

CFD SIMULATION OF HELICOIDAL MAGNETOHYDRODYNAMIC PUMP IN CLOSED CIRCUIT

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Abstract: In the framework of the ARCHYMED-DI2E project, an experiment has been built to test an electromagnetic pump (EMP) in quasi saturated salty water. The closed-circuit facility includes an EMP with a helicoidal channel submitted to a steady vertical magnetic field up to 4 T. The magnetic field is generated by a low-temperature superconducting magnet cooled with liquid helium and the platinum-coated titanium electrodes are placed concentrically on both sides of the channel to allow the electric current to travel. A portion of the circuit loop was modified to accept the presence of either a vane or a straight tube. The purpose of the numerical simulations presented in this paper is to model the pump's behaviour in the straight tube configuration. After a mesh convergence study, the performance of the EMP was estimated for 3 T, 3.5 T and 4 T and compared to experimental data.

Keywords: Electromagnetic pump, superconducting magnet, computational fluid dynamics.

1. Introduction The first part of the ARCHYMED-DI2E project (Aimants supraconducteurs Refroidis par Conduction, HTS, YBCO, et Magnétohydrodynamique en Eau De mer – Décharge Impulsionnelle d'Énergie Électrique) consists in preliminary MHD experiments in saturated salty water pumping in a 4 T magnetic field (general overview of the test bench in Figure 1). MHD pumping can be used for various applications [1]: in metallurgy for liquid metal pumping, in nuclear energy for molten salts and liquid sodium reactors in primary circuit loop and also in marine applications for water pumping on ships, such as hull emptying, firefighting tank filling, heat exchanger cooling. EMP require low maintenance, are leak-tight thanks to their rotor-less feature and remain silent.

An experimental test bench in quasi saturated salty water has been built at the LEGI in Grenoble to assess the performances of an EMP among other topics like electrochemistry and corrosion. The full description of the experimental setup can be found in the companion paper [2] from the present conference.

The EMP is a closed-circuit pump with a helicoidal channel submitted to a steady vertical magnetic field. Electrodes are placed concentrically on both the inner and outer sides of the channel to allow the electric current to travel and remain quasi-perpendicular to the magnetic field. This orthogonality of the current and the magnetic field creates a Laplace force that creates a favourable pressure gradient in the channel and moves the fluid in the pump.

This paper describes the numerical CFD (Computation Fluid Dynamics) simulations performed to evaluate the performances of the EMP for the smooth pipe closed loop hydraulic circuit configuration. The present paper enlightens the comparison between the CFD simulations and the experimental data.

The objective of doing CFD simulations here is to validate them against experimental data and thus use them to design future experiments with higher magnetic field; coming by 2026 at the LEGI.

The numerical model was created with ANSYSTM and the magnetohydrodynamics were solved with FluentTM as a steady 3D turbulent flow adjoined to a MHD module implemented as a User Defined Function (UDF) [3].

2. Presentation of the numerical setup The ARCHYMED-DIE2 experiment is a rigid plastic tank filled with saturated water at approximately $200 \text{ g}_{\text{salt}}/\text{L}_{\text{water}}$ in which a helicoidal channel is inserted; the water electrical conductivity is around 19.5 S/m . The inner side walls of the helicoidal channel are titanium electrodes connected to a power supply that delivers at maximum 400 A under 24 V . The tank is connected at the bottom to the rest of the hydraulic circuit and it is maintained in the core of the superconducting magnet as shown in Figure 1. In the CFD model, the hydraulic circuit is not modelled as shown in Figure 1.

The computational domain has a flow rate inlet and a pressure outlet. The flow rate measured in the experiments is imposed in the calculation. Maximum flow rate being approximately $25 \text{ m}^3/\text{h}$. Regarding the electric supply of the electrodes, their boundary condition type is “constant electrical potential” so that the current travels from the outer electrode to the inner electrode. The electrical potential applied is adapted to reach the current measured in the experimental setup. All the walls have no slip boundary conditions except the top part of the tank which is “zero wall shear stress” because it models a fixed free surface. Three values of magnetic field were used: 3 T , 3.5 T and 4 T . Each value refers to the vertical component of the magnetic field at the centre of the magnet. The 3D magnetic field applied in the calculations is generated by a 2D axisymmetric electromagnetic model of the superconducting magnet. For the case of 4 T in the centre, the vertical component of the magnetic field in the plane $x = 0$ can be seen in Figure 2. Regarding pressure in the MHD channel, six pressure values have been extracted at the same location as pressure sensors in the experimental setup.

