Finite Element Simulation of Induction Heating of a Tubular Geometry

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ABSTRACT

In Pressurised Heavy Water Reactors, the fuel bundles are located inside horizontal pressure tubes made of Zr 2.5 wt% Nb alloy. During reactor operation, pressure tubes undergo corrosion with the heavy water coolant flowing through it and picks up a part of the hydrogen evolved. An in-situ technique for the measurement of hydrogen concentration in pressure tube is being developed. In this method, a tool head is inserted in the pressure tube and the hydrogen concentration is measured using an innovative technique. The tool head consists of a few modules and one of them is an induction coil for heating the pressure tube. Design of the coil geometry and other parameters are to be optimised to get the required heating pattern in the pressure tube. The problem has been simulated using finite element software COMSOL. This paper gives details of the analysis and parametric studies carried out and results obtained.

Key words: Induction heating, pancake coil, split type coil, ferrite flux concentrator

1.0 INTRODUCTION

In Pressurised Heavy Water Reactors (PHWRs) the fuel bundles are located inside horizontal pressure tubes made of Zr 2.5 wt% Nb alloy. During reactor operation, pressure tubes undergo corrosion with the heavy water coolant flowing through it and picks up a part of the hydrogen evolved. Assessment of the hydrogen concentration in the pressure tube forms an important part of the programme to assess the integrity of the component for continued operation. An in-situ technique for the measurement is being developed for measurement of the hydrogen concentration. In this method, the pressure tube is heated locally non-intrusively at a constant rate. The temperature of the pressure tube and its electrical conductivity are measured continuously at the centre of heating region and recorded during the process. An eddy current probe-thermocouple assembly is located in the middle of the heating area to measure the temperature and electrical conductivity. The information is processed later to estimate the hydrogen concentration in the pressure tube. Considering the advantage of induction heating, it is being considered for heating the pressure tube. As there is a limit on the temperature to which the pressure tube can be heated, it is necessary to minimise the difference between the peak temperature in the heating area and at the measurement area. Two different versions of the heating coil are being proposed for the purpose. Both the geometries have been modelled and analysed using COMSOL to decide the best option and also to finalise other parameters.

2.0 DIMENSIONAL DETAILS OF THE GEOMETRY TO BE HEATED

The pressure tube to be heated is a part of the coolant channel assembly of PHWRs, as shown in Fig. 1. Inside diameter of the pressure tube is 103.4 mm and its wall thickness is 4.7 mm. It is surrounded by a concentric calandria tube. Radial gap between the pressure tube and calandria tube is about 8 mm. The pressure tube is to be heated from inside by locating the induction coil properly.

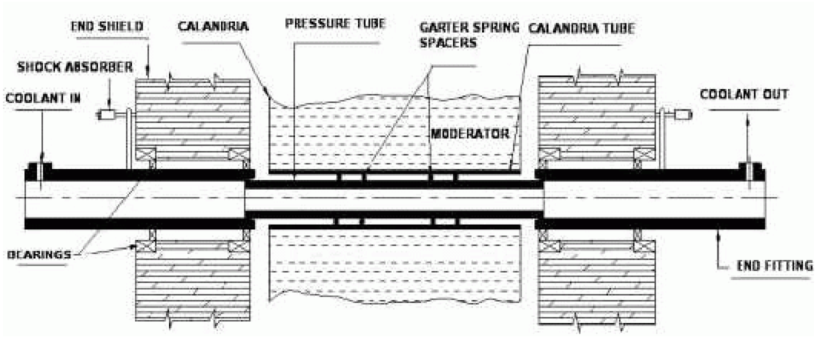

Fig. 1 Schematic coolant channel assembly of PHWRs.

3.0 FINITE ELEMENT ANALYSIS

Two types of induction heating coil geometry have been used for the analysis: 1) Split type 2) Pancake type with opening in the middle. In split type geometry, the induction coil has been split into two sections and same current flows through both. The eddy current probe, used for monitoring the change in conductivity of the pressure tube material is housed in a copper chamber located in the gap between the two halves of the coil. The entire assembly is mounted inside the pressure tube. In the pancake type geometry, the eddy current probe is housed in a copper block located in an opening provided in the middle of the coil. Finite element model has been prepared using the software COMSOL Version 3.5a. The option: Electro Thermal Interaction→Azimuthal Induction Heating (Vector potential)→Transient Analysis, available with AC/DC Module of COMSOL has been used for the analysis.

