Analysis of an Electromagnet for Diverse Safety Rod Drive Mechanism

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Abstract: Prototype Fast Breeder Reactor (PFBR) has two independent, diverse, fast acting & fail safe shut down systems to achieve the required level of safety & reliability (1). The shut down systems comprises of nine numbers of Control & Safety Rod Drive Mechanisms (CSRDM) & three numbers of Diverse Safety Rod Drive Mechanisms (DSRDM). DSRDM facilitates SCRAM of the reactor on abnormal condition by rapid insertion of Diverse Safety Rod (DSR) into the core. SCRAM is achieved by dropping both Control & Diverse Safety Rod's. SCRAM is acronym for Safety Control Rod Accelerated Movement. An electromagnet located at the bottom end of DSRDM holds the DSR in the core during normal operation. The electromagnet is immersed in sodium and undergoes temperature variations (180ºC - 580 ºC) as seen by the liquid sodium which is a coolant in fast reactor. When the electromagnet is de-energized, the DSR falls under gravity leading to shutdown of the reactor. The electromagnet should be capable of lifting the DSR at all temperatures and should be able to drop the DSR within a specified time on demand. This requires calculation of the lifting capacity of the electromagnet at different currents and at various temperatures. In this work COMSOL has been used to calculate the lifting forces of the electromagnet at different currents and operating temperature (550ºC) and the predictions have been compared against the experimental data.

Keywords: Electromagnet, DSR, Shutdown, lifting capacity, SCRAM

1. Introduction

PFBR has two shutdown systems. The absorber rod of the first system is called Control & Safety Rod (CSR) and of the other system is called Diverse Safety Rod (DSR). The respective drive mechanisms are called Control & Safety Rod Drive Mechanism (CSRDM) and Diverse Safety Rod Drive Mechanism (DSRDM). CSRDM facilitates start-up, control of reactor power and controlled shut-down of reactor by raising and lowering of CSR and shutdown of reactor at off normal conditions by insertion of CSR into active core under gravitational force. DSRDM facilitates SCRAM of the reactor on off normal conditions by rapid insertion of DSR into the core. An electromagnet (EM) at the lower end of the DSRDM is fully immersed in hot pool sodium and holds the DSR head during normal operation and parks it above core. Roller screw-nut mechanism is used for raising/lowering of electromagnet. On receiving the SCRAM signal the EM is de-energised & DSR is released to fall under gravity.

2. Description of Electromagnet

A schematic diagram of DSRDM EM is shown in Fig.1.The EM is made up of inner core, outer core, armature & coil. Soft iron is chosen as the material for the inner and outer cores of EM. MgO insulated SS sheathed copper coils are wound over the inner core. The material of armature of the DSR is 2.25 Cr - 1 Mo steel. The inside of EM is sealed from sodium to achieve the required response time and to prevent the exposure of EM coil to sodium. Adequate leak tightness is achieved by welding the bottom ends of inner and outer cores with inconel filler. A projection of 0.1 mm is maintained below the cores in the filler region to avoid a direct contact of armature of DSR with cores. This is to reduce the response time as well as risk of self-welding. The flux lines between the inner & outer cores are closed through the armature of the mobile DSR held at the bottom end of the EM, thereby making the magnetic coupling possible between the drive mechanism and the mobile DSR.

The electromagnet should be able to lift the DSR at all temperatures and should be able to drop the DSR within a specified time. The weight of DSR is 40 kg and maximum allowable response time is 100 ms. As a part of the development of EM, a full scale EM was manufactured and tested in air, in sodium up to 550ºC to find out its lifting capacity and response time.

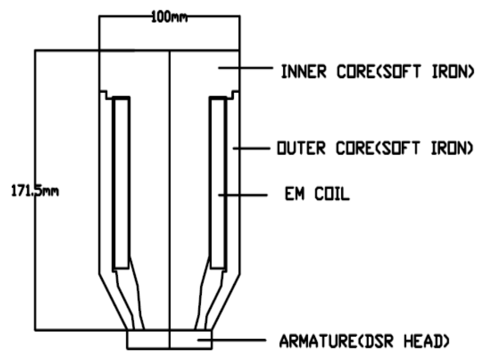

Fig.1 Schematic diagram of DSRDM EM

2.1 Specification of electromagnet:

Maximum diameter of electromagnet	0.10m
Maximum diameter at armature	0.06m
Design of lifting capacity	1177N
Weight of DSR	393N
Coil excitation (DC)	Continuous
Response time	0.1s
Operating temperature	550ºC
Gap between pole & armature	0.1mm
Operating environment	Sodium

