Experimental and numerical analyses of the magnetic field spatial measurement inside an electromagnetic pump channel duct

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EXPERIMENTAL AND NUMERICAL ANALYSIS OF MAGNETIC FIELD SPATIAL MEASUREMENTS INSIDE AN ELECTROMAGNETIC PUMP CHANNEL DUCT

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Abstract: This article is a summary of a full paper that will be presented at the X International PAMIR International Conference - Fundamental and Applied MHD, to be held from 20 – 24 June, in Cagliari, Italy.

In the framework of the ASTRID R&D programme, it has been proposed to use an electromagnetic (EM) induction pump in the secondary cooling system. This paper describes the current status of the experimental and numerical analysis in progress to investigate liquid sodium flow instabilities in the PEMDYN loop with the objective of better managing the EM pump and preventing magnetohydrodynamic (MHD) instability. This paper discusses the analysis of 3D measurements of the magnetic fields along a path inside the annular linear induction pump (ALIP) channel measured with a Hall sensor. It also describes the numerical finite-element models that have been built to gain a more in-depth understanding of the interdependent MHD phenomena specific to EM pump operation. These measurements were obtained before the operative condition so as to retrieve as much information as possible on the EM field inside the channel pump without the fluid dynamics.

Key words: ALIP, magnetic field, numerical and experimental analysis, PEMDYN

1. Introduction

In the framework of the French Alternative Energies and Atomic Energy Commission's (CEA[1]) R&D programme on the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID), it has been proposed to use an electromagnetic (EM) induction pump in the secondary cooling system due to its superior safety features, e.g. no moving parts in liquid metal and a completely leaktight construction. However, detailed studies will be required to better manage EM pump operation and prevent an undesirable phenomenon called magnetohydrodynamic (MHD) instability. The main objective is to develop and qualify a numerical finite-element model of the electromagnetic instabilities occurring inside an annular linear induction pump (ALIP).

In the last three years, the CEA has been in charge of the design, engineering and construction of a new sodium loop named PEMDYN intended for CEA studies on experimental high flowrate EM pumps. The experimental EM pump for this loop has been designed with similar magnetohydrodynamic characteristics to those expected for the ASTRID secondary loop. This pump will provide us with experimental results that are needed

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to validate the numerical models used for the preliminary design, with the main objective being to develop and qualify a finite-element model of electromagnetic instabilities of ALIP.

This ALIP prototype is designed for studies involving different magnetic system configurations and hydraulic configurations. The inner core can be removed to implement sensors or it can be replaced with a second inductor where coils are embedded in a laminated ferromagnetic core. These configurations should help us gain a better overall understanding, as well as quantify any additional MHD effects and instabilities of double-supply-frequency ALIPs [1] and [2].

This paper describes the current status of the experimental and numerical analysis carried out to detect and investigate liquid sodium flow instabilities in the innovative ALIP installed in the PEMDYN loop (Fig 1). It also discusses the analysis of 3D measurements of the magnetic fields along a path inside the ALIP channel measured with a Hall sensor. It then details the numerical finite-element models that have been built to gain a more in-depth understanding of the interdependent MHD phenomena specific to EM pump operation. These measurements were obtained before the operative condition so as to retrieve as much information as possible on EM field inside the channel pump without the fluid dynamics.

