Comparison of COMSOL® Simulation of Annular Linear Induction Pump with Mesh / Matrix and Equivalent Circuit Based Methods

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Abstract

This paper deals with numerical simulation of Annular Linear Induction Pump (ALIP) using Finite Element Method based software COMSOL®. ALIP is used for pumping of liquid sodium in various experimental facilities and in auxiliary circuits of fast reactors. Usually, the performance of ALIP is evaluated using equivalent circuit based approach. With advent of multi-physics based softwares like COMSOL®, attempts have been made to model ALIP employing such software. This paper presents the results of this modeling of ALIP in COMSOL®. The model developed is a 2-dimensional axisymmetric model. The problem is solved in the time-harmonic domain where the currents and associated fields are assumed to be varying sinusoidally with time. Comparison of the results is made with conventional equivalent circuit method based calculations and also with results of mesh/matrix based code reported in literature.

1. Introduction

This paper deals with the numerical simulation of Annular Linear Induction Pump (ALIP) using Finite Element Method based software COMSOL®. ALIP is used for pumping of liquid sodium in various experimental facilities and in auxiliary circuits of fast reactors. Usually, the performance of ALIP is evaluated using equivalent circuit based approach [1]. With advent of multi-physics based softwares like COMSOL®, modeling of ALIP is carried out employing such software. This paper presents the results of the modeling of ALIP in COMSOL®. Comparison is also made with results of mesh/matrix method reported in literature [2].

2. Electrical Equivalent circuit based approach

Normally for design and performance evaluation of ALIP an equivalent circuit based approach is followed [1]. This approach is based on lumped parameter model and is quite good at design stage. This approach is also based on many assumptions some of which are :

a. It assumes a closed magnetic circuit i.e. the flux leakage at the ends is neglected.
b. The velocity of liquid metal is assumed constant in the duct i.e. the velocity profile of liquid metal flow is not considered. Liquid metal is considered as a solid body.
c. End effect due to entry of conducting liquid metal in magnetic field is taken care by introduction of an empirical co-efficient in formula for pressure calculation.
d. The variation of magnetic field with depth inside liquid metal i.e. skin effect is neglected.
e. The equivalent circuit model is a per phase model based on assumption of balanced voltages and balanced currents in all the three phases.

In the simulation model some of the limitations of equivalent circuit have been overcome. These are :

a. Magnetic circuit is modeled with discontinuity.
b. End effects also modeled so phase unbalance current can also be evaluated.
c. Skin depth effect is considered.
d. Liquid metal is treated as a liquid and effect of velocity profile is modeled.

e. Hydraulic losses are considered but since all the features are not modeled in the 2-D model, they may be different from actual.

3. Assumptions in simulation model

The simulation model is based on the following assumptions :

a. Symmetry along the pump axis is assumed, though the lamination stacks are not symmetrical with respect to the central axis. But the flux coming out of these lamination stacks enter the annular region in axisymmetric mode.
b. Permeability of the laminations has been assumed constant. Therefore hysteresis losses have been neglected.
c. Electrical conductivity of laminations stacks has been taken as 1 so that the losses in the laminations are not taken into account in simulation.

4. Aspects not covered in simulation model

The following aspects of actual pump are not covered in this 2-D, time harmonic model:

a. Stacked nature of laminations is not modeled, rather as explained above 2-D axis symmetry of the laminations is assumed.
b. The model simulates electrical phenomenon in time harmonic mode and fluid flow in steady state so called "stationary mode", therefore the transient phenomena are not covered.
c. In actual ALIP the inner duct is supported by means of non-magnetic stainless steel supports at regular intervals along the length of the pump. These supports have not been modeled in simulation model and therefore the hydraulic losses may be somewhat lower than actual.
d. Temperature variation in different parts of the pump like conductor, lamination and duct are not modeled. The electrical conductivity for winding and duct is calculated assuming a uniform specified temperature.

