Indian Journal of Engineering & Materials Sciences
Vol. 14, June 2007, pp. 209-214

Performance testing of indigenously developed DC conduction pump for sodium cooled fast reactor

B K Nashine*, S K Dash, K Gurumurthy, U Kale, V D Sharma, R Prabhakar, M Rajan & G Vaidyanathan
Fast Reactor Technology Group, Indira Gandhi Center for Atomic Research, Kalpakkam 603 102, India

Received 6 December 2006; accepted 13 April 2007

Liquid sodium is a good electrical conductor and this property enables utilization of electro-magnetic (EM) pump for sodium service. Being non-intrusive EM pumps are well suited to sodium system as the chance of any sodium leak is minimized. However, EM pump utilization is restricted to auxiliary sodium circuit and centrifugal pumps are preferred for main circuits in view of their higher efficiency. DC conduction type EM pump is utilized for low flow and high temperature application. It comprises of stainless steel duct through which sodium passes and the magnetic field is produced by an electromagnet covering the duct. A DC conduction pump has been designed, built and tested for its performance in sodium before putting in the reactor. This paper presents the design approach and the performance *vis-a-vis* prediction.

IPC Code: H01F

In fast reactor, sodium is preferred as coolant by virtue of its neutronic and thermal properties. 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. These pumps find wide application in auxiliary systems of fast reactors, experimental facilities due to their operational simplicity, less maintenance, non-intrusiveness and advantage of hermetically sealed construction[1,2]. The advantages mentioned above outweigh their poor efficiency, compared to centrifugal mechanical pump for low capacity. There are many types of EM pumps, viz., Flat linear induction pump, annular linear induction pump, AC conduction pump and DC conduction pump. The DC conduction pump is good for low flow and high temperature operation. One such pump was indigenously developed for use in failed fuel location module of fast breeder reactor[3] based on available design. It was manufactured and performance tested. As per the process requirement, the pump has to be immersed in high temperature liquid sodium (approximately 800 K) in the nuclear reactor. At this high temperature, pump operating at lower voltage will have less stringent electrical insulation requirement compared to pump operating at higher voltage. Hence DC conduction pump, which operates at 2 V was preferred despite its lower efficiency compared to annular linear induction pump which operates at > 100 V. Insulating material required for DC conduction pump is available in the country. This paper presents the design approach and the performance *vis-a-vis* prediction of indigenously developed DC conduction pump.

Construction Details

The DC conduction pump works on the principle that a current carrying conductor placed in the magnetic field, experiences force in the direction decided by Fleming's left hand rule. The Lorentz force 'F' developed is equal to $B \times i \times l$, where B is the flux density, 'i' is the current in the conductor and 'l' is the length of the conductor. In DC conduction pump, current is forced through sodium kept in the pump duct placed in magnetic field. Hence, force is developed in the sodium, thereby moving it. Current which is passed through sodium, is also passed through copper coil wound over electro-magnet, which is used for producing magnetic field in the duct region of the pump. The current path is from one coil to stainless steel duct filled with sodium and back to the other coil. Fig. 1 shows the general schematic of internals of DC conduction pump.

The pump consists of an electromagnet, current carrying coil and stainless steel duct. All the above

*For correspondence (E-mail: bknash@igcar.gov.in)