3.1 Split type heating coil

Due to axi-symmetric nature of the problem, only one half of the geometry has been modeled. Geometry used is shown in Fig. 2 and the finite element mesh is shown in Fig. 3. There are five turns for each half of the induction heating coil and a ferrite base is provided below it as a flux concentrator. A copper block is located in the middle in which the eddy current probe and the thermocouple are housed.

3.2 Pancake type induction heating coil

The pancake type coil is shaped to match the inside diameter of the pressure tube to be heated. There is an opening in the middle in which a copper block is located. Eddy current probe and the thermocouple are housed in the copper block. The induction coil is placed over a ferrite base, which acts as a flux concentrator and the whole assembly is mounted on a stainless steel pipe. In order to simplify the analysis, the pressure tube is assumed to be in the form of a plate and the coil is assumed to be flat. Due to axi-symmetric nature of the problem, only one half of the geometry has been modeled as shown in Fig. 4 and the finite element mesh is shown in Fig. 5.

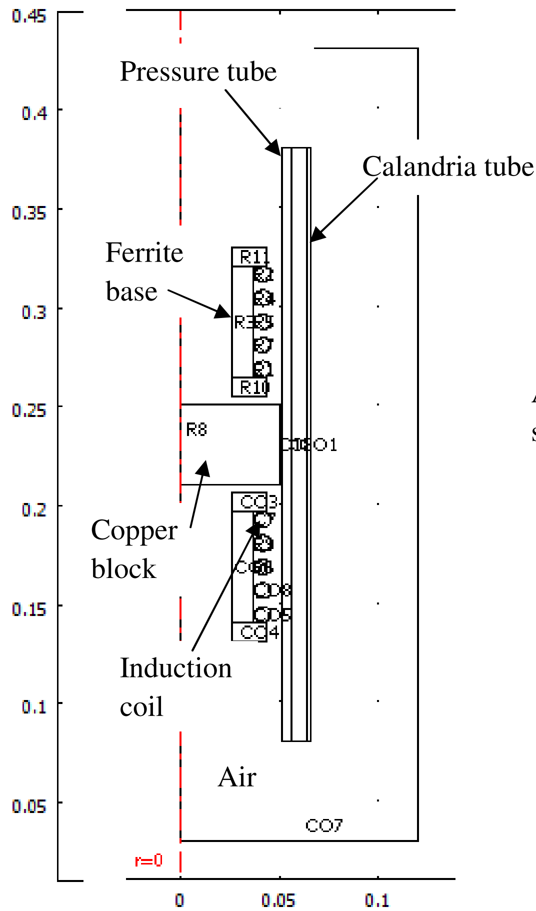

Fig. 2 Geometry of split type coil used for the analysis.

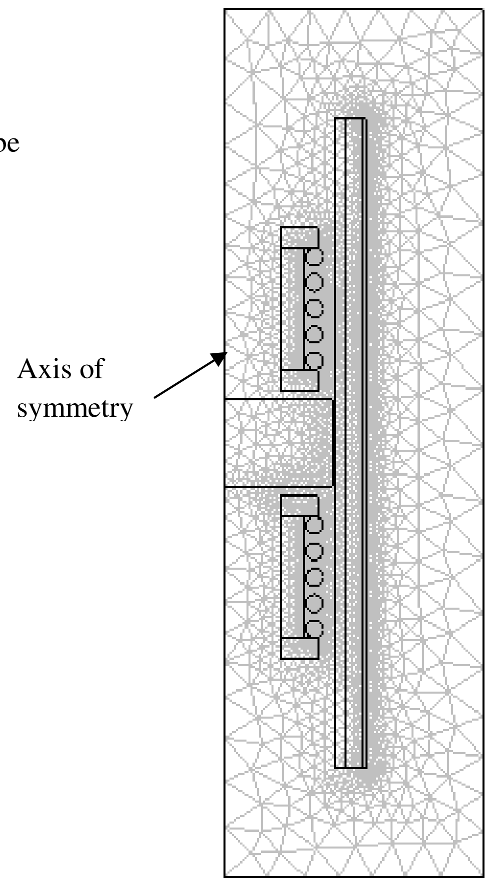

Fig. 3 Finite element model.

