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Design, in-sodium testing and performance evaluation of annular linear induction pump for a sodium cooled fast reactor

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ABSTRACT

Annular linear induction pumps (ALIPs) are used for pumping electrically conducting liquid metals. These pumps find wide application in fast reactors since the coolant in fast reactors is liquid sodium which a good conductor of electricity. The design of these pumps is usually done using equivalent circuit approach in combination with numerical simulation models. The equivalent circuit of ALIP is similar to that of an induction motor. This paper presents the derivation of equivalent circuit parameters using first principle approach. Sodium testing of designed ALIP using the equivalent circuit approach is also described and experimental results of the testing are presented. Comparison between experimental and analytical calculations has also been carried out. Some of the reasons for variation have also been listed in this paper.

1. Introduction

Fast reactors form the second stage of Indian nuclear program (Chetal et al., 2006). In fast reactors, sodium is preferred as coolant by virtue of its favourable neutronic and thermal properties. Pumping of sodium is required for transferring heat generated from nuclear fuel to other parts of the heat transfer circuit and also in many auxiliary circuits. Pumping of sodium can be achieved either by a mechanical centrifugal pump or by an electromagnetic pump. Mechanical sodium pump imparts pumping energy to sodium by means of mechanical movement of the impeller. There is a relative motion between stationary parts and moving impeller of the pump.

Liquid sodium is also a good electrical conductor and this property is effectively used in the design of electro-magnetic (EM) pumps for pumping sodium. The EM pumps have no moving part, which makes it maintenance free and more reliable (Aizawa et al., 2011, Andreev et al., 1982). Sodium is hermetically sealed in EM pumps, which eliminates the problem of sodium leakage. However, it has got lower efficiency as compared to mechanical pumps. The EM pumps find wide application in low capacity requirements such as auxiliary systems of fast reactors (Anisimov et al., 2012), purification circuits of the fast reactor, experimental sodium facilities (Sharma et al., 2011) due to their operational simplicity, less maintenance, non-intrusiveness and advantage of hermetically sealed construction.

The EM pump works on the principle that when a current carrying conductor is placed in a perpendicular magnetic field it experiences a force. The various types of electromagnetic pumps can be categorized as – (a) Conduction type and (b) Induction type (Watt, 1958; Blake, 1957).

The conduction pumps are further classified as D.C. Conduction pumps and A.C. Conduction pumps. In conduction pumps (Watt, 1958; Blake, 1957) there is a direct physical contact of the external current carrying circuit with the liquid sodium. In induction pumps (Watt, 1958; Blake, 1957) no such physical contact with the liquid sodium is there and current is induced in liquid sodium via a traveling magnetic field. The induction pumps are also of various types like the helical induction pump, the flat linear induction pump and the annular linear induction pump (Baker and Tessier, 1987; Blake, 1957) but it is only the last one that is now most frequently used. This paper deals with design of annular linear induction pump (ALIP) with derivation of its governing equations used in design of pump and experimental test results of tested ALIP.

2. Design methodology of annular linear induction pump

Design and performance evaluation of annular linear induction pumps has mostly been done using formulas which have been derived using a model similar to an induction motor (Say, 2000). Though the equivalent circuit of ALIP does not take into account the end effects (Werloff, 1991), fluid dynamics and flow instability

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(Araseki et al., 2003) which may occur in some of the designs under some operating conditions, the equivalent circuit approach has many advantages. Various numerical models of ALIP have also been formulated to analyze the effects not accounted in equivalent circuit approach (Kirillov and Obukhov, 2003). Normally these numerical models form the second stage of EM pump design because numerical models require various inputs which are usually taken from the design done using equivalent circuit (Kim and Lee, 2011). Therefore the equivalent circuit based approach is a very important step in the design of ALIP.

The equivalent circuit approach is a lumped model of ALIP and uses a number of formulas for determining various parameters of ALIP (Baker and Tessier, 1987). Derivation of formulas used in design is very important for better understanding of ALIP design. The aim of this paper is to derive the relevant formulas of the equivalent circuit and compare the experimental results of developed pump with theoretical prediction.