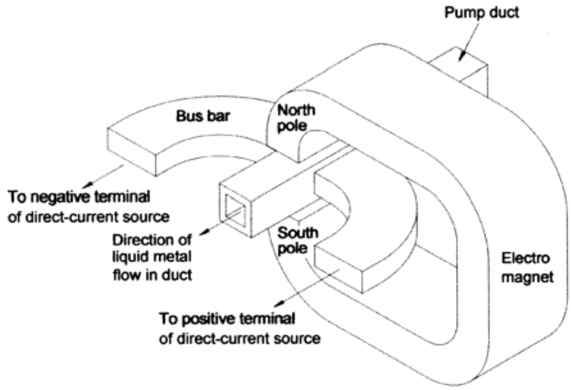

Fig. 1—General schematic of DC conduction pump

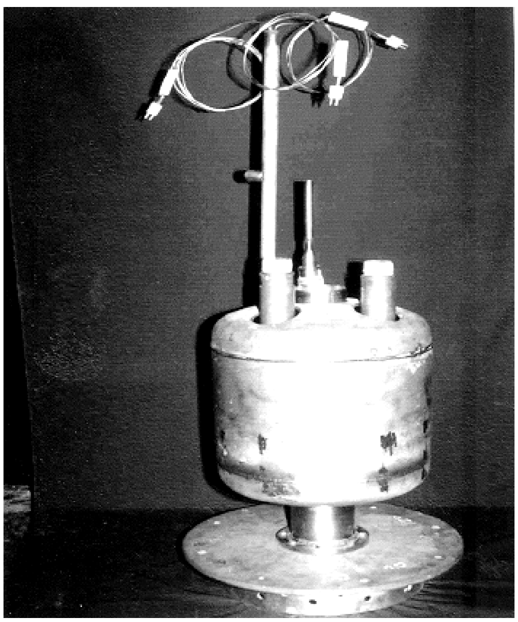

Fig. 2— Photograph of DC conduction pump (with thermocouples and bus bars)

components are housed in a leak tight stainless steel shell. Figure 2 shows the picture of the manufactured DC conduction pump. Stainless steel 316LN is used as principal material for construction because of high temperature requirement. Low carbon magnetic iron as per ASTM A 848 is used for electromagnet. Oxygen free electrolytic copper with 1% silver bearing is used for current carrying parts like bus bar and coil of electromagnet for higher conductivity requirement at operating temperature. The copper coil is joined to stainless steel duct by brazing. Ceramic beads, ceramic spacers and alumina coating are provided as per the requirement for electrical insulation, which can withstand operating high ambient temperature.

Specification of DC conduction pump

Nominal flow rate	0.36 m^3/h (100 cc/s)
Operating temperature	833 K (560ºC)
Head to be developed by the pump at nominal flow and temperature	142245 Pa
Shut-off head	176580 Pa at 2000 A
Operation	Continuous
Mounting position	Vertical
Pump design pressure	490500 Pa at 873 K (internal)
Duct material	Stainless Steel 316 LN
Duct thickness	1.5 mm

Design

The DC conduction pump is designed on the basis of the specified pressure head and flow rate. But the design should take into account the various pressure drops taking into the system. The two main pressure drops taking place in the system are the hydraulic pressure drop and the eddy current braking pressure drop. The hydraulic pressure drop is given by

$$P_2 = \frac{f l v_f^{\,2} \rho}{2D_e} \quad \ldots(1)$$

where f is friction co-efficient given[4] by:

$$f = 0.0055\left(1 + \frac{20000\varepsilon}{D_e} + \frac{10^6}{\mathrm{R_e}}\right)^{1/3} \quad \ldots(2)$$

R_e is the Reynolds number, D_e is the equivalent diameter given by (4 x flow area)/wetted perimeter, l is the length of the duct, ε is roughness factor and ρ is the density of the liquid, v_f is velocity.