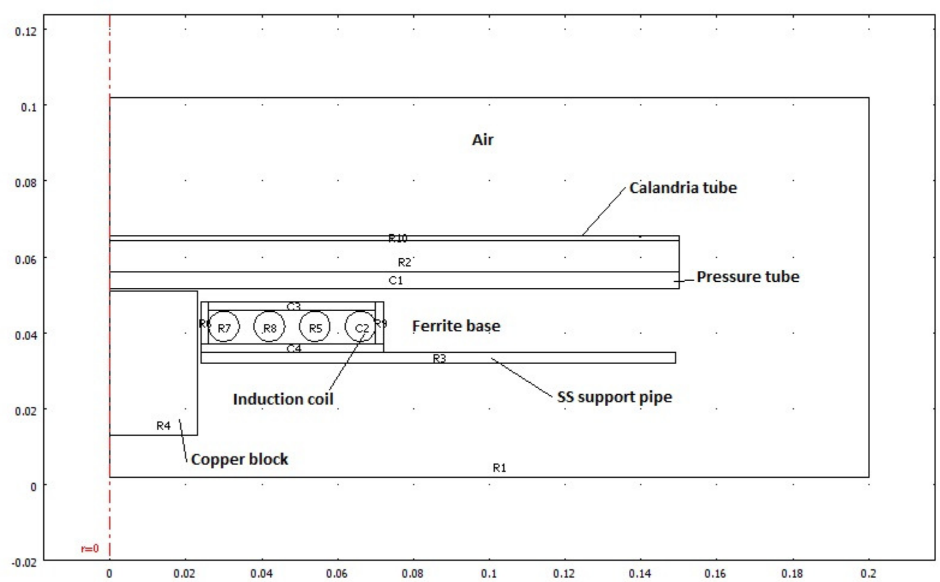

Fig. 4 Geometry of pancake type induction heating coil.

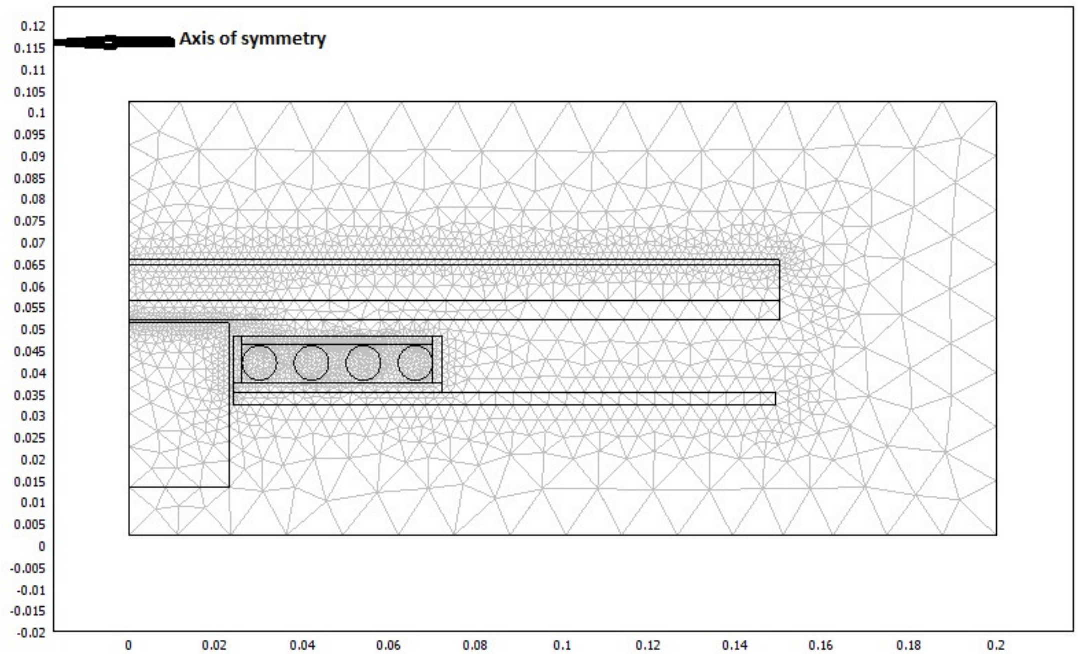

Fig. 5 Finite element model of pancake type coil assembly.

4.0 MATERIAL PROPERTIES

The material properties of pressure tube and other associated parts of the model used for the analysis are given in Table 1.

Table 1 Material property data.

Material property	**Name of material**				
	SS 304	**Ferrite**	**Insulation**	**Zr 2.5 wt% Nb**	**Air**
Thermal conductivity (W/m.K)	18.8	5	0.195	16.64+0.01436xT	0.03
Density (kg/m^3)	8000	1600	2150	6500	1.128
Specific heat (J/kg. K)	475	400	1172	278+0.08205xT	1000
Electrical conductivity (S/m)	1.428x10^6	0.1	-	10^8/(51.54+0.1384xT)	-
Relative magnetic permeability	1	50	1	1	1

T is temperature in ^{0}C.

