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Numerical Investigation of Flow in a New DC Pump MHD

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ABSTRACT

Electromagnetic pumps have several advantages to mechanical pumps. They offer maneuverability by directional thrust along with quietness and are conceived with an aim of eliminating all moving parts, being also free from problems of wear and tiredness of use. The flow field in the channel is treated as steady state, incompressible and fully developed laminar flow conditions. Our numerical code DCPMHD uses cylindrical coordinates (r, φ , z) and solves the incompressible MHD equations for magnetic vector potential A and fluid velocity V. Using finite volume method for numerical calculation. The numerical results of the performance characteristics of a DC electromagnetic pump are discussed and show that our new concept is capable to deliver bi-directional activation and have a satisfactory controllability, because of its proportional output force and input current relationship.

Keywords: Design, Fluids mechanics, Finite volume method, Magneto-hydrodynamic pumps, Navier-stokes equations, Seawater pumps.

NOMENCLATURE

$\vec{A}$	magnetic vector potential
$\vec{B}$	magnetic induction
$\vec{D}$	electric flux density (displacement electric)
$\vec{E}$	electric field
$\vec{J}$	electric conduction current density
$\vec{J}_i$	induced current density
$\vec{J}_{ex}$	electrical current source density
$\vec{J}_a$	electrical current density injected by electrodes
P	pressure
$\vec{V}$	flow velocity
υ	kinematic viscosity coefficient
σ	electric conductivity
μ	permeability magnetic
$\vec{\xi}$ *(r,z)*	vorticity vector
$\vec{\psi}$ *(r,z)*	vector potential hydrodynamic
v_r, v_z	components of the velocity
ω	component of vorticity
β_i	projection function
Ω	domain in element

1. INTRODUCTION

Magneto hydrodynamics (MHD) covers research on the generation of phenomena (such as stirring, mixing, separating and moving) under a magnetic action exerted on fluid. The utilization of MHD effects is multiple: among those, the MHD pump effect is one of the important effects. Contrary to the ordinary mechanical pump necessarily equipped with a rotary moving part like a blade, the MHD pump is notable for the complete absence of the blade- lake part; Chia-yuan (2004 a,b). To produce such an MHD pump effect, it is required from the pumping mechanism on imposition of a constant magnetic field on a fluid which is crossed by a DC current to create a fluid movement. Hence, these pumps are designed without using any movable part and thus are free of wear and fatigue problems caused by pressure-drop across the mechanical parts.

Figure 1 represents a new DC electromagnetic pump design. It consists of a magnetic in the torus shape, two winds, four electrodes and channel (Bennecib *et al.* 2007). It is assumed that fluid is an incompressible, laminar and that material properties such as kinematics viscosity and density are constants; Hughes *et al.* (1995). The fluid in this case is seawater pure or "seeded" by NaCl to enhance the conductivity. In this paper, a solution was obtained from both Navier-stokes and Maxwell equations under some assumptions which have acceptable physical meanings.

The present paper shows the results of the DC pump MHD numerical simulation that we carried out. The proposed pump produces an axial flow. As a consequence, magnetic field can be obtained before calculating of flow field.

2. Numerical Analysis of Flow and Electromagnetic Field

The axisymmetric problem describing magneto hydrodynamic devices is obtained from the electromagnetic equation in terms of the magnetic vector potential $\vec{A}$.

$$\overrightarrow{rot}\left(\frac{1}{\mu}\overrightarrow{rot}\,\vec{A}\right)-\sigma\left(\vec{v}\wedge\overrightarrow{rot}\,\vec{A}\right)=\overrightarrow{J}_{ex}+\vec{J}_a \tag{1}$$

where J_{ex} , J_a, μ and σ are the current density in the exciting coil, the current density injected by electrodes, the magnetic permeability and the electric conductivity, respectively. In this study, electromagnetic field is considered to be constant.