3. Theoretical Background

The force for flat faced electromagnet can be written as follows.

$$Force = \frac{(Air\ gap\ flux\ density)^2 * area}{2\pi\mu_0\mu_r}$$

Where

μ_0 = absolute permeability $4\pi * 10^{-7}$

μ_r = relative permeability (for air =1)

In simulation lifting force is computed using the principal of virtual work

$$Force_{armature} = \left.\frac{dW(g,i)}{dg}\right| i = const$$

Where

$Force_{armature}$ = Net force on armature in (N)

g = air gap

dg = incremental distance traveled

i = current

W (g, i) = Co-energy of the system

4. Use of COMSOL Multiphysics

COMSOL 3.4 has been used for simulation of DSRDM EM. It is an FEM based software. The DSRDM electromagnet has axi-symmetry geometry. Therefore, a 2D Axis symmetric model was made, the geometrical representation of which is shown in fig. 2. The electromagnet is energised by a constant current D.C. source. The winding of electromagnet consists of mineral insulated cable, which is suitable for high temperature operation. The mineral insulated cable consists of a copper conductor in centre surrounded by MgO which acts as an electrical insulation. The MgO insulation is contained by stainless steel sheath. For DC mangetostatic model, it is sufficient to model the coil region with copper conductor only. SS and MgO do not affect the behavior of Direct Current powered electromagnet, hence need not be modeled. All the turns are in series and have been fed with constant current density in the sub-domain properties. Both the outer and the inner core are made up of high permeability Midhani grade soft iron to provide a low reluctance path for magnetic flux. The armature is made up of 2 ¼ Cr-1 Mo magnetic steel. The materials of the electromagnet and the armature are kept different to prevent self welding at high temperatures.

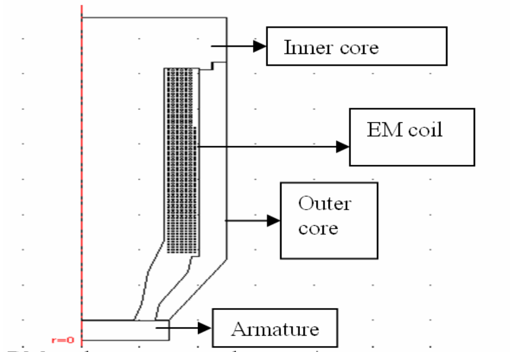

Figure 2: Axis-Symmetry model of DSRDM EM

Both soft iron and 2¼ Cr-1-Mo steel are magnetic materials with non-linear B-H curves. The corresponding B-H curves are specified in the sub-domain properties. The B-H curves used in the analysis are depicted in fig. 3 & 4.The electromagnet is immersed in sodium which is having a magnetic permeability equivalent to air. The boundary conditions used are shown in fig. 5. The analysis has been carried out using the Magnetostatics application mode in AC/DC module. The calculation of lifting force on the armature has been done by specifying the force name in the tab forces in sub-domain setting in Physics menu as shown in fig 6.