The eddy current braking pressure drop is given[5] by

$$P_3 = 2.6 * 10^8 * Q_{spec}^{\;\;1.8}\ \mathrm{N/m^2} \quad \ldots(3)$$

where Q_{spec} is specified flow in m^3/s

Derivation of Equivalent Circuit for DC Conduction Pump

The DC conduction pump has sodium duct as shown in Fig. 3a placed in magnetic field through which current is passed to produce pumping action. The current passed through duct is also sent to coil of electromagnet for producing magnetic field in duct region. Copper bus bars are used to facilitate current entry and exit to the pump. The equivalent resistance offered by various materials in the path of current flow is modeled to obtain equivalent circuit of DC conduction pump[5]. The objective of the model is to obtain required current and voltage for generating specified pressure and flow in the pump. It can be seen that total applied current will be divided in to three part (I_1, I_2, I_3) in duct region. Current I_1 flows through sodium whose equivalent resistance is R_{Na}, current I_2 flows through stainless steel duct side wall whose equivalent resistance is R_{SS}. R_{Na} and R_{SS} are determined from relation (*Resistance= resistivity*length/area*). Length and area are computed from the duct dimensions and resistivity is known for the given material at the given constant temperature. Current I_3 flows through up stream and down stream of sodium. This is the fringing/leakage current and resistance offered to this current is R_L, which is expressed as[5], $\rho_{Na}/k\ D_I$ where ρ_{Na} is resistivity of sodium, k is constant and D_I is height of sodium in duct. Total input current I_4, which is sum of I_1, I_2, I_3 encounters resistance of bus bar, electromagnet coil, sodium duct front wall resistance in series with three parallel resistances R_{Na}, R_{SS}, R_L earlier defined. Pumped sodium moves in magnetic field so back emf is produced in sodium in the duct region. The back emf E_1 generated, opposes the current I_1 so it is put in series with R_{Na} in direction opposite to I_1. E_3 is the total terminal voltage required to force I_4 current which is required to produce specified differential pressure in the pump for pumping the sodium. The following assumptions have been taken in the model.

(i) The variation in temperature due to i^2R losses in sodium and stainless steel duct in pumping region is assumed negligible. This is justified by the fact that sodium being very good thermal conductor, it takes away heat generated due to i^2R losses and thus maintaining constant temperature in various current carrying parts in duct region. The temperature of the duct region is governed by the temperature of sodium in the system.

(ii) Magnetohydrodynamic effect has been neglected[6].

Figure 3 shows the equivalent circuit of DC conduction pump, which is obtained step-wise as per basis mentioned.

