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Performance maps of a high flowrate EM pump
Experimental and numerical analysis

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Abstract
In the framework of the Fast Reactor R&D programme, an experimental electromagnetic (EM) induction pump has been designed with similar magnetohydrodynamic (MHD) characteristics to those expected for the secondary cooling system. This pump will provide us with experimental results that are needed to validate the numerical models used for the preliminary design 2, with the main objective being to develop and qualify a finite-element model of MHD instabilities of Annular Linear Induction Pump (ALIP). 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 with the objective of better managing the EM pump and preventing MHD instability. In this paper we present the experimental results collected during the operation of the test campaign aiming establishing at performance maps of the high flowrate ALIP. It also describes the numerical finite-element models that have been built to gain a more in-depth understanding of the interdependent MHD phenomena 1.

Key words: Magnetohydrodynamic, induction pump, sodium-cooled fast reactor, performance curve.

I. INTRODUCTION
In the framework of the French Alternative Energies and Atomic Energy Commission’s (CEA) Sodium Fast Reactor R&D programme, it has been proposed to use an electromagnetic linear induction pump (EMIP) in the secondary cooling system. EMIP are an interesting alternative to mechanical pumps for the transportation of liquid metals such as sodium in secondary cooling systems of fast reactors, 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 improve control EMIP operation and prevent the undesirable phenomenon called MHD instability. The CEA has been in charge of the design, engineering and construction of a new sodium loop named PEMDYN intended for studies on experimental high flowrate EMIP. The ALIP (Fig 1) will provide us with experimental results that are needed 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 inside an annular linear induction pump for a maximum flowrate of 1500m^3/h and a pressure of 3bar 4.

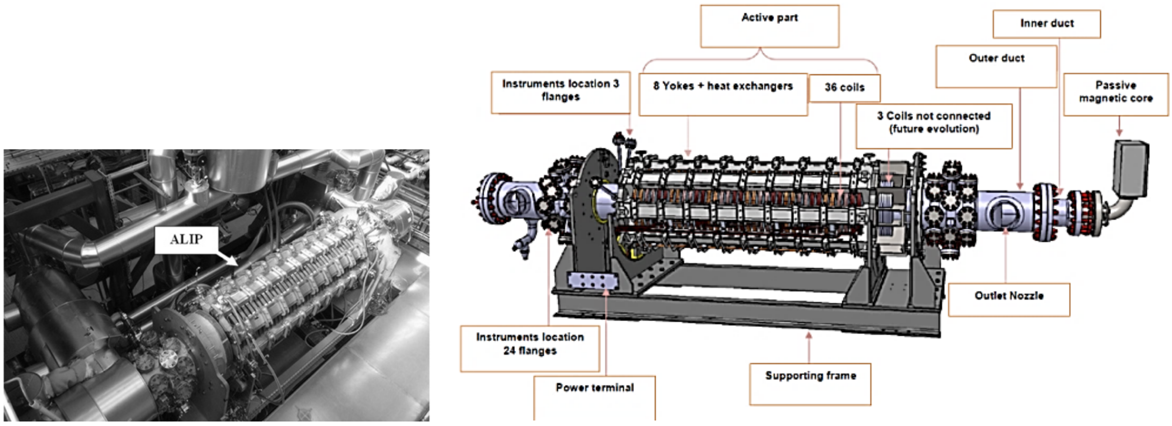

Fig. 1: PEMDYN experimental pump

That ALIP can be described as a three-phase alternating current machine with a cylindrical inductor generating a magnetic field, variable over time and in the pump channel space, that induces currents directly in the volume of the conducting fluid (ig. 2). The above described ALIP is allows 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 4.

