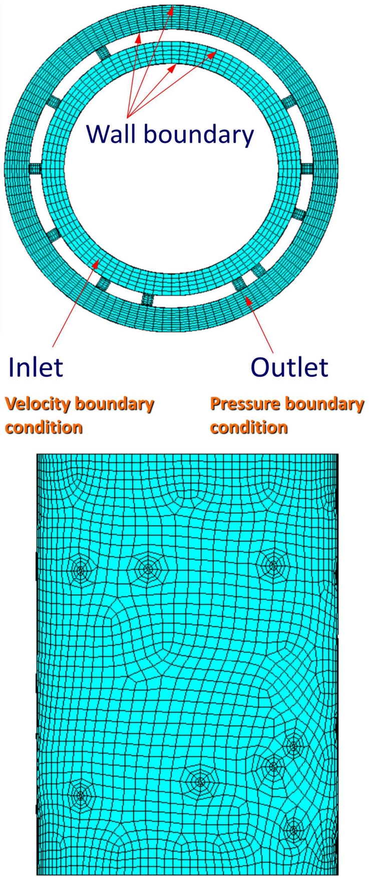


Fig. 6 Meshed model of dashpot with boundary conditions

Of the three curves in the plot one corresponds to the CFD results and other two curves were made with the pressure drop values obtained by Ward Smith correlation using equation (3) with the cross sectional area of duct (A) as area of inner cylinder ($\pi/4 *(D_o^2 - D_i^2)$) once and as curved surface area of inner cylinder ($\pi/4 *D_o^2L$) next time. From the plot it can be noted that the CFD results fall in between the other two cases. It can be noted that the pressures drop values are closer to case with annular area as cross sectional area.

IV. CFD AND RESULTS

The geometry for CFD study is created using the preprocessor code with the volume creation/edition commands. The fluid volumes of the model are modeled as a 3D geometry. The connectivity between the faces is established properly. The Fig. 6 shows the meshed model. The behavior of the model with the dimensions as specified in the manufacturing drawing of project CSRDM is analysed by CFD code. The voulme filled by the oil is only modelled. The 3D model is discritiesed by hex mesh. The pressure drop is obtained by steadty state analysis of this model.

A. Steady state CFD analysis

The objective of this analysis is to extract the velocity versus pressure characteristics of the oil dashpot. To obtain this characteristic fifteen cases are considered. The cases have been defined based on the available orifice flow area, details of the cases are listed in Table 3. For each case eight sub cases were defined based on the inlet velocity.

TABLE III. DEFINITION OF CASES WITH AVAILABLE FLOW AREA

S. No	Case description	Position of piston from 250 mm level	Total number of orifices in opened condition	Total available flow area in mm^2
1	Case all	<22.9	16	804.25
2	Case one	22.9 to 26.9	15.5	779.11
3	Case two	26.9 to 30.9	14	703.72
4	Case three	30.9 to 34	12	603.19
5	Case four	34 to 36.9	11	552.92
6	Case five	36.9 to 147	10	502.65
7	Case six	147 to 165.9	9	452.39
8	Case seven	165.9 to 180.4	8	402.12
9	Case eight	180.4 to 197.6	7	351.86
10	Case nine	197.6 to 210.3	6	301.59
11	Case ten	210.3 to 221.6	5	251.33
12	Case eleven	221.6 to 231.3	4	201.06
13	Case twelve	231.3 to 240.1	2.5	125.66
14	Case thirteen	240.1 to 243.6	1.5	75.40
15	Case fourteen	243.6 to 246.8	0.5	25.13

The analysis result i.e., pressure in the inner cylinder of the dashpot was obtained for all the cases and their sub cases. As shown in Fig. 6, on the top face of the inner cylinder velocity boundary condition is applied which is the inlet boundary condition. The outlet boundary condition is applied on the top face of outer cylinder. The outlet boundary condition is pressure boundary condition and it is set to atmospheric pressure. All other face/ surfaces are given wall boundary condition. Various inlet velocities say 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, and 4.0 m/s were applied with same outlet boundary condition. These eight inlet velocities form eight sub cases for the above 15 cases defined by available flow area.

B. *CFD results*

The pressure values obtained from the CFD analysis is plotted against their respective inlet velocities as shown in the Fig.7. The various positions of the piston resulting in different flow areas are defined as cases for the steady state CFD analysis. For different flow areas various inlet velocity inputs were given as boundary conditions. The resulting pressure developed in the inner cylinder is recorded and the pressure Vs velocity is plotted below. Plot shows the dependence of pressure on flow area and velocity. Each curve represents pressure versus velocity characteristics for a specified flow area defined in Table 3. Fifteen equations were fitted for fifteen cases/curves which gives pressure in terms of velocity.