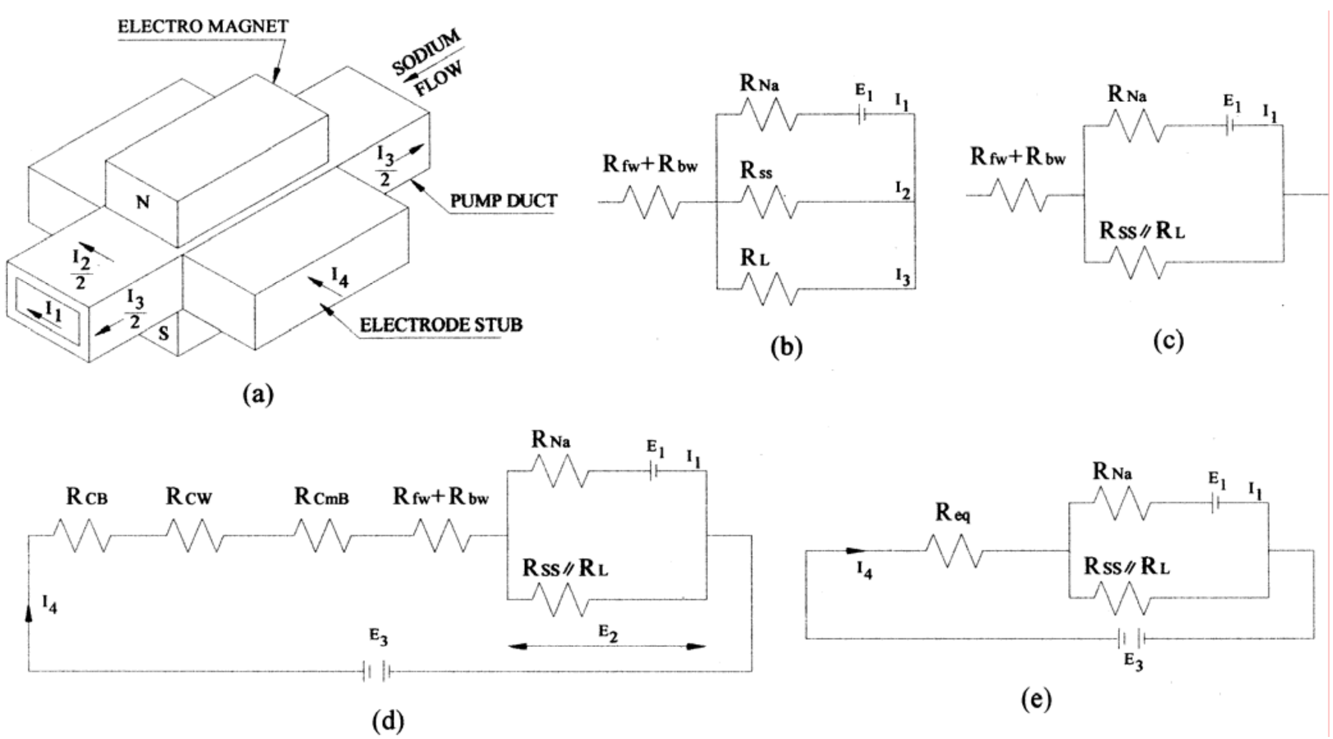

Fig. 3— Equivalent circuit of the DC conduction pump (R_{CB} = resistance of the copper bus bars, R_{CW} = resistance of the copper winding, R_{CmB} = resistance of connecting bars;, R_{fw} = resistance of the front wall, R_{bw} = resistance of the back wall, R_{Na} = resistance of the sodium, R_{SS} = resistance of the stainless steel duct, R_L = resistance of the leakage path, E_1 = back EMF developed in sodium, E_2 = EMF across the duct, E_3 = total EMF across bus bar, I_1 = current required for pumping in sodium, I_2 = current through stainless steel duct, I_3 = current through leakage path, I_4 = Total input current drawn by the pump)

Expressions for air gap flux density, current and efficiency are depicted in Appendix.

Test facility

The pump was tested in an experimental sodium test facility at temperature up to 833 K (560°C). Figure 4 shows the schematic of experimental sodium loop facility. Power supply to DC conduction pump was fed through 2 V, 3000 A DC power supply source (rectifier). Temperature was measured using K-type thermocouple. Flow was measured using permanent magnet type flow meter (having accuracy 7%). Current and voltages were measured with suitable meters. Pressure developed by pump was measured using pressure balance technique with pressure pots at pump inlet (PP1), outlet (PP2) and by measuring differential pressure between the pots. The differential pressure was measured by differential pressure transmitter (having accuracy 1%) digital indicator type in addition to separate dial type Bourdon gauge for pressure pots. In pressure balance technique for measuring pressure developed by pump, sodium level in pressure pot PP1 and pressure pot PP2 are maintained at same level by adjusting argon supply pressure to PP1 and PP2 independently for any pump operating condition. The difference of argon pressure in PP1 and PP2 gives the pressure developed by the pump for that operating condition.

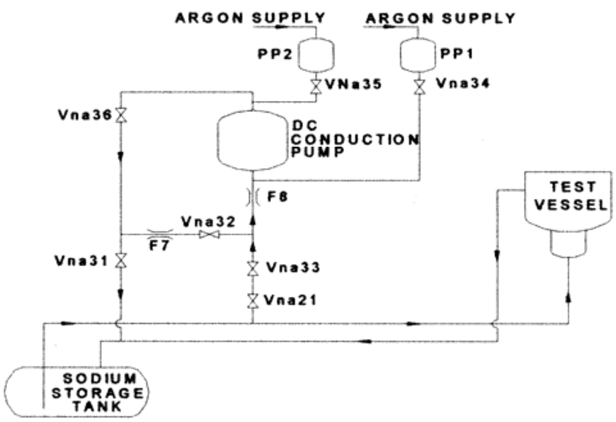

Fig. 4— Experimental sodium loop

Test Results

Hydraulic performance characteristic mentioned below were obtained for sodium temperature ranging from 523 K (250°C) to 833 K (560°C) and at currents from 500 A to 2000 A.

