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MHD interaction in an Electromagnetic Pump for high flow rate loop of ASTRID Sodium Fast Reactor secondary circuit - performances

S. Letout¹, Y. Duterrail¹, Y. Fautrelle¹, M. Medina¹, F. Rey² and G. Laffont²

¹Grenoble Institute of Technology/CNRS, SIMAP-EPM laboratory, 38402 Saint Martin d'Hères, France

²Commissariat à l'Énergie Atomique et aux Énergies Alternatives, 13108 Saint Paul Lez Durance, France

Corresponding author: frederic.rey@cea.fr

Abstract

The present paper deals with the analysis of the performances of a very large Annular Linear Induction Pumps (ALIP) for liquid sodium. This pump is able to provide high flow rates (more than $7,000 \text{ m}^3 \cdot \text{h}^{-1}$ with a pressure discharge of about 3.7 bar). Dimensions of pumping channel under the active part are of an average diameter of 966 mm and a length of 4,500 mm. It's a double sided inductor pump. On the base of an imposed 2D axisymmetric geometry, performances (discharge pressure vs. deliver flowrate) are calculated by means of two methods for the point of optimal frequency of the supply currents. In a first approach, Maxwell equations are solved taking into account a rigid body velocity field for the fluid. These calculations give the opportunity to determine the most suitable operating frequency of the supply currents and their average intensity. In a second approach the full magnetohydrodynamic interaction is computed (using $k\text{-}\epsilon$ turbulent law with enhanced wall functions). A comparison is done between the results obtain from the two hypotheses: rigid body velocity field vs. computed turbulent flow field. This set out that rigid body velocity field lowered the pressure discharge.

Key words : electromagnetism, magnetohydrodynamic, EMP, Electromagnetic induction pump, ALIP, annular pump

Introduction

The use of electromagnetic induction pumps (EMP) is widespread in metallurgy. EMP may be found mainly in various liquid light metal processing, for example aluminium, magnesium or sodium. There are mainly two different types of EMP, namely the FLIP (Flat Linear Induction pump) and the ALIP (Annular Linear Induction pump). Many works have been performed so far on such pumps [1-4].

There is a recent interest on the development of large-size ALIP, since CEA is now engaged in the development of the pilot plant ASTRID. ASTRID is the acronym for "Advanced Sodium Technological Reactor for Industrial Demonstration". ASTRID is a prototype of Sodium Cooled Fast Breeder Reactor, generating electricity, sufficiently powerful to be considered as industrial demonstrator. It must fill the criteria of the 4th generation. Because of the maturity of the knowledge in the technology of the RNR-Na, the prototype ASTRID is registered like preceding a head of series before the commercial deployment. This electrical plant will have a significant power of about 600 MWelec (1,500 MWth).

One point of study and discussion is the possibility to use EMP as circulating pump for the sodium contained in the secondary circuit in replacement of classical mechanical pumps. To ensure a sufficient heat transfer through the secondary circuit, one needs to push the sodium with a flow of about $2 \text{ m}^3 \cdot \text{s}^{-1}$ and a head of about 3 to 4 bar. ALIP have been identified as one of the most promising technology for such application.

The major points to be studied in order to make a choice between ALIP and mechanical pumps are related to questions of stability of flow and to the ability of the pump to work at high temperature with a high reliability (nominal working temperature of about 400°C with the possibility to rise up to 600°C during some accidental transients). CEA is regarding technologies to make ALIP able to pump high temperature sodium. CEA owns numerical codes and analytical tools usable for the design of pump running far from any area of instability. Up to now, the MHD design consists in the use of analytical codes and finite element softwares in order to predict the performances of ALIP by the mean of a harmonic resolution of the Maxwell's electromagnetic equations in the frequency domain. It was acted that these tools are not sufficient to predict instabilities. So, CEA and GIT/SIMAP have undertaken studies with the objective to be able to design high flow rate ALIP for sodium reactors taking into account the aspect of fluid stability. These studies are founded on numerical simulations associated with experimental validations on a specific bench. This bench is under design and will contain and ALIP EMP that will be pushed to work into instable working range.

The present paper studies specific pumping characteristics of the ALIP with travelling field for liquid metals taking into account the full magnetohydrodynamic interaction between the electromagnetic field and the liquid metal flow inside pump channel. Attention is focused on pumps (the so-called ASTRID pump) which are able to provide high flow rates, typically pressure difference of $\Delta p_m = 3.7$ bar and flow rate around $Q = 7,000 \text{ m}^3 \cdot \text{h}^{-1}$. The specifications of the pump are: mean diameter 966 mm, magnetic gap thickness 66 mm, active length 4.5 m, pole pitch 0.318 m,

Determination of the optimal currents frequency

In a first approach, on the base of an existing geometry we look for the optimal operating point (discharge pressure of about 3.7 bar for a flowrate of $7,000 \text{ m}^3 \cdot \text{h}^{-1}$), i.e. the optimal frequency of supply currents for the target flow rate. For that, a 2D axisymmetric model is build taking into account geometry of yoke, generic magnetic properties of materials and property of sodium.