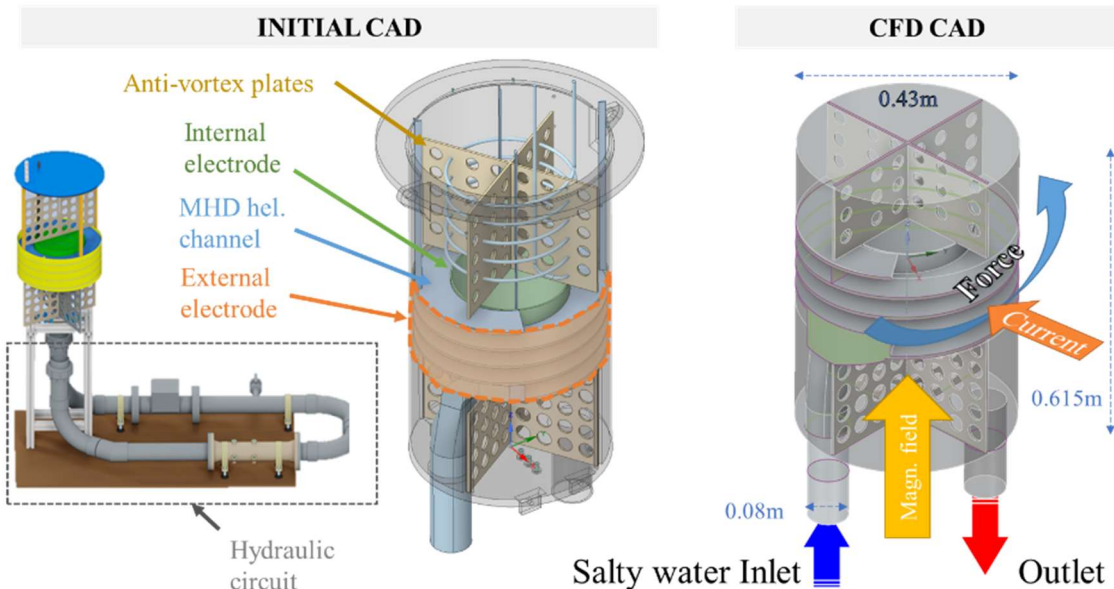


Figure 1. MHD helicoidal canal (blue) inside the vessel (grey) with vortex-breaking grids (yellow).

The inner wall of the channel (green) and the outer wall (orange) are concentric electrodes. The superconductor magnet (not modelled) is located around the vessel and centred on the MHD channel.

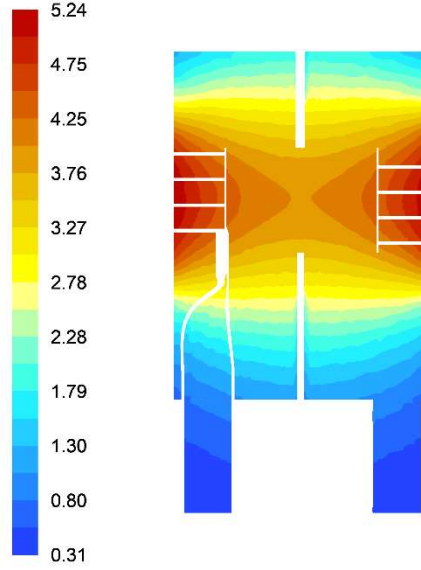


Figure 2. The vertical component of the magnetic field B_z [T] in the plane $x = 0$.

The mesh is polyhedral because it usually leads to better and faster convergence [4]. It has polygonal base prismatic cells on the walls and polyhedral cells away from the wall. It is a 1 million cells mesh with a prism layer of 6 cells, 150 μm first layer height and continuity between the size of the last cell of the layer and the first polyhedral element in the volume. The prism layer characteristics make the turbulent boundary layer discretized in such a way that y^+ is above 30 in most parts of the MHD channel.