(i) head versus flow
(ii) input power versus flow
(iii) efficiency versus flow

The following tests were also done on pump.

(i) Cavitation testing to establish suction pressure requirement (NPSHR) for cavitation free operation was carried out. The suction pressure in the system in the worst case can go minimum up to 34629 Pa (0.353 kg/cm^2) (abs). Pump was operated for suction pressure of 31588 Pa (0.322 kg/cm^2) (abs), which is lower than worst system suction pressure, without

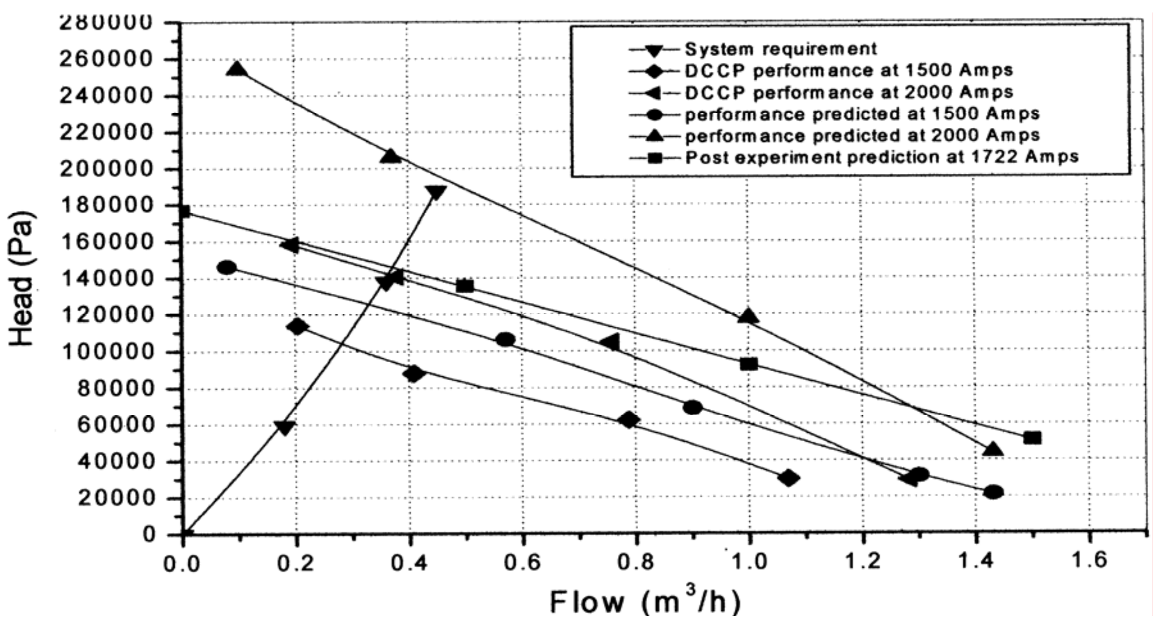

Fig. 5— Head versus flow characteristics at 833 K (560ºC) and system requirements

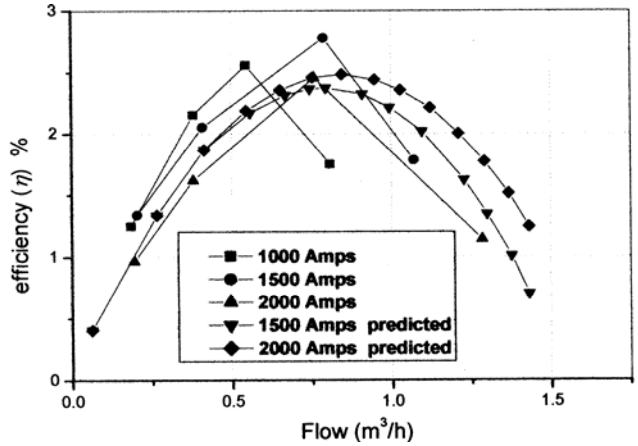

Fig. 6— Efficiency versus flow characteristics at 833 K (560ºC)