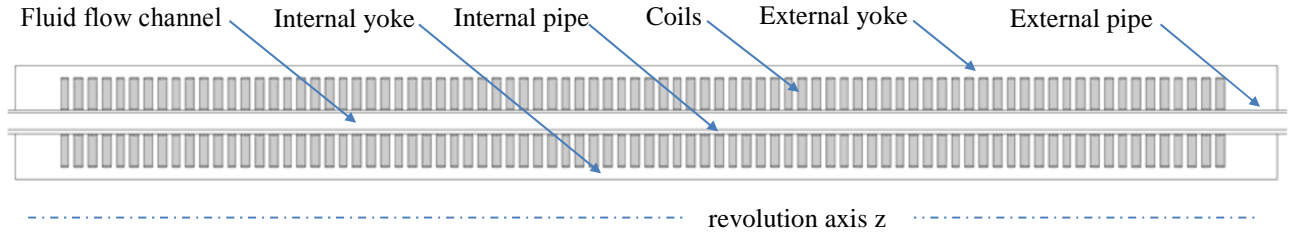


Fig. 1: Reference geometry of the EMP for this study

The model solves Maxwell's equations in the entire geometry, including a finite (but verified as sufficient) surrounding space of air, required to let the magnetic field propagate outside of magnetic ferrous part in complement the field inside the magnetic gap of the pump. Equations involve in this study are the following:

$$\text{Maxwell Faraday's law} \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (1)$$

$$\text{Maxwell Ampere's law} \quad \nabla \times \frac{\mathbf{B}}{\mu} = \mathbf{J} \quad (2)$$

$$\text{Magnetic line closure} \quad \nabla \cdot \mathbf{B} = 0 \quad (3)$$

$$\text{Constitutive relations:} \quad \mathbf{B} = \mu \mathbf{H} \quad (4)$$

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \quad (5)$$

where :

\mathbf{E} : electrical field intensity [$\text{V} \cdot \text{m}^{-1}$]

\mathbf{B} : magnetic flux density [T]

\mathbf{J} : current density [$\text{A} \cdot \text{m}^{-2}$]

\mathbf{u} : velocity of fluid [$\text{m} \cdot \text{s}^{-1}$]

ρ : electric charge density [$\text{C} \cdot \text{m}^{-3}$]

μ : magnetic permeability [$\text{H} \cdot \text{m}^{-1}$]

σ : electrical conductivity [$\text{S} \cdot \text{m}^{-1}$]

Supply electric currents are sinusoidal shaped waves. Computations are performed in the time harmonic space, by the use of a vector potential formulation.

In the present first approach velocity \vec{u} of sodium is imposed within the approximation of bloc pumping flow. That is to say, velocity field of flow is not computed but imposed in the model as a constant value everywhere in the fluid domain. The velocity is has the following form $\vec{u}(0,0,w)$ in the cylindrical coordinate system (r, θ, z) . The longitudinal \vec{z} axis is the revolution axis of the model and the axis bearing the single velocity component w which is the constant velocity applied on the entire volume of pump fluid. The pump is supplied by a three phase alternating current. It is applied into the model as imposed current densities in area of homogeneous equivalent coil windings.

Several criteria can be taken into account to define an optimal frequency. Here, the working point should be located in the ideal working zone shown in Fig. 2. Taking into account the velocity of the travelling magnetic field due to the pump design, the working point can be only achieved with frequency over 14 Hz (see Fig. 3).