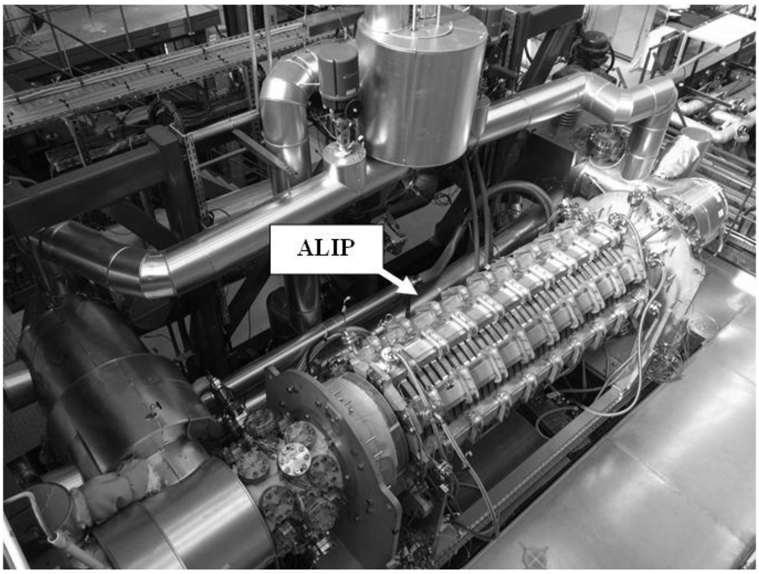

Figure 1: ALIP for the PEMDYN loop.

2. Presentation of the problem An ALIP is an asynchronous electrical machine that uses travelling magnetic fields to create an EM force and motion in liquid metal. The induced magnetic field in an electromagnetic induction pump is a function of the liquid metal velocity. This means that the magnetic field measurement contains information on the flow structure in the channel. A specific device was designed for the 3D measurement of the AC magnetic fields at 3 different points measured simultaneously down the entire length of the pump duct (Fig 2). This device has several important advantages: no metallic component and a high signal-to-noise ratio due to the Hall sensor.

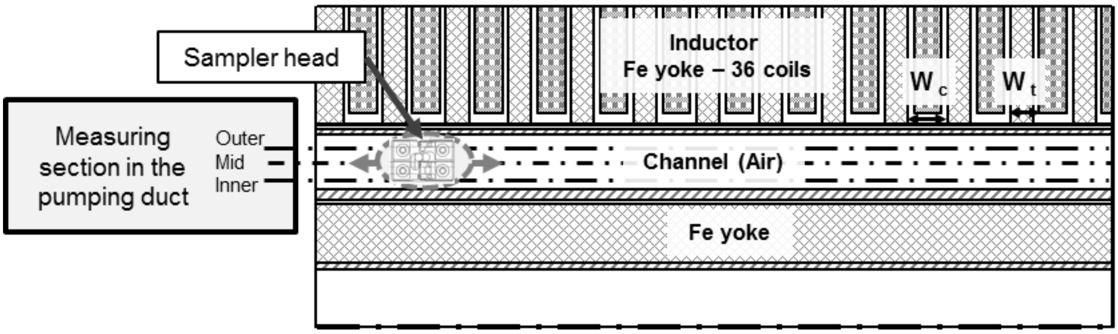

Figure 2: Location of the magnetic field sampler head.

Measurements were performed every 5 mm with 9 Hall-effect sensors in order to measure the 3 components of the field (radial-Br, axial-Bz, and azimuthal-Bφ) at 3 different radial positions inside the channel (outer, mid, inner) for 11 azimuthal positions (Fig 3).

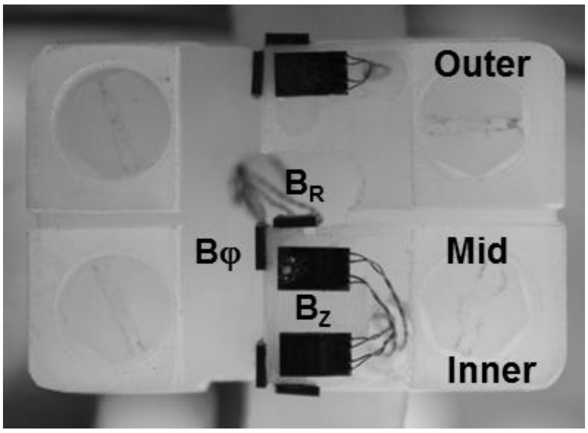

Figure 3: Magnetic field sampler head used in the experiment.