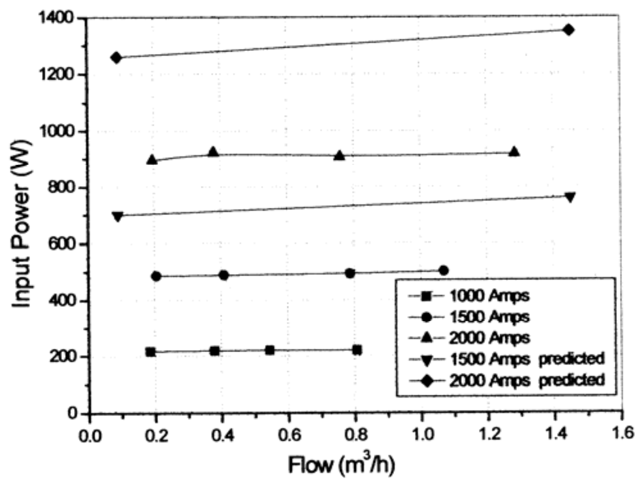

Fig. 7— Input power versus flow characteristics at 833 K (560ºC)

any flow fluctuation or noise, indicating absence of cavitations.

(ii) Endurance test for continuous run at nominal flow/head for 750 h at 833 K (560°C), 2000 A.

Various test results obtained and predicted characteristics are plotted in Figs 5-7. (results of 833 K (560°C) tests only are indicated here).

Observation

Figure 5 shows that the predicted characteristic is above the experimental characteristic for same current. Fig. 6 shows the efficiency versus flow characteristics obtained from prediction as well as experiment which are typical for this type of pump. Fig. 7 shows that the input power increases slightly with increase in flow for fixed input current. This is due to marginal increase in the pump terminal voltage due to redistribution of current through duct wall and through sodium in the duct, maintaining total current unaltered. The difference between calculated and experimental results can be attributed to the following reasons:

(i) While calculating the resistance of bus bars and coils, the temperature has been assumed constant at 573 K (300°C) and 873 K (600°C) respectively, but during the testing the temperature would have been slightly different, causing variation of bus bar and coil resistance. Due to non-availability of temperature measuring device on bus bar and coil, actual temperature is not known.

(ii) In the calculation of the resistance of fringing current path in sodium (R_L), the constant k has been taken[5] as 0.4. However, in experimental set-up its actual value would be different depending on geometry. Post-experimental calculation shows that by taking k as 0.5 and by considering higher iron mmf (50% of the air mmf instead of 30% of air mmf as taken during design calculation), predicted head versus flow characteristic moves closer to experimental characteristic for this pump.

(iii) The experimental value of head at a given flow rate is different from that obtained through calculation. This is attributed to the lower values of flux density in the experimental set-up. The lower values of flux density is due to factors like flux leakage, flux fringing and variation of magnetic properties at high temperatures and deviation in air gap length.

Conclusions

The DC conduction pump was designed based on a simple model. The materials of construction were selected as per required operating conditions. The pump was tested in an existing sodium loop. The performance tests indicate that while there is good match in the trends of different parameter, the predicted values are higher than measured. Post analysis has indicated that factor for current fringing in sodium and flux fringing, which was based on literature value needs to be tuned to match the experimental data. It is established that the performance requirement have been met for desired purpose.

References

1 Kwant W, *et al*., *In sodium testing and performance of a 43.5 m³/min electromagnetic pump for LMR application*, 5th Int Conf Nuclear Engineering, Nice, France, May 25-30, 1997.

2 Araseki Hideo, *et al*., *Nuclear Eng Design*, 227 (2004) 29-50.

3 Trapp J P, *et al*., *Nuclear Sci Eng*, 106 (1990) 88-93.
4 Moody L F, *Mech Eng*, 69 (1947) 1005.
5 Baker Richard S & Tessier Manuel J, *Hand book of electromagnetic pump technology* {Elsevier Science Publishing Co.Inc, New York), 1987.
6 Hughes M, *et al*., *Appl Math Model*, 19 (1995).
7 Roters H C, *Electromagnetic Devices*, {John Wiley and Sons, Inc, New York), 1970.