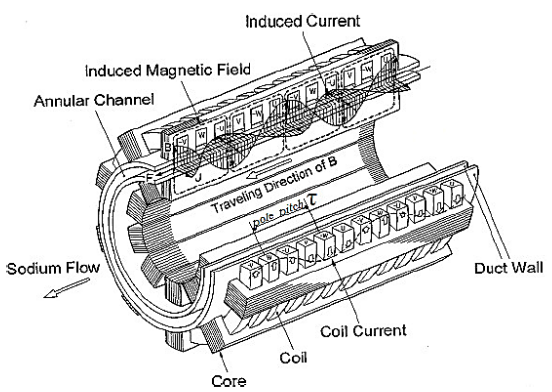

Fig. 2: Working principle of an ALIP

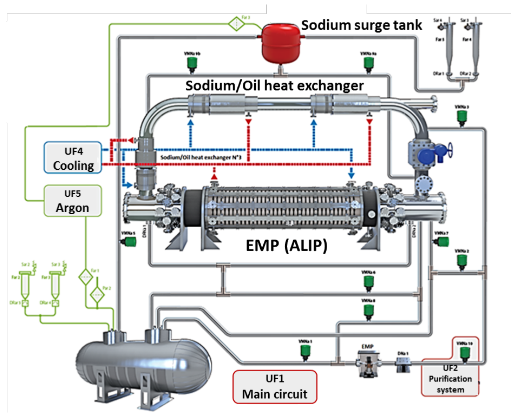

Fig. 3: Diagram of PEMDYN facility

PEMDYN design comprises one external inductor where three phase coils are embedded in laminated ferromagnetic core, an annular channel where liquid metal flows in the direction of the traveling magnetic field and an inner ferromagnetic core, which can be removed and replaced by an inner inductor equipped with sensors. The aim of this construction is to generate a magnetic field perpendicular to the direction of the flow (radial component). From cross product of azimuthal induced currents in sodium and radial component of magnetic field, axial electromagnetic force in the direction of travelling field is induced in the liquid metal. This force is responsible for pumping. The PEMDYN diagram presented in Fig. 3 is composed of the ALIP and a ball valve implemented to regulate and adjust the pressure drop of the circuit, to determine the performance curves of the ALIP. Three oil/sodium heat exchangers are implemented on the circuit to maintain the sodium temperature constant. The flowrate is measured with an ultrasound flowmeter.

II. ANALYTICAL

The MHD system of equations governing an ALIP is the same as presented in 1 and 4. It is composed by coupled Navier-Stokes (1) equation and induction equation in terms of vector potential A taking into account Coulomb gauge. It can be written in the following form (2). The terms responsible for the coupling of the system are $j \times B$ in equation (1), which consists of adding the volumetric force creating the pumping, and $-u \times \nabla \times A$ in equation (2), which is the convective term in transport equation for A. As system of (1) and (2) is non-linear it can be precisely solved using only iterative methods. However, in praxis so called solid body or electrodynamic approximation is often used, neglecting (2) and using only mean velocity of the flow. Basic model of electromagnetic induction pump is so called ideal machine Ideal model of EMIP (Fig. 4).

$$\rho\frac{\partial u}{\partial t} + \rho(u \cdot \nabla) \cdot u = -\nabla P + \rho\nu\nabla^2 u + j \times B \quad (1)$$

$$\Delta A = \mu_0\sigma\left[\frac{\partial A}{\partial t} - (v \times \nabla \times A)\right] - \mu_0 J_e \quad (2)$$

$$\nabla \times A = B \quad (3) \qquad \nabla A = 0 \quad (4)$$

$$\Delta p = \frac{\sigma B_0^2 v_B s l}{2} \cdot k_w k_l - \lambda \frac{l}{D_h}\frac{\rho v_m^2}{2} \quad (5)$$

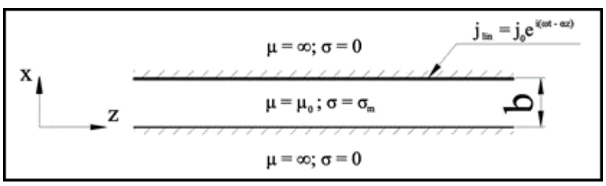

Fig. 4 Ideal model of EMIP

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It consists of two infinite length perfect ferromagnetic plates and between them conductive media, sodium, moves with constant velocity. On surface of upper ferromagnetic plate linear current is applied in harmonic form. For more details on MHD refer to 2. The analytical formula for estimation of quasi stationary developed pressure using solid body approximation is given in (5), where the last part represents pressure losses due to the walls friction. The solid body approximation quantify in integral characteristic estimations, and if $R/b \geq 2$ and $\tau/b \geq 2$, the influence of cylindrical system curvature on integral parameters is negligible (order of 1 – 2 %). Nevertheless, it was found that due to the fluid secondary circuit, in the case of high magnetic Reynolds number, MHD machine can experience instability [4]. While in the case of ALIP this effect is strongly connected with a break of axial symmetry, it should not be forgotten that hydrodynamic part can play significant role in such machine and should be taken into consideration.

III. EXPERIMENTAL

The objective of this test programme was to measure operating points under steady-state conditions so as to plot the flow and pressure performance curves of the EM pump. This involved measuring the flowrate and pressure during a steady-state flow at given power supply parameters. Fig. 5 compares trace the variation of the EM pump impedance for the simulation results and the experimental measurements 3. The simulation results and experimental measurements for each operating point of the EM pump are consistent in terms of impedance.

