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# MHD interaction in an Electromagnetic Pump for high flow rate loop of ASTRID Sodium Fast Reactor secondary circuit, behavior

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## Abstract

The present paper deals with the analysis of the behaviour 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 m<sup>3</sup>/h 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. The global and local stability of the pump are analyzed. It is found that in the nominal conditions, stable operation may be obtained. The start-up of the pump is also investigated. The coil current switch-on must be carefully analyzed in order to avoid large over-pressure occurring during the transient.

**Keywords:** electromagnetic pumps, magnetohydrodynamics, full coupling, transient behavior

## Introduction

The main text of the paper starts with the 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]. I.

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 electromagnetic pumps (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 m<sup>3</sup>.s<sup>-1</sup> and a head of about 3 to 4 bar. Annular Linear Induction Pumps (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 EMP 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). LCIT 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 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 an ALIP EMP that will be pushed to work into instable working range.

The present paper studies specific pumping characteristics of the Annular Linear Induction Pumps (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  $Q = 7,000$  m<sup>3</sup>.h<sup>-1</sup>. 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, supply frequency  $f = 18.3$  Hz. In such induction pumps the effect of magnetic convection over the magnetic diffusion is very important. Various types of possible instabilities or transients are dealt with.

### Global stability of the pump

In a first approach, which can be called “OD global stability study”, this work aims to study the behaviour of this EMP in terms of stability analysis taking into account the external characteristic of the circuit. In the present part, the pump characteristic curve is computed by means of a coupling between two softwares COMSOL and FLUENT in steady conditions and axisymmetric conditions. The external hydraulic characteristic curve is of parabolic type with a friction coefficient  $k$ . The time evolution of the flow rate  $Q$  or the mean velocity  $U$  is governed by

$$\rho \frac{V}{S} \frac{dU}{dt} = \Delta p_m(U) - k \frac{1}{2} \rho U^2, \quad (1)$$

$\Delta p_m(Q)$  being the pressure delivered by the pump,

$V = 4.57 \text{ m}^3$  = total volume of sodium in the whole circuit,

$S = 0.200 \text{ m}^2$  = average area of the duct cross-section,

$k$  = effective (turbulent) friction coefficient in the whole circuit.

The stability analysis of Eq. (1) shows that the global stability of the whole circuit depends on the sign of the difference

$$\tau_1 = \left[ \frac{1}{\rho L} \frac{\partial(\Delta p_m)}{\partial U} - k \frac{U}{L} \right]^{-1}, \text{ with } L = V/S. \quad (2)$$

The difference  $\tau_1$  is an effective characteristic time related to the evolution of any perturbation of the mean flow velocity in the hydraulic circuit. It put forth two characteristic times linked to turbulent friction and electromagnetic forces. Each time scales are represented in Fig. 1. The velocity corresponding to the maximum of the computed pump characteristic curve (not shown here) is equal to  $U \approx 9 \text{ m.s}^{-1}$ . Beyond that maximum  $\frac{1}{\rho L} \frac{\partial(\Delta p_m)}{\partial U}$  is negative, as shown in Fig. 1. This means that the descending branch of the pump characteristic is always negative as expected. However, the stability is also linked to the value of the friction coefficient  $k$ . In the present case the term  $k \frac{U}{L}$  is always greater than  $\frac{1}{\rho L} \frac{\partial(\Delta p_m)}{\partial U}$  except when  $U < 2.5 \text{ m/s}$ . The overall circuit is stable in the operating conditions near the maximum of the pump characteristic.

### Three-dimensional instability

It is usual to determine the pump characteristic as a function of the slip magnetic Reynolds number  $\varepsilon \equiv \mu_0 \sigma \omega G / k^2$ , with  $\mu_0$ ,  $\sigma$ ,  $\omega$ ,  $G$  and  $k$  respectively denoting the magnetic permeability, the electrical conductivity, the pulsation, the slip and the coil wavenumber. The slip  $G$  is defined as  $(1 - kU / \omega)$ . The corresponding pump characteristic curve is shown in Fig. 2.