5. Applicable equations

The simulation of ALIP has been done in time harmonic domain and coupled with steady state hydrodynamic Navier Stokes equations [2,3]. Following are the applicable equations.

$$\nabla \times H = J \quad \text{… (1)}$$

$$\nabla \times E = -\frac{\partial B}{\partial t} = -j\omega B \quad \text{… (2)}$$

$$J = \sigma(E + V \times B) \quad \text{… (3)}$$

$$\nabla . B = 0 \quad \text{… (4)}$$

$$f_{EM} = J \times B \quad \text{… (5)}$$

Navier Stokes equation for steady state flow is given by

$$\rho\,(V\nabla)\;V = -\nabla p + \eta\,\nabla\,V + f_{EM} \quad \text{… (6)}$$

For incompressible steady state flow, the mass conservation equation becomes

$$\nabla .(\rho\;V) = 0 \quad \text{… (7)}$$

The coupling between electromagnetic field and the fluid flow is simulated by adding the volume electromagnetic force f_{EM} to the force term of the Navier Stokes equation. The effect of velocity on the magnetic field is incorporated by adding the term $V \times B$ to the ohms' law $J = \sigma E$.

6. COMSOL® simulation

The simulation of ALIP has been done in the following three stages in COMSOL [4].

a. First Navier Stokes equations are solved for flow and the velocity profile is obtained for the specified flow.
b. Electromagnetic force is computed for the velocity obtained in *a*.

c. Flow equations are once again solved for the electromagnetic force obtained in *b* and the pressure developed is computed.

6.1 Boundary Conditions

6.1.1 EM Boundary Conditions

For electromagnetic boundary conditions the central axis is assigned axisymmetric boundary condition where as the outer boundaries are assigned magnetic insulation boundary condition which makes the magnetic field tangential to the outer boundary or in other words the magnetic field does not cross the outer boundary. The outer boundary is a rectangular box whose edges are 250 mm away from the pump outer boundary. Since the simulation is in low frequency range (<1000Hz) this distance was found to be acceptable.

COMSOL® feature of multi-turn domain was used to model the coils with specified number of turns. The conductivity of the conductor material (i.e. copper) was set as per coil temperature. Voltage was given as input to the coil. All the 3-phase coils were excited by the same voltage but displaced in phase by 120°electrical.

6.1.2 Fluid flow Boundary Conditions

The central axis was assigned axisymmetry boundary condition. The fluid flow has been solved using the k-ε turbulence model. The inlet was assigned a pressure of zero pascals and the outlet boundary was assigned the velocity corresponding to the desired flow rate.

6.2 Coupling Between Electromagnetic And Fluid Models

The electromagnetic force produced in the liquid metal is coupled to the fluid flow by adding the electromagnetic force to the Navier-Stokes equation as a volume force. Then the resultant pressure obtained from solving Navier Stokes equation yields the pressure developed by the pump. The hydraulic losses are already accounted in the Navier Stokes equation.

In COMSOL® simulation, first flow is simulated without the electromagnetic field and the velocity profile in the annular duct region is obtained. Thereafter, the electromagnetic force corresponding to the obtained velocity is computed. In the third stage, Navier-Stokes equation is solved once again and the pressure developed by the pump is obtained. Thus, the effect of velocity profile and end effects due to motion of conducting liquid metal in magnetic field are accounted in the simulation model.

6.3 Details of simulation model

In literature, simulation or predicted characteristics of many ALIPs are reported but very few documents provide all the geometrical and technical details of the ALIP. Unless all the design details of ALIP are provided, comparison of models cannot be made.

One of the documents which provide most of the relevant data is the work reported by G. B. Kliman [2] wherein, analysis of an ALIP has been done using mesh/matrix method [2]. Therefore, simulation of ALIP as per the data given in [2] is carried out and the results of COMSOL® simulation compared with the results given in [2] and also with electrical equivalent circuit based calculations.

6.4 Data of ALIP

The reported ALIP is a reflux type of ALIP with centre return configuration. The pump winding is water cooled and has jacket on laminations. These cooling arrangements have not been modeled in the COMSOL® model. The data of this ALIP is given in Table 1 [2].