V. NUMERICAL ANALYSIS OF THE TWO DEGREE SPRING MASS SYSTEM

The two degree of computation includes the effect of cushion. The cushion has been considered to have a complex stiffness, i.e., a variable spring and a variable damper as recommended in the literature[4,5]. Numerically Equations (1) and (2) are solved simultaneously for small time step.

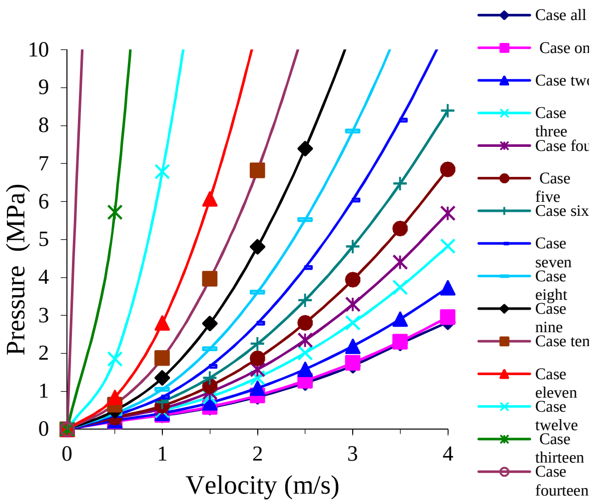


Fig. 7 Consolidated Pressure Vs Velocity plot

Steps in computer simulation are briefly described below:

- The velocity of the falling mass is estimated based on the height of free fall
- The combined velocity of the falling mass and piston is estimated based on momentum balance.
- Fluid pressure is obtained from the CFD analysis of the dashpot.(steady state analysis)
- Calculations are made for small displacement step. Time, velocity, deceleration, pressure are estimated at each step.
- The fifteen equations obtained from the CFD study is used in the FORTRAN code for two mass two degree of freedom system.

VI. RESULTS AND DISSCUSSION

The values for various parameters obtained from running the FORTRAN code are displacement, velocity, acceleration of piston and mobile assembly and pressure developed in the inner cylinder with respect to time. The plot between time and acceleration of MA is shown in Fig. 8. The peak deceleration of 30.9 g was observed from the results. There is a second peak visible which ramps up to

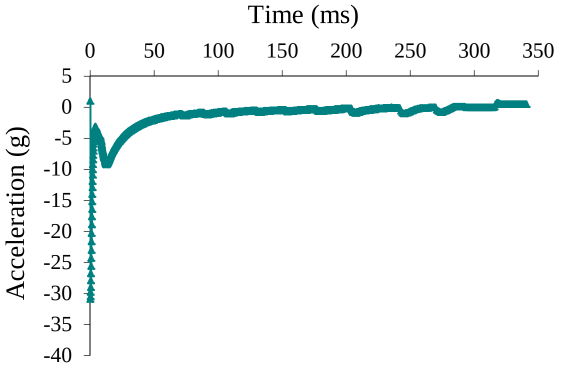


Fig. 8 Time Vs Acceleration of Mobile assembly of CSRDM

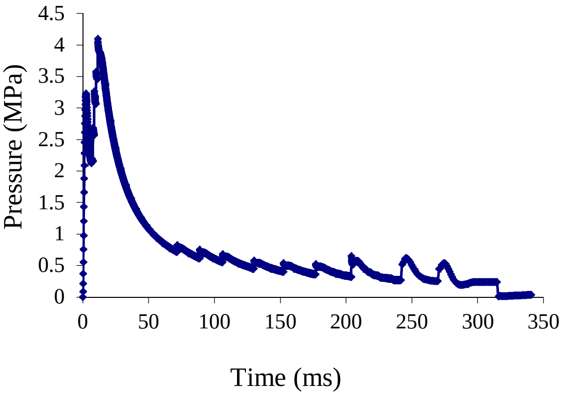


Fig. 9 Evolution of Pressure with respect to Time

9.2 g at 10 ms which corresponds to the closure of first orifice. The deceleration plot shows monotonic fall in deceleration except at the end of travel. Near the end of piston travel (braking travel), the plot shows some small peaks, corresponding to the closure of the orifices.