3. Power balance equations The vector of surface current density \mathbf{j} in A/m^2 , is given by Ohm's law:

$$\mathbf{j} = \sigma(\mathbf{E} + \mathbf{U} \wedge \mathbf{B}) \quad (1)$$

σ is the electrical conductivity of the fluid in S/m , \mathbf{E} the electric field in V/m , \mathbf{U} the channel velocity calculated from channel's cross-section and flow rate \dot{Q} in m^3/s , finally \mathbf{B} is the magnetic field vector in Teslas. Applying a scalar product by \mathbf{j} and integrating over the channel's volume $V_{channel}$, the equation (1) leads to a power balance:

$$\overbrace{\iiint_{V_{chann}} \mathbf{j} \cdot \mathbf{E} dV}^{P_{electro}} = \overbrace{\iiint_{V_{channel}} j^2 / \sigma dV}^{P_{Joule}} + \overbrace{\iiint_{V_{cha}} \mathbf{U} \cdot (\mathbf{j} \wedge \mathbf{B}) dV}^{P_{MHD}} \quad (2)$$

With P_{Joule} the Joule power, $P_{electro}$ the electrical power transferred by the electrodes to the fluid and P_{MHD} the power of Laplace forces. Regarding the EMP performance, the Bernoulli theorem can be applied from the helicoidal channel's entrance until the end. One can write:

$$p_{in} + \frac{1}{2} \rho U_{in}^2 + \Delta p_{MHD} = p_{out} + \frac{1}{2} \rho U_{out}^2 + \Delta p_{losses} \quad (3)$$

p , U , ρ , Δp_{MHD} and Δp_{losses} being respectively static pressure in Pa, velocity in m/s , fluid density in kg/m^3 , pressure difference generated by Laplace forces and pressure difference generated by regular and singular losses in Pa.

Considering mass conservation from the inlet to the outlet of the MHD channel and identical cross-sections at inlet and outlet, the dynamic pressures in the equation 3 cancel out and gives:

$$\overbrace{\Delta p_{chann}}^{p_{out} - p_{in}} = \Delta p_{MHD} - \Delta p_{losses} \quad \text{where} \quad \Delta p_{MHD} = \overbrace{IBL_{chann}}^{\text{"MHD force"}} / A_{channel} \quad (4)$$

With $L_{channel}$ and $A_{channel}$ being respectively length and cross-section area of the MHD channel. Noting that in the experiments and calculations, Δp_{losses} is small compared to Δp_{MHD} . Then, by multiplying equation 4 by the flow rate \dot{Q} , one can read the power balance:

$$\overbrace{\dot{Q}\Delta p_{channel}}^{P_{hyd}} = \overbrace{\dot{Q}\Delta p_{MHD}}^{P_{MHD}} - \overbrace{\dot{Q}\Delta p_{losses}}^{P_{losses}} \quad (5)$$

P_{MHD} is the power of Laplace forces applied to the fluid, P_{hyd} is the available power for the pump and P_{losses} is the power generated by regular and singular losses. From the equations 2 and 5, a power distribution of the electrical power P_{gener} up to the mechanical power used to move the fluid P_{hyd} can be computed. The experimental values of $\Delta p_{channel}$ were measured for several values of I , B and \dot{Q} and Δp_{MHD} and Δp_{losses} were separated by splitting then into a part proportional to $I \cdot B$ and a part proportional to \dot{Q}^2 . From the numerical point of view, P_{Joule} and P_{MHD} were computed directly from the integrals shown in equation 2.

4. Results CFD simulations using the FluentTM finite volume solver were conducted to analyse various magnetic fields and mass flow rate boundary conditions. The study encompassed 3 values of magnetic field and 9 values of flow rate for each magnetic field. **Figure 3** illustrates the MHD behaviour of the EMP according to electrical potential, volumetric flow rate and Laplace force. The experimental data is related to the smooth pipe closed loop hydraulic circuit configuration only. More details can be found in the companion paper [2]