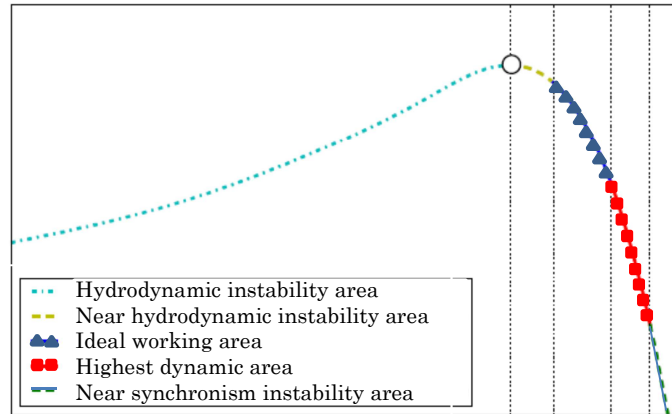


Fig. 2: generic characteristic of electromagnetic pump

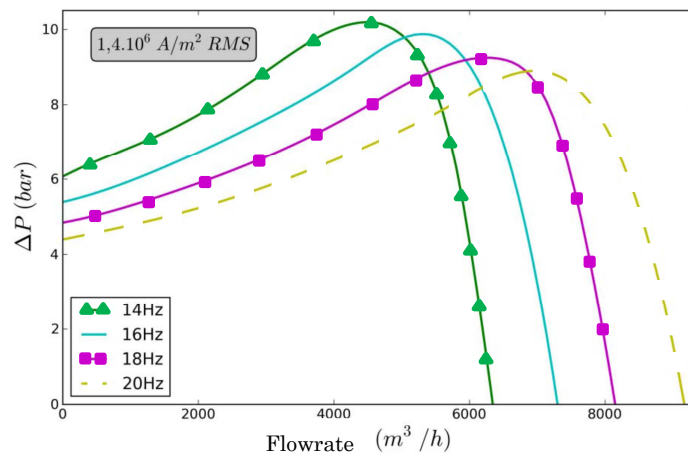


Fig. 3: Characteristic performance map of ASTRID EMP

Finally, the working point can be achieved with a frequency between 16.4Hz to 18.4Hz associated with respectively a supply current density from 1.4 down to 0.9MA.m².

Coupling between electromagnetism and real flow computation

In order to precise the acquired previous results, we deal in this section with a more realistic physical model. It couples electromagnetism and fluid flow computations with a strong-coupling schematic. Full Maxwell equations are solved in the time harmonic domain. The back reaction of the velocity field is taken into account. As for the turbulent fluid flow, Navier-Stokes equations are solved in time stationary domain. Turbulence is accounted via a $k-\epsilon$ model associated with enhanced wall functions. These computations are performed through the use of two commercial software (COMSOL Multiphysics for electromagnetism and ANSYS FLUENT for fluid flow computation) associated with a dedicated proprietary supervisor software. Exchanges of data between the two softwares are ruled by the importance of feedback between electromagnetic forces and fluid flow.

Results show comparable flow and electromagnetic fields in both cases, as shown in Fig. 4. Nevertheless, bloc pumping underestimates the discharge pressure at the outlet of the pump. Indeed, computations involving real flow show a better arrangement of the electromagnetic force density inside the flow, improving overall performances although Hartmann friction effect.

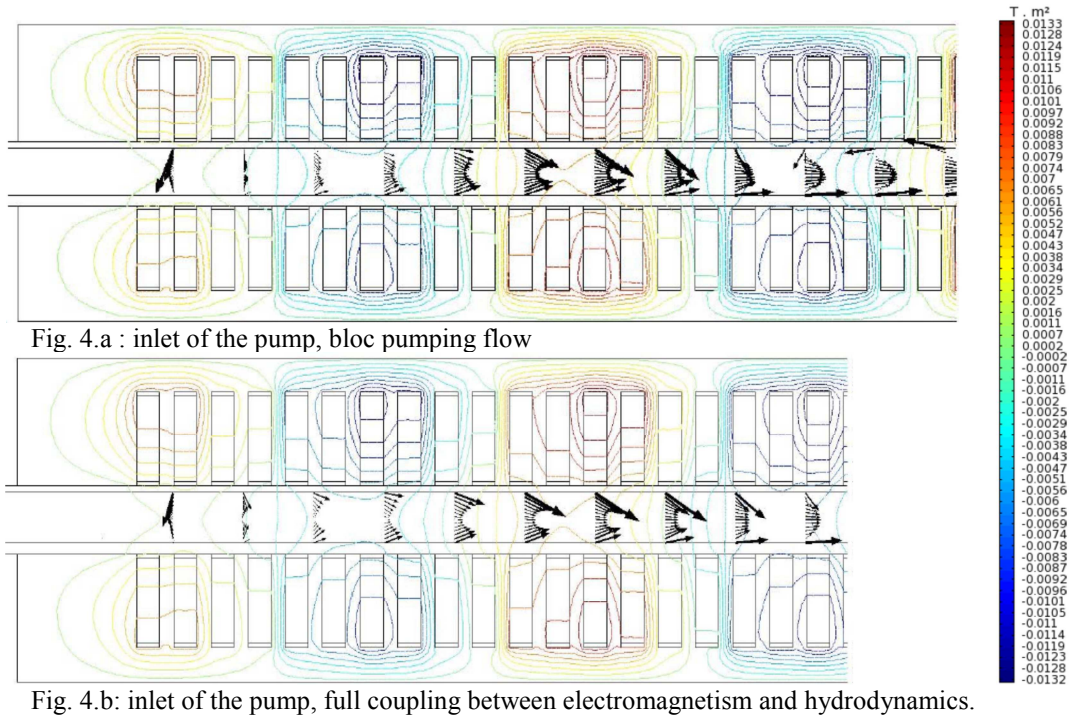


Fig. 4: Comparison between the two cases: bloc pumping and full coupling; magnetic field lines and average electromagnetic force density

Conclusions

We have analysed the performances of a large size electromagnetic pump, the so-called ASTRID pump. First was determinate the optimal frequency for supply currents by the use of uncouple computation between electromagnetism and fluid flow. Then, needed current density was found to reach the wished operating point. In a second time, a strong coupling computation was done between electromagnetism and fluid flow. It has showed that bloc pumping hypothesis lowered the overall performances of the pump in comparison to real flow computation.

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