Table 1: Rated Parameters of ALIP [2]

Flow	3294 m^3/h
Developed Pressure	12.62 x 10^5 Pa
Fluid Temperature	459 °C
Line Voltage	3236 V, rms
Phase Current	435 A, rms
Synchronous Velocity	19.45 m/s
Gap for Sodium Flow	32.3 mm

Though, detailed drawing of the pump is not available in the reference document [2], from the description provided, it seems that the centre duct is tapered and has more area at ends than at its centre. Since all the geometrical details of this tapering of central duct are not provided, it has not been modeled in the COMSOL® model, rather a duct of uniform dimensions has been modeled. Tapered duct leads to some reduction in flux density and hence reduction in developed pressure at the ends but improves the overall flux profile.

6.5 Geometry model

A 1:1 scale modeling of reflux ALIP with the parameters as given in Table 1 was carried out in COMSOL®. Figure 1 shows the 2-D axisymmetric picture of the geometry. The inlet of sodium is from the bottom right and it enters the annular channel where the winding arrangement pumps sodium upwards. At the upper end, sodium takes a turn and returns along the centre line i.e. r = 0 axis. Since the finer details of the pump geometry like converging and diverging ends is not provided in [2], the dimensions of these ends have been taken approximately. In order to define the finite domain in which electromagnetic equations need to be solved, an outer domain has also been defined.

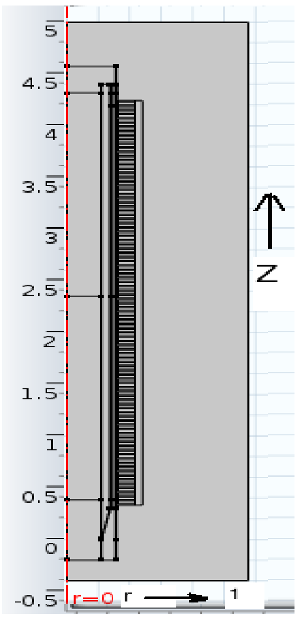

Figure 1: Geometry of ALIP as modeled in COMSOL®

7. Simulation Results & Discussion

The simulation was carried at a sodium temperature of 459 °C which is temperature given in ref [2]. The differential pressure variation along the length of the pump at centre of annular duct is shown in Fig. 2.

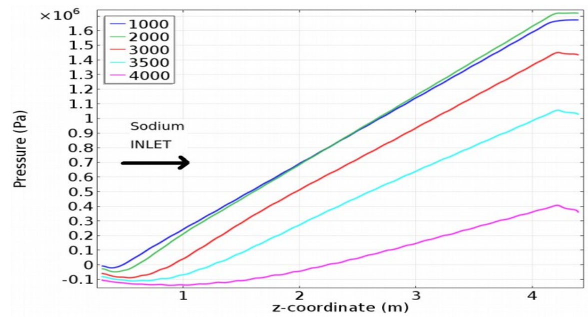

Figure 2. Variation of developed pressure along length of pump at annular duct centre at various flow rates (m^3/h)

From figure 2, it can be observed that the pressure increases linearly with length of the pump. Initially the developed pressure increases with flow and thereafter, it starts decreasing with flow. As discussed earlier, the volume force is the product of J_{in} *X* B (Eqn. No. 5). B increases with flow where as J_{in} decreases with flow. So up to a certain flow the volume force and hence pressure increases and then it starts decreasing. Moreover, hydraulic losses also increase with flow rate and contribute to pressure reduction.

7.1 Pump Characteristics

The pressure vs flow characteristics of the ALIP as obtained from COMSOL® model is plotted in figure 3 and is compared with pressure obtained from electrical equivalent circuit approach [1] and those reported by Kliman [2] .

