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Passive temperature compensation in hydraulic dashpot used for the shut-off rod drive mechanism of a nuclear reactor

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HIGHLIGHTS

- Passive temperature compensation in hydraulic dashpot has been studied numerically as well as experimentally.
- Temperature compensation is achieved by reducing the clearances in the hydraulic dashpot at elevated temperature to compensate for the viscosity reduction.
- Temperature compensation effects due to difference in thermal expansion of common engineering materials and use of bimetallic strips have been analyzed.
- Design of a novel passive temperature compensating hydraulic dashpot is presented, which can be used for wide range of temperature variations.

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ABSTRACT

Passive temperature compensating hydraulic dashpot has been studied numerically as well as experimentally in this paper. Study is focused on reducing the clearances of the hydraulic dashpot at elevated temperature which intern compensates for the reduction in viscosity of damping oil and the dashpot gives uniform performance for wide range of temperature variation. Temperature compensation effects are mainly due to difference in the thermal expansion of materials. Different combinations of materials are used to reduce the dashpot clearances at elevated temperature. Finite element commercial code COMSOL Multiphysics 5.1 has been used for numerical analysis. Fluid-structure analysis has been carried-out to study the thermal expansion and pressure generated in the hydraulic dashpot. Multiphysics study with solid mechanics, laminar flow and moving mesh interfaces has been carried-out. Thermal expansion results of study-1 (solid mechanics) are further extended in to study-2 (laminar flow and moving mesh) and dashpot pressure is estimated. These results show that bimetallic strip improves the dashpot performance at 55 °C but do not fully compensate beyond that and less severe impacts occurs. Specific combinations of design and materials have been presented in this paper for obtaining maximum temperature compensation. A novel passive temperature compensating hydraulic dashpot design has been presented, which is suggested for use over wide range of temperature change without much variation in the damping performance.

1. Introduction

Shut-off rods are used to shutdown a nuclear reactor and these rods are moved using Shut-off Rod Drive Mechanisms (SRDM). At the time of reactor start-up, rods are withdrawn at a given speed and are held in position during the reactor operation. On actuation of reactor trip, shut-off rods fall freely into the reactor core. However, at the end of rod travel, rod velocity is smoothly brought to zero using a passive device called as ‘Hydraulic Dashpot’. In this, fluid (typically silicone oil) is allowed to flow from one chamber to the other through narrow clearances, giving damping action. After dashpot engagement, there is a sudden increase in oil pressure inside the high pressure chamber and thereafter it reduces at the end of travel as oil passes to low pressure chamber through narrow clearances. The hydraulic dashpot vane rotates typically by 120° in one rod drop cycle. In present study the hydraulic dashpot of ‘Critical Facility’ reactor (a research reactor) is studied in detail. General arrangement of the shut-off rod drive mechanism for ‘Critical Facility’ reactor is shown in Fig. 1. Shut-off rod falls freely for 90% of the travel and hydraulic dashpot brought into action for the

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Nomenclature

C	elasticity tensor
cc	cubic centimeter
cst	centistokes
det	determinant
F	deformation gradient tensor in Eq. (1b)
F	volume force vector ($N\,m^{-3}$) in Eq. (4)
F_v	Body force per unit volume
Fig.	figure
I	identity matrix
J	jacobian matrix
ID	inner diameter
Kg	kilogram
m	meter
mm	millimeter
Ma	Mach number
No.	number
OD	outer diameter
p	pressure (Pa)
Pa	pascal
RPM	rotation per minute
S	stress tensor
S_0	Initial stress value
s	second
T	absolute temperature in Eq. (2b)
T_{ref}	reference absolute temperature
T	transpose at rest of places
u_2	velocity field (u_2,v_2,w_2) ($m\,s^{-1}$)
u	displacement field (u, v, w) (m)
w.r.t.	with respect to

Greek symbols

ϵ	strain tensor
ϵ_0	initial strain value
ρ	density of fluid ($Kg\,m^{-3}$)
∇	divergence
μ	dynamic viscosity (Pa s)
α	coefficient of thermal expansion
σ	stress