The intrinsic instability arises when the slip magnetic Reynolds number  $\varepsilon \equiv R_{mG} = \mu_0 \sigma \omega G / k^2$  is greater than the value of  $\varepsilon$  corresponding to the pump characteristic maximum (cf. [5]). In the present case the characteristic curve maximum corresponds to  $\varepsilon = 1.713$  as shown in Fig. 2. It is clear that regarding the nominal operating conditions the mean velocity in the pump must be larger than 9 m/s.

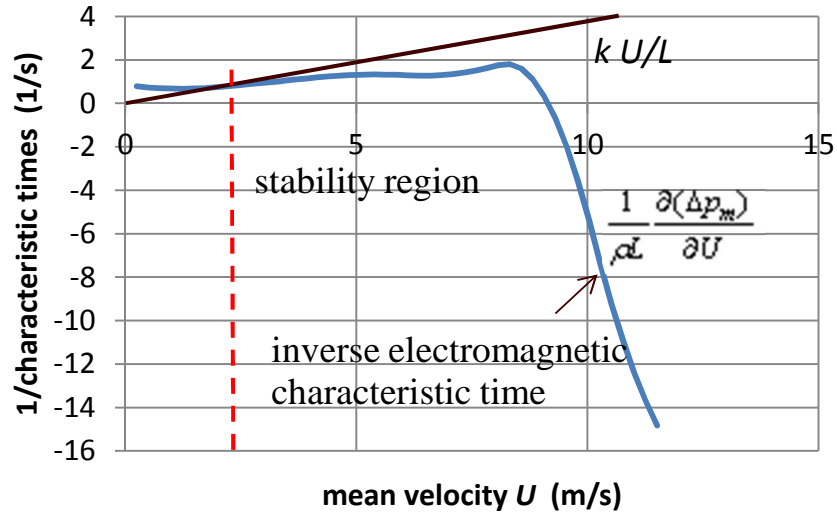


Fig 1 : inverse characteristic times (electromagnetic and friction) versus the mean velocity for the ASTRID pump.

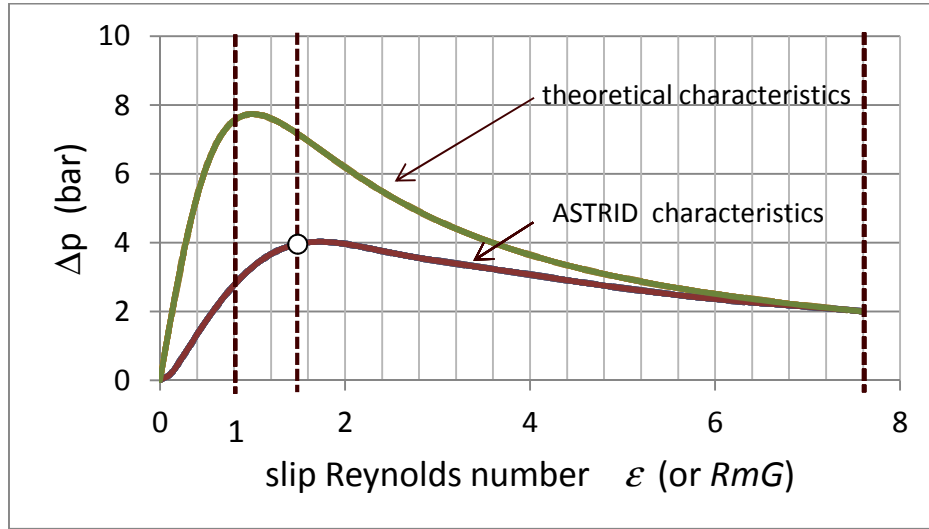


Fig. 2 : ASTRID pump characteristic curve as a function of the slip magnetic Reynolds number.

The theoretical curve corresponds to the characteristic of an infinite ALIP.

