

Thermal Analysis of the Electro Magnetic Pump

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Abstract: Electro magnetic (EM) pumps are used in auxiliary circuits of liquid metal cooled fast breeders to pump liquid sodium. There is a need to develop these sensitive items indigenously. The pumps work on the principle of electro magnetic induction. During operation heat generation takes place in the coil windings and laminations. Heat is also transferred to the coils from the hot sodium. The coils are covered with varnish insulation whose temperature should not cross 180⁰ C. To limit this temperature, forced air is blown over the coils. Thermal analysis has been done using the HEATING5 code. The paper highlights the modeling and results where all the three modes of heat transfer and materials with anisotropic properties are considered.

Introduction

The Prototype Fast Breeder Reactor (PFBR) is a pool type liquid sodium cooled fast breeder reactor and is in the final stages of design at Kalpakkam. It is a 500MWe reactor with liquid sodium as the coolant in the primary and the secondary heat transport circuits. A schematic of PFBR is shown in Fig 1. The heat generated in the nuclear reactor is transferred by the primary liquid sodium to the secondary liquid sodium in the Intermediate Heat Exchange (IHx). The secondary sodium passes the heat to water in the Steam Generator (SG) to produce steam to run the turbines as in any conventional power plant. In the main heat transport systems liquid sodium is pumped using centrifugal pumps which have an efficiency of ~ 85%. However, in the auxiliary systems EM pumps are used. Even though their efficiency is low these pumps are simple to construct and easy to operate and are totally maintenance free due to the absence of any moving parts.

Annular Linear Induction Pump (ALIP)

These are pumps which work on the principle of linear induction motor. A linearly traveling magnetic field induces current in the conductor placed within, resulting in its motion. A schematic of ALIP – reflux type is shown in Fig 2. It essentially consists of a sodium duct surrounded by a electric stator. Sodium flows in the annulus of the outer and inner pipes and returns through the return pipe. The stator is made of stacks of magnetic steel laminations with copper windings. When the stator is excited with three phase supply, current is induced in the circumferential direction in sodium in the annulus. The interaction of this current with the linearly traveling magnetic field produced by the stator windings pumps the sodium in the axial direction. The magnetic laminations stacked between the inner and return pipes provide a low reluctance path for the magnetic flux. During operation heat generation takes place in the lamination and coil. Heat is also transferred to the coils from the hot sodium. The copper coils are covered by impregnating varnish. The permissible temperature of the varnish is 180⁰ C. To limit the temperature of the coil, forced cooling is resorted to by blowing air between the casing and laminations. In the auxiliary circuits it is proposed to use ALIP of 170 m³ / h capacity pumping sodium at 355⁰ C. However, during transients the sodium temperature can go as high as 500⁰ C. So the pump is designed for a sodium temperature of 500⁰ C.

Methodology

The general purpose heat conduction code HEATING5 is used for heat transfer analysis. The governing equations are solved using the finite difference technique. The physical problem is discretised into a system of nodes each associated with a finite volume of the solution domain. A heat balance about each node is written and the resulting system of equation is solved. A typical internal node 'o' defined by the intersection of planes in the Cartesian co-ordinates is shown in Fig 3. For this node the heat balance equation is,

$$P_o + \sum_{m=1}^6 {}_oK_m (T_m - T_o) = 0 \quad (1)$$

Where T_m is the temperature of the mth node adjacent to 'o', P_o is the heat generation rate at node 'o' and ${}_oK_m$ is the conductance between node 'o' and its neighbour 'm'. The nodes 'o' and 'm' can exchange heat by conduction, natural convection and radiation. Accordingly the conductance ${}_oK_m$ consists of contribution due to molecular conduction, forced/ natural convection and surface thermal radiation. Solving for T_o we get.

$$T_o = \frac{P_o + \sum_{m=1}^6 {}_oK_m T_m}{\sum_{m=1}^6 {}_oK_m} \quad (2)$$

Similar equations are derived for all the nodes in the calculation domain. The set of algebraic equation is solved by Gauss-Siedel iteration method. To speed up the convergence an over relaxation factor of 1.9 is used in the present calculations.

Modeling

The modeling is done in 3-D cylindrical polar co-ordinate system. A cross section view of the slot and copper windings is shown in Figs 4a and 4b. Though there are 36 slots, due to near symmetry only a half of the lamination and a half of the coil is modeled. There are fourteen laminations equispaced circumferentially. Due to symmetry in the θ direction, an angle of 12.857 degrees is considered for the analysis. In the radial direction, the inner side of the outer pipe is maintained at 500⁰ C. The outer portion of the lamination and coil are cooled by forced air with an ambient temperature of 40⁰ C. For conservative predictions the outer region of the casing is treated as adiabatic. The coil region consists of 13 X 2 turns of cooper with insulation and this region is treated as a single lumped material with anisotropic properties with different effective conductance in the three directions. This is required to reduce the number of nodes to reasonable limits. Conduction is the only mode of heat transfer in this region. In the narrow air gap (0.5 mm) between the thermal insulation and lamination/coil radiation and conduction through air is considered. To be conservative the emissivities in this region is taken as unity.