3. Derivation of governing equation of annular linear induction pump using first principle approach

The schematic construction of ALIP is shown in Fig. 1. It consists of annular stainless steel duct over which three phase winding is wound for generating travelling magnetic field. Laminated stator core and centre core as shown in Fig. 1 provides high permeance path for flux. The sodium to be pumped is housed in stainless steel duct as shown in Fig. 1. ALIP has a 3-phase distributed winding which produces a linearly traveling magnetic field. This traveling magnetic field induces currents in liquid sodium. Interaction of induced currents with traveling magnetic field gives rise to a pumping force as per the formula $F = IL \times B$ (Fig. 1) where I is the induced current, B is the flux density and L is the length of conductor carrying I current. The mechanical arrangement of coils, laminations and sodium duct is done in such a way that the angle between I current and B magnetic field is 90°.

3.1. Equivalent circuit of ALIP

The equivalent circuit of ALIP which is similar to equivalent circuit of induction motor is depicted in Fig. 2. The constructional details of ALIP along with the definition of various parameters are shown in Figs. 3 and 4 (Baker and Tessier, 1987). The coil in ALIP is a circular pan-cake type which surrounds the central core and sodium completely. The coils are placed in slots and are thermally and electrically insulated from the stainless steel duct. The conductor in the coil does not occupy the full space due to insulation. The entire flux produced by primary winding does not link the secondary and hence the primary winding has got a leakage reactance. The magnetic circuit is completed by cold rolled grain oriented (CRGO) laminations which are stacked together and arranged along the periphery of the duct as shown in Fig. 4. The non-magnetic stainless ducts form the annular space through which liquid sodium flows. This duct also has circulating current in them and acts as secondary of an induction motor with unity slip. The sodium in the duct is equivalent to a single turn secondary of an induction motor. In the equivalent circuit all the parameters of the secondary are referred to the primary side. Leakage inductance of secondary is assumed to be negligible. The symbols used in derivation are given in Table 1. The symbol Eb in the equivalent circuit (Fig. 2) represents the applied phase voltage. Various parameters related to coil and slots are indicated in Fig. 3.

The equivalent circuit analysis is done on per phase basis and assumed as a symmetrical phase distribution of voltages and currents in all the three phases. The end-effects are neglected in this approach. Parameter estimation of equivalent circuit is based on electrical quantity. In the estimated parameter, instability in the flow and dynamics related to flow are neglected. However in the design of pump the pressure drop in the pump duct due to sodium flow is subtracted from the pressure drop obtained from calculated value and reduced pressure drop is taken as estimated pressure developed by the pump.

4. Estimation of equivalent circuit parameters – a first principle approach

Design and performance evaluation of annular linear induction pump is done using equivalent circuit approach. Following section presents the derivation of the formula for equivalent circuit parameters from first principles.

4.1. Stator Winding Resistance (R_1) Ω/ph

The circular pan-cake winding is made up of enameled insulated copper wire. This circular winding is housed in stator slot. The expression for winding resistance is obtained from the formula Resistance = ρ (length)/area.

$$\text{Total length of one phase of primary winding} = \frac{D_{15}N_7N_4}{N_2} \tag{1}$$

Assuming 60% of slot cross-sectional area is occupied by copper

$$\text{Copper area in one slot} = \frac{D_{14}D_{11} \times 0.6}{N_7} \tag{2}$$

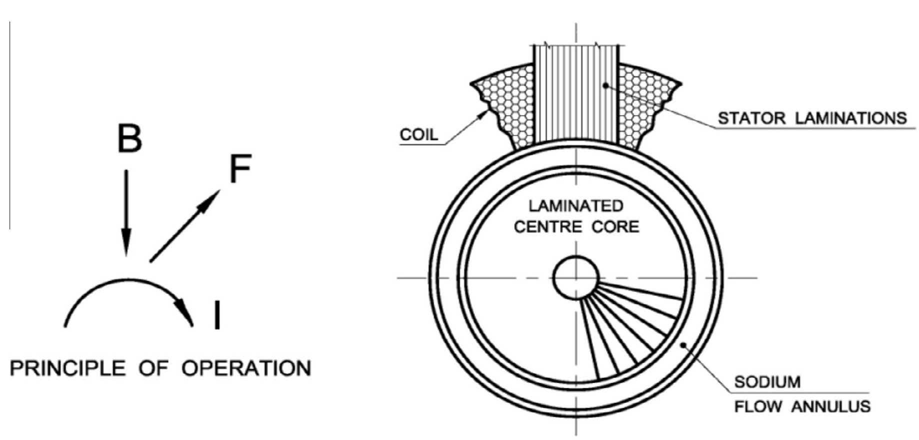

Fig. 1. Schematic construction and working principle of ALIP.