Abbreviation

AHWR	Advanced Heavy Water Reactor
ALE	Arbitrary Lagrangian Eulerian
CFD	Computational Fluid Dynamics
EM	Electro-magnetic
FSI	Fluid structure interaction
MWe	Megawatt electric
PHWR	Pressurized Heavy Water Reactor
SRDM	Shut-off rod drive mechanism

last 10% of the travel and rod velocity comes to zero smoothly. Hydraulic dashpot is brought into action with the help of pick-up rings in the mechanism. These pick-up rings are arranged by design in such a way that they keep on picking up the next-one for initial 90% of travel and connect the hydraulic dashpot to the sheave shaft for the last 10% of the travel. Sheave is a deep groove type of pulley on which wire rope wounds and the other end of wire rope is connected to the Shut-off Rod (SOR). Pressure in the hydraulic dashpot starts building-up after 90% free fall, reaches a peak value and then reduces. The damping force in the hydraulic dashpot mainly depends on the pressure generated in the pressure chamber. Detailed study is presented in Singh et al. (2014).

Shut-off rod drive mechanisms are to be qualified at room temperature during reactor start-up as well as at elevated temperature during reactor operation, where heat comes from environment. In Indian standardized Pressurized Heavy Water Reactors (PHWRs) (Bajaj and Gore, 2006), these drive mechanisms are placed in boiler room, where environment temperature remains at about 65 °C. While in upcoming Advanced Heavy Water Reactor (AHWR) (Sinha and Kakodkar, 2006), these mechanisms are to be placed in tail pipe vault area, where environment temperature remains at about 285 °C. Although cooling jackets are provided around these drive mechanisms, but in event of cooling failure, these mechanisms are required to operate at high temperature. Hydraulic dashpot designs are finalized with an optimum combination of dashpot clearances and oil viscosity. If a hydraulic dashpot with fixed clearances utilizes less viscous oil, then it works well at room temperature, but we see impact at elevated temperature as viscosity reduces and dashpot becomes under damped. Otherwise if we go for high viscous oil with same clearances, then we do not see the impact at elevated temperature, but we get higher rod drop times at room temperature as the dashpot becomes highly over damped and we do not meet the drop time criterion. These calls for a hydraulic dashpot design that can passively compensate for viscosity change and dashpot can be used for wide range of temperature variation.

2. Review of previous work

Literature survey reveals various temperature compensating techniques utilized by different researchers. Predominantly, these techniques are based on the idea of modifying the viscosity as per requirements. Most common technique is based on utilization of smart fluids (Katrin, 2010). Smart fluids can change their viscosities quickly as and when required. The two common types of smart fluids are electro-rheological (ER) and magneto-rheological (MR) fluids. Smart fluid techniques are active and require a control system to change the viscosity. As SRDMs are placed in the radiation area, these kinds of controls are not possible. Additionally SRDM has to be a passive device, which should work reliably in any eventuality like station black-out. Thus hydraulic dashpot design requires a passive temperature compensating technique, so that it can work for a large variation of temperature with uniform performance.

The present study for making hydraulic dashpot temperature compensating is based on reducing the dashpot clearances at elevated temperature and best way is to use a bimetals. Various researchers have worked on thermal expansion based devices. Piotr et al. (2012) have developed a method for optimizing the design of a disc spring valve system by reducing the aeration and cavitation effect which negatively influence the performance of a shock absorber. A Fluid Structure Interaction (FSI) model is used in order to modify the geometry of the valve interior and, in turn, to achieve better performance of shock absorber, Samantaray (2009) developed mathematical models for passive liquid spring shock absorbers, which are suitable for heavy load military applications. Venkateswara Rao et al. (2012) have done FEM analysis of bimetallic beam under thermal loading and proposed an empirical formula which predicts the deflection of bimetallic beam for a given temperature. Danut (2011) has done the detailed structural analysis of helical bimetallic strip thermostat using FEM. Sever and Oancea (2013) have done the thermal expansion analysis of the complex body assemblies using FEM. In this analysis the assembly is loaded with a uniform distributed thermal field and the thermal expansion for internal sections of engine block is determined. Sebastien et al. (2012) studied a bimetal-based heat engine for thermal energy harvesting. In this device, a curved bimetallic strip turns the thermal gradient into a mechanical movement. Adrian (2013) has done the thermal analysis of overload protection relays using FEM and a