3. Governing equations The MHD problem implies the Maxwell equation, Ohms' law and the Navier – Stokes equation. Without liquid metal, the governing equation in electromagnetics is the induction equation for the vector potential taking into account Coulomb gauge. It can be written in the following form (1):

$$\Delta A = \mu_0 \sigma \left[\frac{\partial A}{\partial t} - \left(v \times \nabla \times A \right) \right] - \mu_0 J_e \qquad (1)$$

The basic model for an electromagnetic linear annular induction pump consists of two perfect, infinite-length ferromagnetic cylinders (Fig. 4).

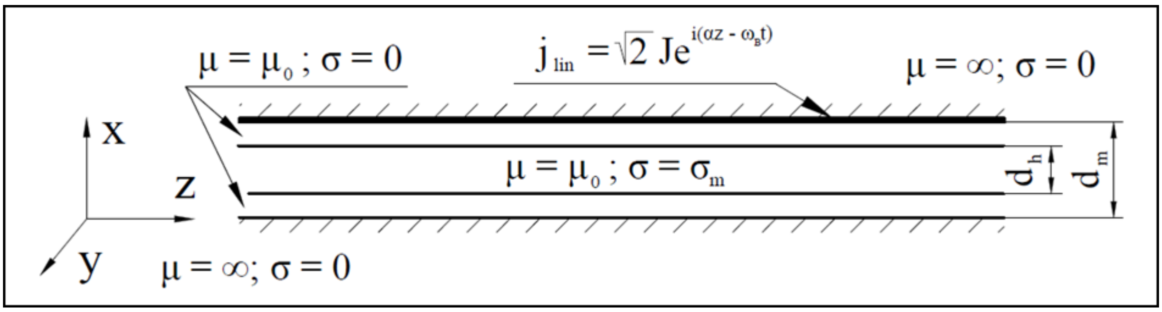

Figure 4: Ideal ALIP.

On the surface of the top ferromagnetic cylinder, a linear current is applied in harmonic form with the following boundary conditions (2):

$$\begin{cases} \left.\frac{\partial A}{\partial x}\right|_{x=0} = 0 \\ \left.\frac{\partial A}{\partial x}\right|_{x=d_m} = \mu_0 \boldsymbol{j_{lin}} \end{cases} \quad (2)$$

Then the 2nd order differential equation for the complex amplitude of the vector potential can be written in form (3), where the complex coefficient m^2 and the slip magnetic Reynolds number reads eq.4.

$$\frac{\partial^2 A(x)}{\partial x^2} - m^2 A(x) = 0 \quad (3)$$

$$m^2 = \alpha^2(1 - iRms) \quad (4)$$

Applying boundary conditions, the distribution of the vector potential can be expressed (5):

$$A(x,z) = \frac{\mu_0 \cdot \sqrt{2} \boldsymbol{j_{lin}} \cdot cosh(mx)}{m \cdot sinh(md_m)} e^{i(\alpha z - \omega t)} \quad (5)$$

4. Results Electromagnetic simulations were performed using numerical finite-element analysis software before carrying out the test runs on the PEMDYN loop at various power supply parameters and different azimuthal positions. The measurements results were globally consistent with the simulation results, as can be seen in Figure 5. This example concerns the outer sensor measurement in an azimuthal position of 22.5° with the following power supply parameters: I=45A, F=10Hz. Table 1 shows that the mean value and the fluctuation of the magnetic field are very consistent between measurements and simulation.