Fig.9 shows the evolution of pressure in the inner annular space of the dashpot. The pressure reaches a peak value of 3.2 MPa due to acceleration of the piston and the oil in the dashpot. The pressure peaks second time to 4.1 MPa at the instant when the first orifice is closed. After the first two peaks the pressure falls down with some small peaks at the end of the piston travel corresponding to the closure of the orifices. The monotonic falling trend in the pressure versus time plot shows the uniform trend in deceleration.

A. Comparison of experimental and analysis results

The experimental results available in reference [1] are used for comparison of the analytical and experimental results. The experimental and theoretical pressure values are plotted against time as shown in Fig.10. Two pressure peaks are observed at the start of braking travel one corresponding to the acceleration of the piston and the second peak corresponding to the closure of the first orifice. The experimental and theoretical values of the first peaks are 2.7 & 3.2 MPa and that of second peak are 3.2 & 4.1 MPa respectively. From the analysis data it is observed that more energy is being lost in the initial two peaks and hence the velocity fall down excessively and because of the fall in velocity the braking time is increased by 60-70ms.

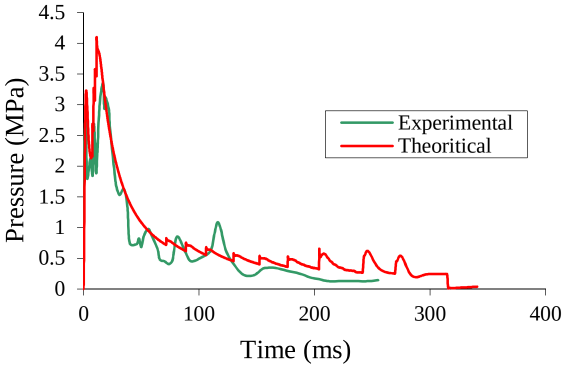


Fig. 10 Evolution of pressure with respect to time

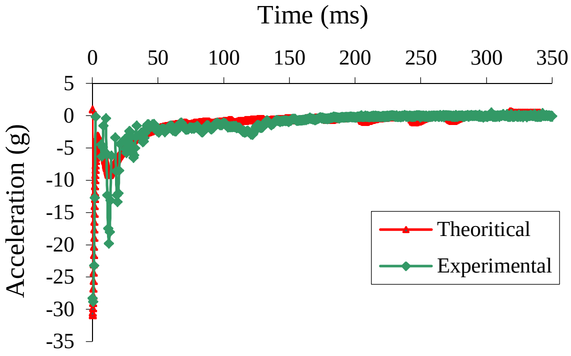


Fig. 11 Deceleration of Mobile assembly with recpect to time

Another important parameter in the performance of dashpot is the deceleration characteristics of the mobile assembly and the same is plotted in the Fig.11. Similar to pressure peaks there are two peaks in the deceleration. The experimental and theoretical values of the first peaks are 28.9 g and 30.9 g and that of second peak are 19.8 g and 9.2 g. The theoretical values and their trend match with the experimental data.

VII. CONCLUSION

The pressure drop characteristics of the oil dashpot with multiple orifices have been determined by detailed 3-dimensional CFD simulations. The study covered a wide range of parameters, including flow area, oil velocity etc. The pressure drop characteristics have been integrated with performance analysis code, which numerically solves the equations that govern the linear motion two degree of freedom system. It is seen that, the braking time is 290 ms which compares well with measured braking time of 250 ms. There is no re-bounding of the mobile assembly during the braking travel, which is a very important design requirement. The time evolution of acceleration and pressure predicted by the code are found to compare reasonably well with the experimentally measured values with marginal deviation in the local values.

REFERENCES

[1] V. Rajan Babu, R. Veerasamy, Sudheer Patri, S. Ignatius Sundar Raj, S.C.S.P. Kumar Krovvidi, S.K. Dash, et all, Testing and qualification of Control & Safety Rod and its drive mechanism of Fast Breeder Reactor, Nuclear Engineering and Design 240 (2010) 1728–1738

[2] I.E., Idel Chick, Handbook of Hydraulic resistance, Israel programme for scientific translations, jerusalem, 1966

[3] A.J. Ward Smith, Pressure Losses in Ducted Flows,Butterworth and Co. Ltd., London, 1971

[4] Ahid D. Nashif,Vibration Damping, John wiely ans Sons, Inc., 1985.

[5] Amitava Sur, Some experimental studies on impact absorber for use in PFBR-CSRDMs**,** Mastaer of Science, IIT Madras ,1992