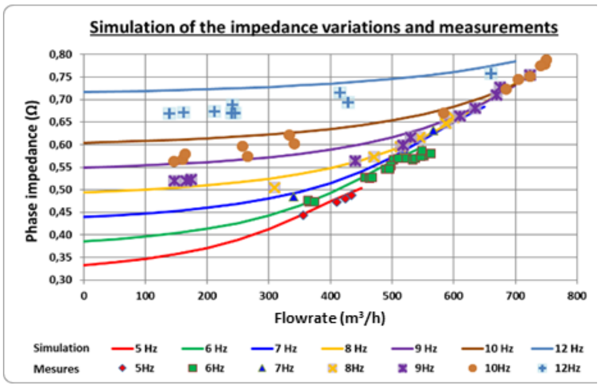

Fig. 5: Measurements and simulation of the impedance variations

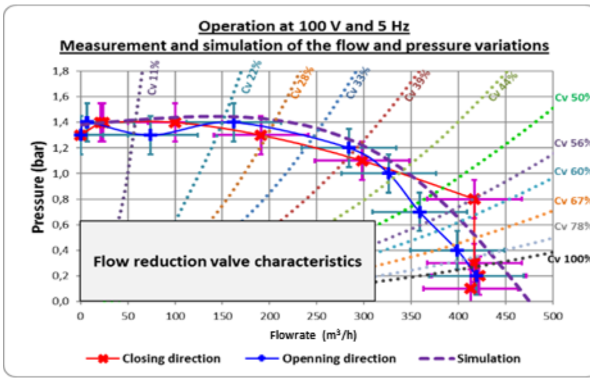

Fig. 6: Measurement and simulation of the flow and pressure variations

In order to obtain the experimental data required to plot the EM pump's characteristic at low power, the campaign involved performing tests by operating the flow reduction valve and by imposing the EM pump voltage and frequency. The measurements were post-processed to produce the following curves in Fig. 6: The dotted curve shows the pressure drop in the circuit according to the CFD assumptions indexed to the opening of the flow reduction valve expressed as a percentage. The dashed curve shows the simulation of the flow and pressure variations in the EM pump. The measurement points are represented by markers and interconnected to illustrate the variations in the series of measurements. The experimental follow the simulation results consistently, the action to close the flow reduction valve reduces the flow and increases the pressure drops, therefore the EM pump adapts well to variations without any regulating action on the power supply.

The campaign for the high flow rate involved performing tests by operating the voltage and frequency of the EM pump by imposing the flow reduction valve characteristics (Fig. 7). The measurement points are represented by marker, the dashed curve shows the linear regression and the standard deviation 10%. Fig. 8 present the first experimental data collected during the operative condition of the test programme aiming to establish performance maps for high flowrate. The dashed curve shows the simulation of the flow and pressure variations in the EM pump as function of the increase in the effective voltage at 15Hz. Markers represent the measurement points obtained during the operative condition. The experimental load curve at high power follows the simulation results consistently.

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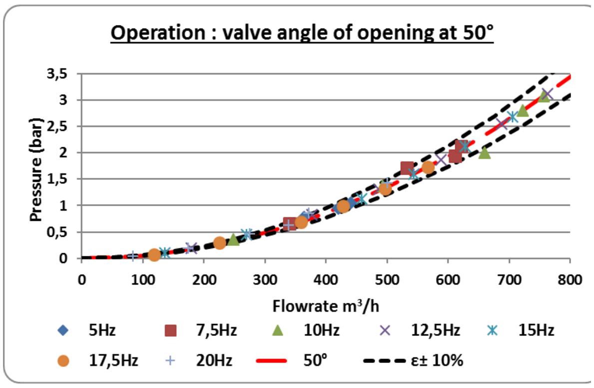

Fig. 7: Load curve for a valve angle at 50°

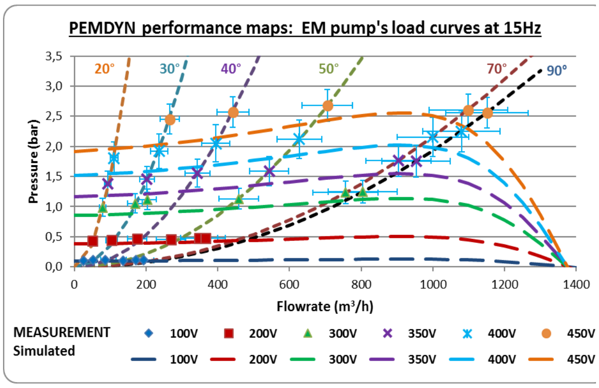

Fig. 8: PEMDYN load curve at 15Hz

IV. CONCLUSION

The results of the test campaigns performed validate the fact that the flow and the pressure vary consistently with the results of simulations performed beforehand. However, the actual sensor are not accurate enough to permit the analyses foreseen by the experimental programme, particularly with respect to post-processing the electrotechnical quantities and analysing the magnetohydrodynamic behaviour of the sodium flow. A dedicated sodium instrumentation was manufactured to be able to measure inlet and outlet static pressures and local flowrate of the EMP.

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