In the axisymmetric analysis the electric current density has only the φ-component which is independent of φ, so the resulting magnetic vector potential $\vec{A}$ has only the φ-component. Using 2D cylindrical r, z coordinates; Eq. (1) is developed as

$$\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{\partial\left(A_{\varphi}\right)}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{\mu}\frac{\partial\left(A_{\varphi}\right)}{\partial r}\right)-\sigma v\frac{\partial\left(A_{\varphi}\right)}{\partial z}=-J_{ex}-J_a \tag{2}$$

If we introduce the transformation

$$A=r\,A_{\varphi} \tag{3}$$

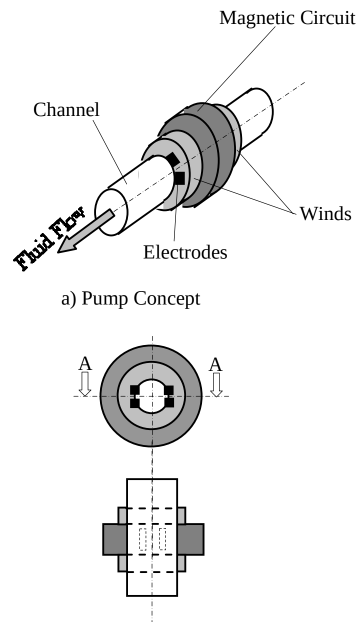
Eq. (2) becomes

$$\frac{\partial}{\partial z}\left(\frac{1}{\mu}\frac{1}{r}\frac{\partial A}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{\mu}\frac{1}{r}\frac{\partial A}{\partial r}\right)-\frac{\sigma}{r}v\frac{\partial A}{\partial z}=-J_{ex}-J_a \tag{4}$$

Let Ω be the study domain enclosed by $\Gamma=\Gamma u\cup\Gamma_q$ with boundary conditions $A=\bar{A}$ on Γ_u, $\frac{1}{r}\frac{\partial A}{\partial n}=\bar{q}$ on Γ_q.

$\bar{A}$ and $\bar{q}$ are the prescribed unknown potential and normal magnetic fluxes, respectively, on the essential boundary Γ_u and on the flux boundary Γ_q and n is the unit outward normal direction to the boundary Γ_q.

The motion of the liquid in the magnetic field can be described as Bahadir and Abbasov (2005)



a) Pump Concept

b) Front view and top sight with an axis cut (A–A)

Fig. 1. Proposed DC MHD pump configuration

$$div\,\vec{V}=0 \tag{5}$$

$$\frac{\partial V}{\partial t}+\left(\vec{V}.\vec{\nabla}\right)\vec{V}=-\frac{1}{\rho}gr\vec{a}d\;P+\upsilon\Delta\vec{V}+\frac{\vec{F}}{\rho} \tag{6}$$

Where $\vec{V}$ is the velocity vector, P is the pressure, ρ is the density of the liquid, υ is the kinematic viscosity and $\vec{F}$ is Laplace forces which are given by

$$\vec{F}=\left(\vec{J}_i+\vec{J}_a\right)\wedge\vec{B} \tag{7}$$

Where J_i is the induced current density and J_a is the electric current density injected by the electrode.

The coupled velocity $\vec{V}$ and magnetic induction field $\vec{B}$ via Laplace forces is developed.

Next, we will apply a method which uses the vorticity vector $\vec{\xi}$ (r, z) and two vector potentials: hydrodynamic $\vec{\psi}$ (r, z) and magnetic $\vec{A}$ (r, z).

2.1 (ψ,ξ , A) Model

We introduce two vector potentials $(\vec{A},\vec{\psi})$, the vorticity vector $\vec{\xi}$, and using the following relationships (Krzeminski et al. 1996; Fermigier 1999).

$$\vec{B}=ro\vec{t}\;\vec{A},\quad \vec{V}=ro\vec{t}\,\vec{\psi},\quad \vec{\xi}=ro\vec{t}\,\vec{V} \tag{8}$$

$$v_r=-\frac{1}{r}\frac{\partial\psi}{\partial z}\quad,\quad v_z=\frac{1}{r}\frac{\partial\psi}{\partial r} \tag{9}$$

$$w = \frac{\partial v_r}{\partial z} - \frac{\partial v_z}{\partial r} \tag{10}$$

Where v_r and v_z are the components of the velocity, w is the component of vorticity.
According to the configuration of the pump proposed a cylinder with ray ‘r’ and infinite length along axis (Oz). Under these conditions, the gauge condition is naturally checked. Using the new dependent variables equation 6 we obtain:

$$\upsilon\left(\frac{\partial^2 w}{\partial r^2} + \frac{\partial^2 w}{\partial z^2} + \frac{1}{r}\frac{\partial w}{\partial r} - \frac{w}{r^2}\right) = \frac{\partial w}{\partial t} + \frac{\partial w}{\partial r} v_r + \frac{\partial w}{\partial z} v_z + + \frac{v_r}{r} w + \frac{1}{\rho}\left(\frac{\partial F_z}{\partial r}\right) \tag{11}$$

$$\frac{1}{r}\left(\frac{\partial^2 \psi}{\partial z^2} + \frac{\partial^2 \psi}{\partial r^2}\right) = -w \tag{12}$$