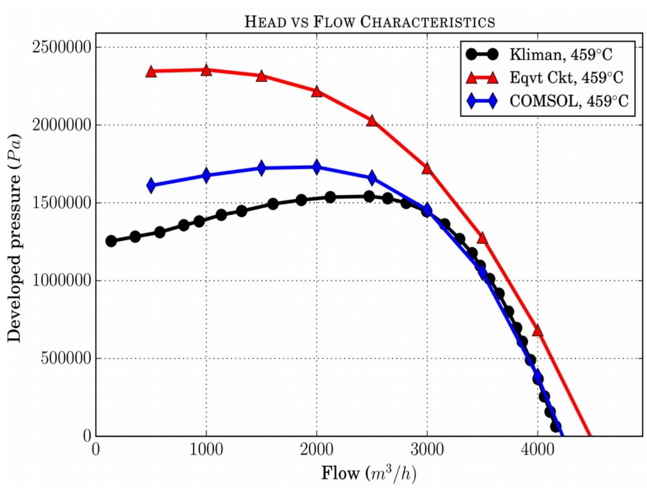

Figure 3. Comparison of Pressure Vs Flow characteristics of ALIP

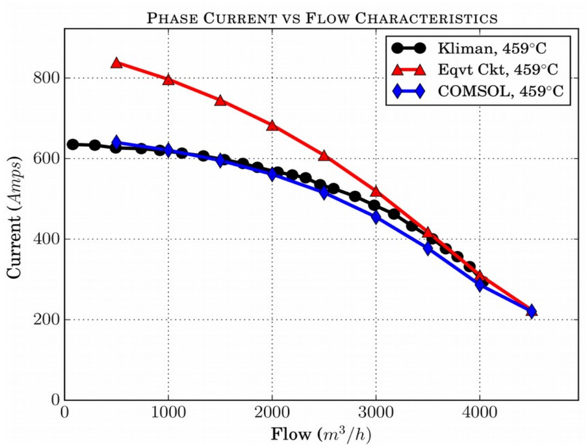

Figure 4. Phase Current comparison

The phase current obtained from COMSOL® and its comparison with the curve reported in [2] and with equivalent circuit approach is shown in figure 4.

The plot of efficiency vs flow along with its comparison with the curve given in [2] and with equivalent circuit approach [1] is depicted in figure 5.

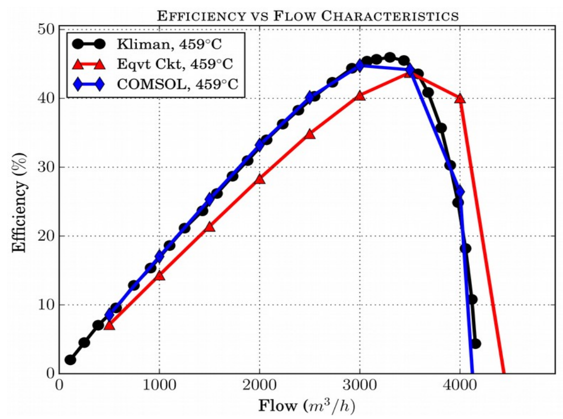

Figure 5. Efficiency Vs Flow characteristics comparison

From figures 3-5, it can be observed that the COMSOL® simulation results are in good agreement with the results reported in [2]. The head vs flow characteristics (figure 3) is like that of an induction motor. The pressure predicted by following equivalent circuit based approach [1] is much larger than that predicted by other two approaches. This may be because at large gap for sodium flow, the effect of skin depth as well as end effects become prominent which are not sufficiently accounted for in equivalent circuit model. The predictions of COMSOL® and Mesh/Matrix method meet almost exactly in the negative slope region of the P-Q curve (figure 3) which is the operating range of the pump where as in the positive slope region of P-Q curve some deviation is observed. Thus, for large air-gap designs, the pump performance should be evaluated by means of models which take these effects in to account.

8. Conclusions

This paper presented the modeling of ALIP using the FEM based software COMSOL. The various assumptions of modeling were discussed. Comparison was made with mesh matrix method results and also with equivalent circuit based calculations. Good agreement with results reported in literature is observed.

References

1. Handbook of Electromagnetic Pump Technology, Richard S. Baker, Manuel J. Tessier, Elsevier Publications, 1987.

2. Kliman, Gerald B. (1979) ‘Large Electromagnetic Pumps’, Electric machines and Electromechanics, 3, 129-142, 1979.

3. L. Goldsteins, L. Buligins, Y. Fautrelle, C. Biscarrat, S.Vitry, Numerical Quasi Stationary and Transient Analysis of Annular Linear Electromagnetic Induction Pump, Proceedings of COMSOL 2013 Rotterdam conference.

4. COMSOL® 5.3a , Reference Manual