Appendix

Expressions for air gap flux density, current and efficiency

Let E_1 be the back EMF induced, B be the flux density between the two pole faces, I_1 be the current required to develop pressure P_4 in the liquid sodium, Q_{spec} is flow and D_1 is duct height and D_2 is the duct width. The pressure in the duct can be obtained by dividing the force produced ($F=Bil$) by the area of the flow ($D_1 \times D_2$). Thus the expression for pressure can be obtained by:

$$\text{Pressure } (P_4) = \frac{\text{Force}}{\text{Area}} = \frac{Bil}{D_1 D_2}$$

l , length of the conductor = D_2, and $i = I_1$, current in sodium

$$\text{Thus,} \quad P_4 = \frac{BI_1 D_2}{D_1 D_2}$$

$$\text{Therefore, } I_1 = \frac{D_1 P_4}{B}$$

The back emf in sodium can be obtained from the relation $e = Blv$:

$$\text{velocity of sodium, } v = \frac{\text{Flow}}{\text{Area}} = \frac{Qspec}{D_1 D_2}, \text{ length } (l) = D_2$$

$$e = Blv = BD_2 \frac{Qspec}{D_1 D_2}$$

$$\text{Thus, Back emf in sodium, } E_1 = \frac{BQspec}{D_1}$$

E_2 is the voltage across the duct which is summation of Back emf E_1 and IR drop in sodium. Thus, $E_2 = I_1 R_{Na} + E_1$.

I_2, the current in the stainless steel duct can be expressed from Ohm's law as $I_2 = \frac{E_2}{R_{ss}}$

I_3, the leakage current can be expressed from Ohm's law as

$$I_3 = \frac{E_2}{R_L}.$$

From Kirchoff's current Law we have total current I_4 (Refer Fig. 3 for current expression)

$$I_4 = I_1 + I_2 + I_3$$

On substituting above-mentioned various parameter I_4 is expressed as given below

$$I_4 = \frac{P_4 D_1}{B_1}\left(1 + \frac{R_{Na}}{R_{ss}} + \frac{R_{Na}}{R_L}\right) + \left(\frac{BQ_{spec}}{D_1}\right)\left(\frac{1}{R_{SS}} + \frac{1}{R_L}\right) \quad \dots (4)$$

The magnetic field intensity in the duct is given by $H = \frac{B}{\mu_0}$

The mmf required to produce the required magnetic field intensity=Bd_6/μ_0

where d_6 is the length of the air gap between magnet poles where sodium duct is placed.
Assuming that iron mmf required is 30% of the air mmf, the total mmf to be produced by the coil is 1.3Air mmf. Therefore, the mmf to be produced by the coil=$1.3Bd_6/\mu_0$. Thus,

The mmf to be produced by the electromagnet coil NI_4 is

$$NI_4 = \frac{1.3Bd_6}{\mu_0} \quad \dots (5)$$

N (number of turn) is 3.5 in the manufactured pump.

Solving the Eqs (4) and (5), the operating value of flux density and the current can be obtained and subsequently, efficiency and other parameters can be evaluated.

To ascertain that the pole faces are not attaining magnetic saturation, flux and flux density values are checked using following equation[7].

$\Phi = F \times P$,

where F is MMF, P is permeance = $\mu_0 \frac{S}{l}$, where S = area, l = length of magnetic circuit

Flux density B = flux/area

The efficiency of pump is defined as ratio of mechanical pumping power developed to the total input electrical power supplied to the pump terminal.

$$\text{Efficiency of pump } \eta = \frac{\text{pumping power}}{\text{electrical in put power}} = \frac{Q_{spec} P_4}{E_3 I_4}$$