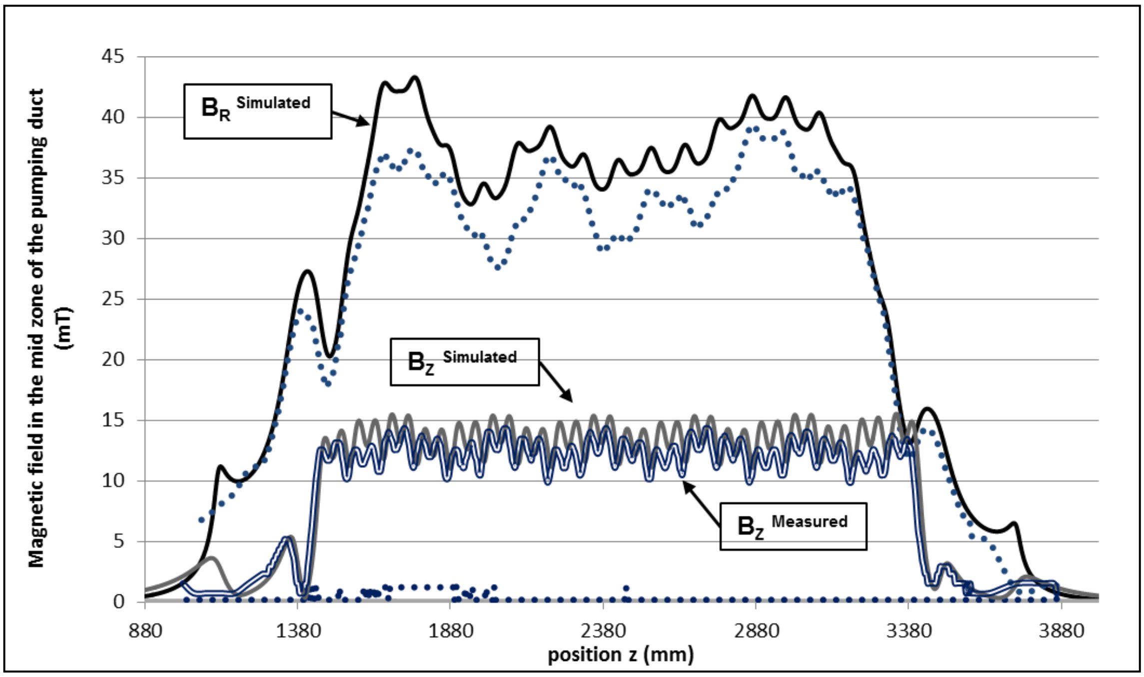

Figure 5: Analytical fit with respect to numerical finite-element model in the centre of channel.

Table 1: Mean values and fluctuation of the magnetic field.

MEASUREMENT		**NUMERICAL FINITE-ELEMENT MODEL**	
Mean value (mT)	Fluctuation (mT)	Mean value (mT)	Fluctuation (mT)
$\overline{B_r(r,\varphi,z)}_{sup} = 33.6$	$B_r\widehat{(r,\varphi},z)_{inf} = 2.36$	$\overline{B_r(r,\varphi,z)}_{sup} = 37.6$	$B_r\widehat{(r,\varphi},z)_{sup} = 2.3$
$\overline{B_\varphi(r,\varphi,z)}_{sup} = 0.37$	$B_\varphi\widehat{(r,\varphi},z)_{sup} = 0.31$	$\overline{B_\varphi(r,\varphi,z)}_{sup} = 0$	$B_\varphi\widehat{(r,\varphi},z)_{\mathrm{sup}} = 0$
$\overline{B_z(r,\varphi,z)}_{sup} = 12.4$	$B_z\widehat{(r,\varphi},z)_{sup} = 0.86$	$\overline{B_z(r,\varphi,z)}_{sup} = 13.5$	$B_r\widehat{(r,\varphi},z)_{sup} = 0.96$

The shape of the magnetic signal obtained during the experiment is also very similar to the numerical finite-element model. To conclude, we can say that the electromagnetic behaviour of the PEMDYN loop is consistent with the predicted characteristics of the pump defined during the development phase.

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[2] L. GOLDSTEINS, L. BULIGINS, Y. FAUTRELLE, C. BISCARRAT AND E. PLATACIS. *MHD Instability Analysis of a Large Scale Electromagnetic Pump for PEMDYN Facility. Paper 15040 Proceedings of ICAPP 2015 May 03-06, 2015 - Nice (France)*

ACKNOWLEDGEMENTS: *Thanks to Christian DOUBRAVA [1], D. CAMBET-PETIT-JEAN [1], P. DEFRASNE [1], M. FAURÉ [1], S. ALBALADEJO [1], C. VERDELLI [1], and JL PORTIER [1] for their action and support during the measurement phase on PEMDYN facility.*