5.0 BOUNDARY CONDITIONS USED

In the case of split type induction coil, longitudinal direction of the pressure tube is taken as the axis of symmetry. The outer boundary of the air medium is assumed to be at constant temperature. Convective and radiation heat transfer has been imposed on the outer surface of calandria tube. The thermal conductivity of the air medium in between the pressure tube and calandria tube has been modified to take into account the effect of convection and radiation.

6.0 RESULTS OF ANALYSIS

In the case of split type induction heating coil, temperature distribution obtained at the end of one hour when a steady current of 115 A at 18 kHz frequency flows through it is shown in Fig. 6 and the temperature profile along the length of the mid-section of the pressure tube is shown in Fig. 7.

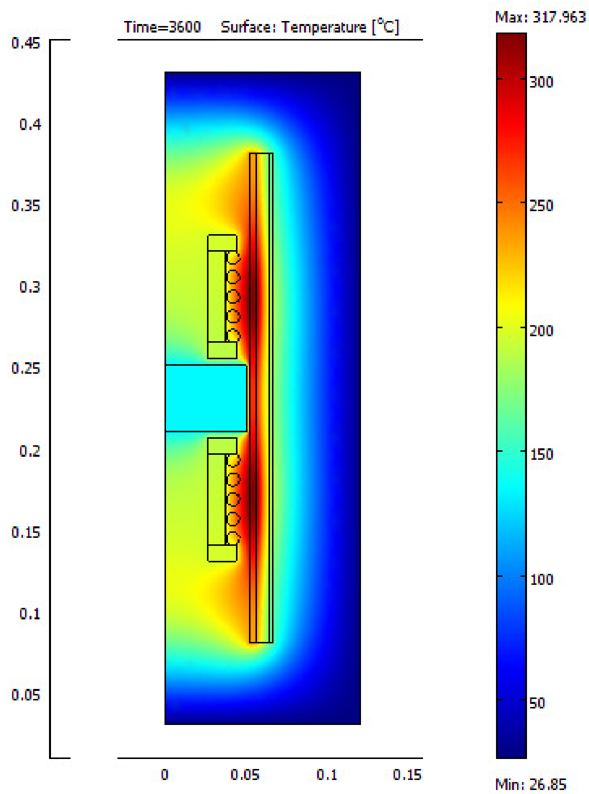

Fig. 6 Temperature distribution at the end of one hour.

In the case of pancake type coil, temperature distribution obtained at the end of one hour when a steady current of 175 A at 18 kHz frequency flows through it is shown in Fig. 8 and the temperature profile along the length of the mid-section of the pressure tube is shown in Fig. 9. It can be observed from Fig. 7 and Fig. 9 that the difference in temperature between the peak location and that at the centre of induction coil is about 50^0 C in the case of helical split type coil and it reduces to about 25^0 C in the case of pancake type coil. Since the number of turns in the case of pancake type coil is less than that in the case of split type coil, the current requirement is higher by about 50%.

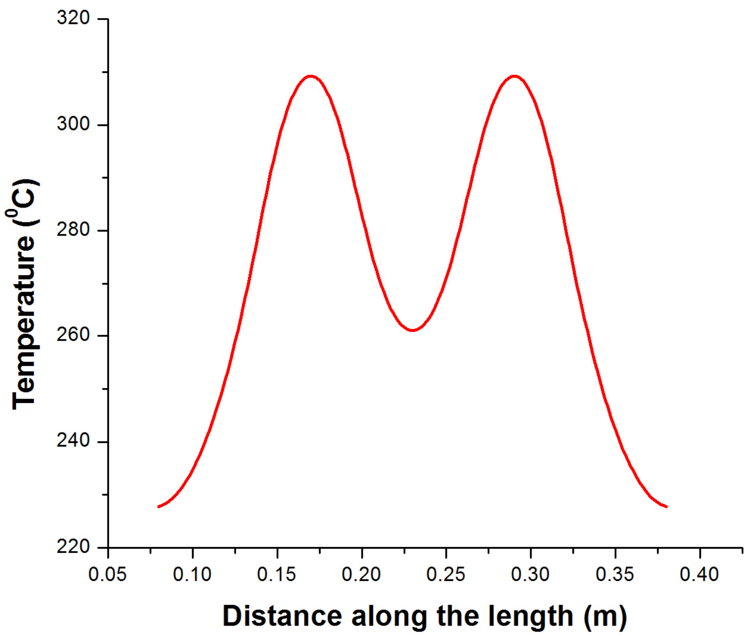

Fig. 7 Temperature profile in the axial direction of the mid-section of pressure tube