### Transient behaviour – start-up of the pump

In the present section we deal with the transient issues and especially the pump start-up. The latter aspect is important in the case of large pump. We now compute the establishment of the magnetic field using the time evolution option in COMSOL. The mean velocity inside the pump  $U(t)$  is time-dependent. The mean flow field inside the pump is governed by a differential equation similar to (1). However, in the present case the pump pressure difference  $\Delta p_m(U(t), t)$  is also time-dependent, and the full nonlinear equation is solved by a Runge-Kutta method simultaneously with the magnetic field. Figs. 3 and 4 show some examples of transient behaviours when the pump is starting. Fig. 3 shows the results when the inductor current is switched on instantaneously. The steady state is reached after some seconds. During the transient the pressure difference admits quite strong oscillations. However, due to the large inertia of the whole circuit the fluid does not respond to the pressure oscillations at the frequency  $2f$ . However, when the coil current is increased by steps, we observe large fluctuations of both the pump pressure and the mean velocity as shown by Fig. 4. It is noticeable that the pump pressure may exceed 7 bar during the transient step. Such over-pressure may be harmful for the pump. The latter results allow us to select the optimum start-up regime of the pump.

## Conclusions

We have analyzed the behaviour of a large size electromagnetic pump, the so-called ASTRID pump. It is shown that the requirements may be fulfilled for a sufficiently large frequency. In that case, stable operating conditions may be found near the pump characteristic maximum. We have also shown that start-up conditions are crucial in order to avoid large over-pressure in the pump.

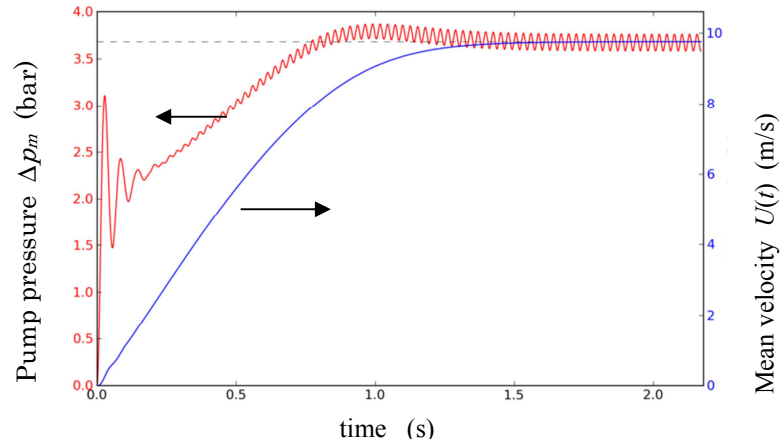


Fig. 3 : Time evolution of the pump pressure (left) and the mean velocity (right) in the case of a sudden increase of the coil current

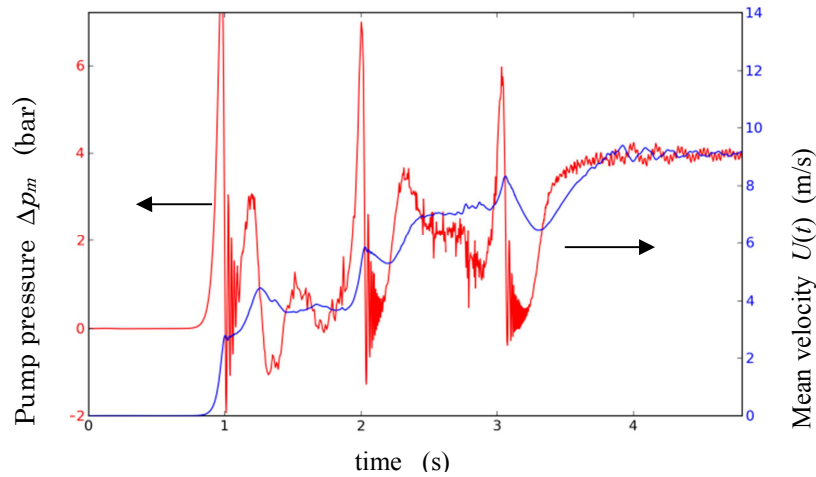


Fig. 4 : Time evolution of the pump pressure (left) and the mean velocity (right) in case where the coil current increases by steps.

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