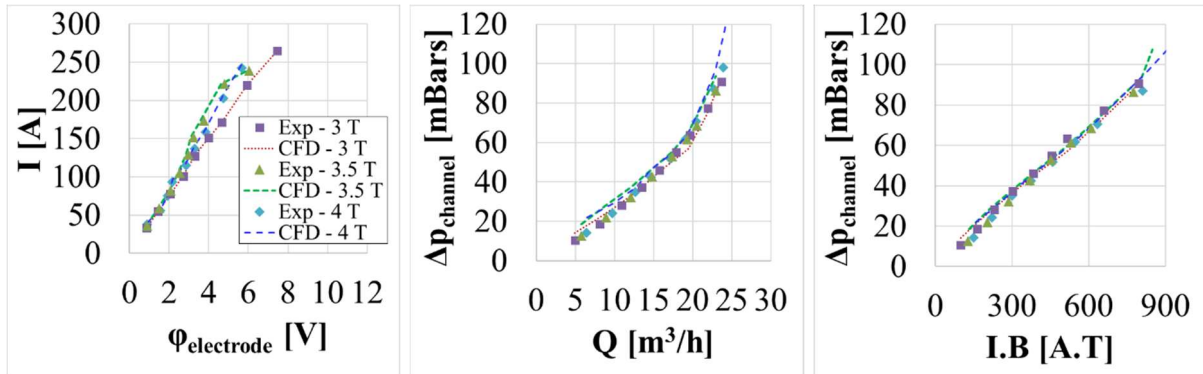


Figure 3. (Left) Evolution of current flowing from one electrode to another according to the electrical potential of the fluid between the electrodes. (Centre) Evolution of pressure difference between exit (probe 6) and entrance (probe 1) of the MDH channel according to volumetric flow rate. (Right) Evolution of the same pressure difference according to Laplace force term $I \cdot B$.

The resistance of the fluid R_{fluid} can be retrieved from Joule power and electric current such that $P_{Joule} = R_{fluid}I^2$. By gathering all the numerical results of P_{Joule} and I^2 , one can calculate the average over the population of calculations (on 3 T and 4 T simulations) of fluid electrical resistance in the EMP. $R_{fluid} = 0.0150 \Omega$; compared to 0.0227Ω found experimentally. The resistance values are different because in our numerical model the resistance of the electrode itself is not taken into account. Regarding the pressure rise in the

MHD channel, the CFD calculations are in fair agreement with the experimental data; the CFD model can predict accurately the hydraulic behaviour of the EMP. Moreover, the pressure rise in the MHD channel follows approximately a linear trend when the Laplace force $I \cdot B$ varies because the ΔP_{losses} term in Δp_{cha} is small compared to Δp_{MHD} ; the latest being simply a linear function of $I \cdot B$ according to equation 6. Table 1 shows a comparison of CFD and experiments regarding the powers involved in the EMP at two different magnetic field. That enlightens a good agreement between the CFD model and the experimental data in terms of power balance. However, the prediction of MHD power by the numerical model is clearly higher than measurements, what could come from imprecisions in the reconstruction of P_{MHD} from experiments, where $\Delta p_{chann} = P_{hydro}/\dot{Q}$ has been measured.

Table 1. Comparison of CFD and experiments regarding characteristics of the EMP. The generator is set to 9V. *Magnetic field vertical component at the centre of the magnet. [‡]Reynolds number based on hydraulic diameter and flow rate velocity in the channel.

Flow rate [m ³ /h]	17.75		19.31	
Reynolds number [‡]	8×10 ⁴ ~ 9×10 ⁴			
Magnetic field* [T]	3		4	
	Exp.	CFD	Exp.	CFD
P_{gener} [W]	1361.5	<i>Not calculated</i>	1230.9	<i>Not calculated</i>
$P_{electro}$ [W]	604.41	607.48 (+0.51%)	448.85	473.53 (+5.50%)
P_{MHD} [W]	38.60	258.02 (+568%)	46.63	183.29 (+293%)
P_{hyd} [W]	32.78	30.60 (-6.65%)	39.51	41.18 (+4.23%)

5. Conclusions The numerical MHD modelling of the EMP with the Fluent™ CFD solver is promising. It was able to match fairly the experimental data both in terms of electrical and hydrodynamic behaviour. Some flaws are to be mentioned such as the fact that the rest of the hydraulic circuit was not modelled. In addition, electrochemistry was not modelled and dioxygen/dihydrogen bubbles production at the electrodes was not taken into account. In the experiments, for high electrical current values (not shown in this paper) the generation of a high number of electrolysis-induced bubbles made the EMP performance plummet. With this CFD numerical model, this electrochemistry phenomenon would not be predicted. The numerical model will be used to design other experiments of this type in the present project or in other MHD projects.

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