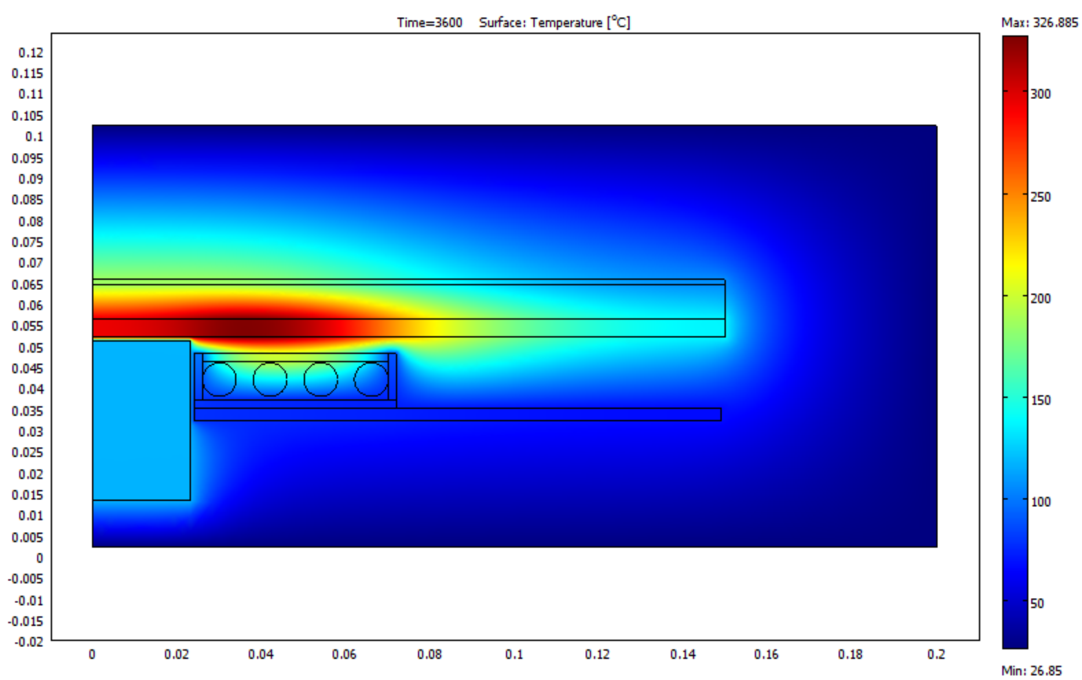

Fig. 8 Temperature distribution at the end of one hour.

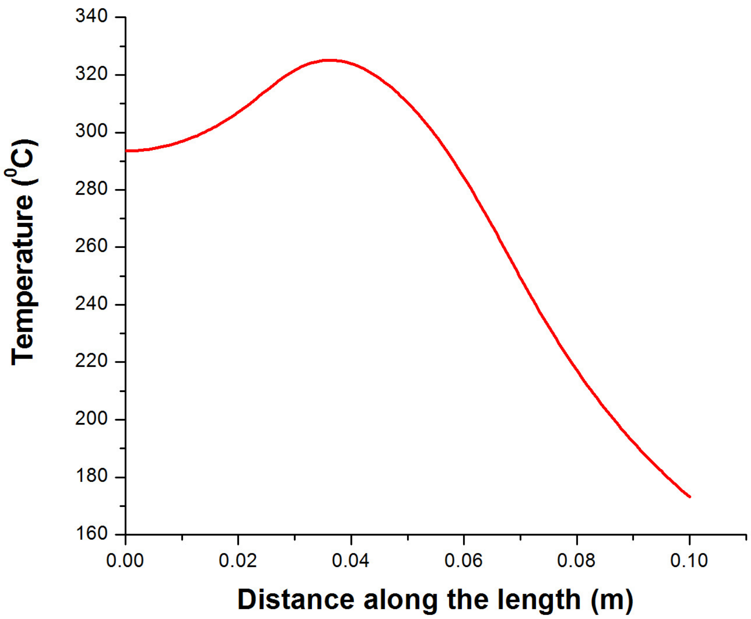

Fig. 9 Temperature profile along the length of the mid-section of pressure tube.

7.0 CONCLUSION

Finite element simulation and analysis of induction heating of tubular geometry has been carried out using the software COMSOL. Two types of coil geometries, namely split-type helical coil and pancake type coil design have been studied. Different parametric studies carried out indicate that pancake type design is more appropriate for the present application. Use of ferrite base enhances the efficiency of heating considerably and also avoids the heating of the structural pipe and copper block present inside the coil.

ACKNOWLEDGMENTS

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REFERENCES

[1] COMSOL Multiphysics Version 3.5a.