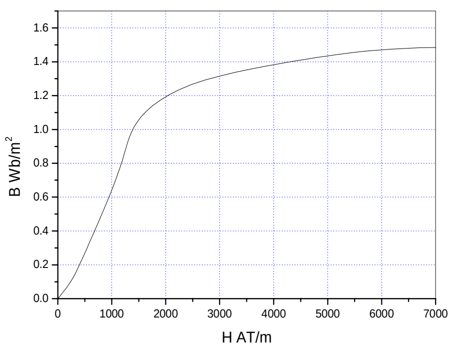

Figure 3: BH curve for 2¼ Cr-1-Mo steel at 550ºC

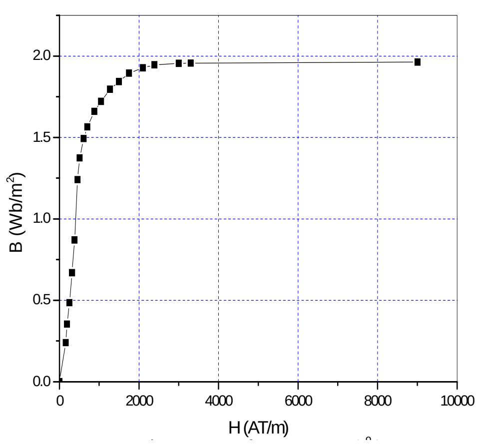

Figure 4: BH curve for Soft iron at 550ºC

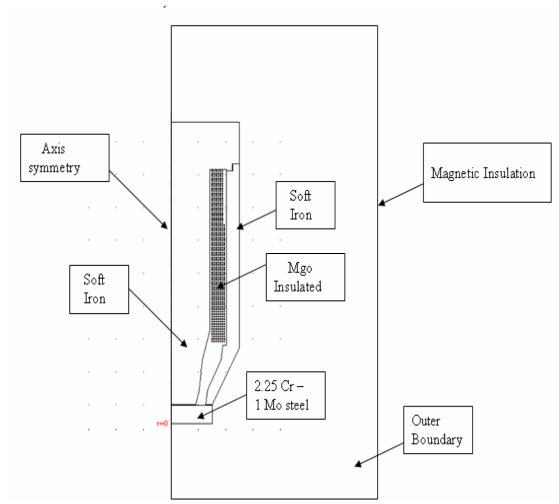

Figure 5: Details of material properties & boundary conditions

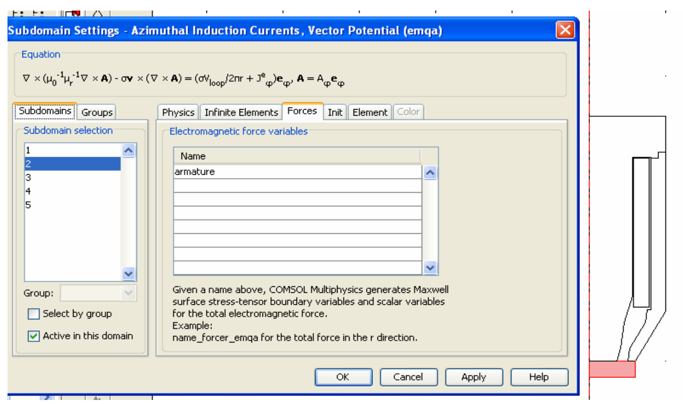

Figure 6: Method of calculating force on armature

5. Comparison of Simulation results with Experimental results

The model was simulated for various values of currents for an air-gap of 0.1mm between the armature and the electromagnet. Figure 7 shows the flux density profile obtained for a current of 1.0Amps. Figure 8 represents the comparison of the lifting force obtained for different currents using COMSOL against the experimentally obtained values at a temperature of 550ºC. A close agreement of within ±5% between the experimental and simulation results is evident from the figure.

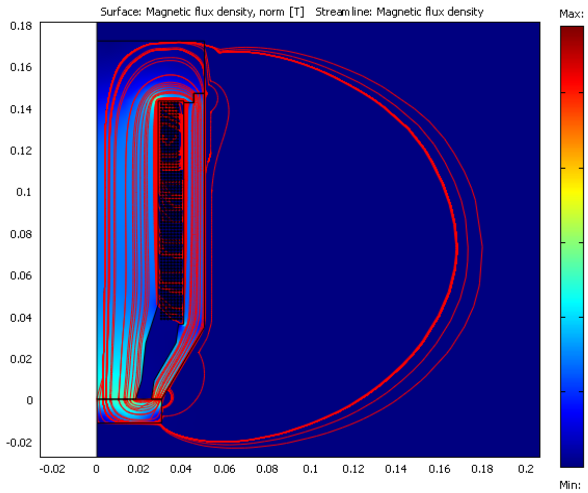

Figure 7 : Flux density profile for 1.0A current

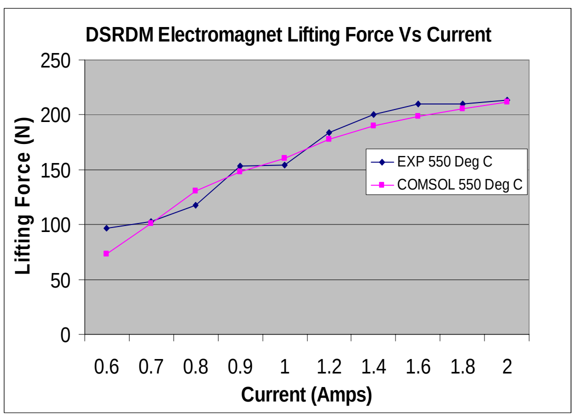

Figure 8: Comparison between Experimental & Simulation results

6. Conclusion

In this paper, finite element based software COSMOL has been used to predict the lifting force of the electromagnet. DSRDM forms the part of the shutdown system of PFBR. Accurate prediction of lifting force of the electromagnet is important from the point of view of design of the electromagnet, keeping in mind the space and other operating constraints. Therefore, a model of the electromagnet was made in COMSOL and simulated using the magnetostatics application mode for various values of current. Comparison with the experimental data was done and a close agreement within ±5% was obtained.

7. References

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