Results and Discussion

In an earlier analysis for a similar pump of smaller capacity (5 m³ /h) pumping liquid sodium at 400⁰ C a blower of 1400 m³ /h was used for cooling the coils. The pump was fabricated and is under operation. The predicted and the measured average temperatures were seen to be in close agreement (80⁰ C and 81⁰ C respectively). For the current pump under development, to start with a blower capacity of 3000 m³ /h is considered. The mean air velocity for this flow is 14 m/s and the Reynolds number is 56200, giving a heat transfer coefficient (HTC) of 50 W/m² C from the Dittus Boelter correlation. Different options like varying the HTC and providing insulation below the coil were studied to see the effect on the coil temperature. Fig 5 gives the nodal map in $\theta = 0^0$ plane where the maximum temperature of the coil/lamination is seen. Table – 1 gives the summary of the results of different cases.

Case 1

For the nominal case, the HTC is 50 W/m² C. It is seen that the temperature of the coil reaches 193⁰ C and crosses the limit of 180⁰ C and hence is not acceptable.

Case 2

In this case the HTC is doubled from 50 to 100 W/m² C. The maximum coil temperature reduces to 157⁰ C. The air flow rate required for this HTC is 7200 m³ /h (axial velocity of air = 33m/s, Re = 133900).

Case 3

The enamel insulation has a thermal conductivity of 0.378 W/m C while that of alumina insulation is 12 W/m C. Thus replacing the enamel insulation over copper with alumina, will enhance the conductance significantly. To see the advantage of alumina insulation, the nominal case was tried with alumina insulation. The maximum coil temperature is only 128⁰ C. This gives a low temperature for the coils. Fabrication of a pump with this ceramic insulation could be explored.

Cases 4 and 5

In order to access the benefit of doubling thermal insulation, cases 1 & 2 were repeated with the thermal insulation as 3 mm. In both the cases the maximum coil temperatures were within the limits and obviously for the height HTC of 100 W/m² C the temperature of the coils is low at 129⁰ C.

Case 6

Another case studied was with 6 mm thermal insulation below the coil and 3mm of thermal insulation over the outer pipe. The maximum coil temperature in this case was 136⁰ C which gives a safe margin for operation.

Cases 7 & 8

The cases studied are for a HTC of $50\text{W/m}^2\text{C}$ with 3mm insulation below the coil and with 1.5/3mm thermal insulation over the pipe. The maximum coil temperatures are 159 and 140°C respectively and are within the limits.

Case 9

This case is same as case 6 with 1.5 mm thermal insulation on the pipe. The maximum coil temperature in this case is 148°C and is thus acceptable.

It may be mentioned that the bulk air temperature is taken to be 40°C in all these calculation. However when the air travels from the first slot to the last slot, for the nominal configuration the total heat transferred to the air is 11.7 KW (6.25 KW generation and 5.45 KW transferred from sodium). Thus the temperature of air from inlet to outlet will rise at the most by 12.3°C , for a flow of $3000\text{m}^3/\text{h}$. Hence the temperature of the coil and lamination in the last slot will be more by 12.3°C .

Conclusions

From the good match seen between the predicted and measured values for the earlier pump of smaller capacity it is seen that the model is validated. For the present pump with a higher capacity we find that barring the first case the rest of the cases give an acceptable temperature. It is seen that the alumina insulation over the copper windings gives the least temperature even for the lower HTC. However the fabrication problems have to be borne in mind for this case. To sum up from the above analysis it can be said that these sensitive items could be fabricated indigenously.

References

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Table-1: The temperatures in the $\theta = 0^\circ$ plane

Case	HTC/Th ins thickness / insulation thickness below the coil	T1	T2	T3	T4	T5	T6
1	$50\text{W/m}^2\text{C} / 1.5\text{mm} / 0\text{mm}$	349	267	139	193	92	102
2	$100\text{W/m}^2\text{C} / 1.5\text{mm} / 0\text{mm}$	339	249	107	157	63	72
3	Alumina Insulation $50\text{W/m}^2\text{C} / 1.5\text{mm} / 0\text{mm}$	331	260	127	128	92	123
4	$50\text{W/m}^2\text{C} / 3.0\text{mm} / 0\text{mm}$	290	203	119	161	84	95
5	$100\text{W/m}^2\text{C} / 3.0\text{mm} / 0\text{mm}$	278	183	91	129	59	69
6	$50\text{W/m}^2\text{C} / 3\text{mm} / 6\text{mm}$	394	201	116	136	83	94
7	$50\text{W/m}^2\text{C} / 1.5\text{mm} / 3\text{mm}$	407	264	134	159	90	100
8	$50\text{W/m}^2\text{C} / 3\text{mm} / 3\text{mm}$	348	201	116	140	82	94
9	$50\text{W/m}^2\text{C} / 1.5\text{mm} / 6\text{mm}$	439	262	130	148	88	98

Reference Book:

Indian Chemical
Engineering Congress 2000