2.2 Poisson equation for pressure

In order to determine the pressure applying the $(\nabla.)$ operator to Eq. (6) with the condition $div\vec{V} = 0$
We get

$$div(\vec{V}.\vec{\nabla}) = -\frac{1}{\rho}\Delta P \tag{13}$$

We used the Eq. (9) and the following expression

$$div(\vec{V}.\vec{\nabla})\,\vec{V} = 2\frac{\partial v_z}{\partial r}\frac{\partial v_r}{\partial z}$$

The pressure is obtained as:

$$\frac{\partial^2 \mathrm{P}}{\partial z^2} + \frac{\partial^2 \mathrm{P}}{\partial r^2} + \frac{1}{r}\frac{\partial \mathrm{P}}{\partial r} = \frac{2\rho}{r^2}\frac{\partial^2 \psi}{\partial z^2}.\frac{\partial^2 \psi}{\partial r^2}$$
$$\Delta \mathrm{P} = \frac{2\rho}{r^2}\frac{\partial^2 \psi}{\partial z^2}.\frac{\partial^2 \psi}{\partial r^2} \tag{14}$$

3. Numerical Method and Results

In finite volume method, each principal node "P" is surrounded by four nodes close that to North "N", the South "S", the East "E", and the West "W". By projection of the differential Eq. (4) on a basis of projection functions β_i, and by integration of this same equation on the volume of control, corresponding to the node "P", we obtain (Patankar, 1980):

$$a_P A_P = a_e A_E + a_w A_W + a_n A_N + a_s A_S - \left(a'_n A - a'_s A_s\right) v_z + d_0 \tag{15}$$

The matrix form of this system of equation is written in the form:

$$\left[M + \nu L\right]\{\mathrm{A}\} = \{F\} \tag{16}$$

Where $[M + \nu L]$: Coefficients matrix, $\{\mathrm{A}\}$ Unknown vector and $\{F\}$ Source vector.
The resolution of the electromagnetic model is realized by an iterative method Wait (1979). After that the hydrodynamic problem will be solved by the same method. The grid remains the same, once the located nodes, we introduce a source term which allows the coupling between the two equations for electromagnetic and flow. The integration of the Eq. (11) on the control volume gives:

$$a_p\, W_P = \sum a_{nc}\, W_{nc} + a_b \tag{16}$$

In which a_p terms are the attractive coefficients on W and nc implies summation over the neighboring nodes of "P" for two dimensional computations and a_b is the source terms.

Finally, the finite volume method is employed for solving the velocity profile across the channel and for a study of a two dimensional electromagnetic model in dynamic mode. Parameters for the applied magnetic fields and electric currents plus specific electrode length and its provision have been adjusted for assessment on the performance of the DC pump MHD.

The computation fluxogram of resolution algorithm is presented in Fig. 2.

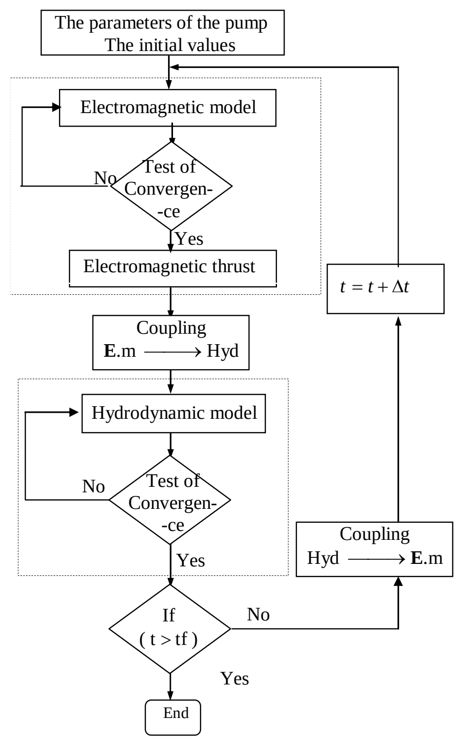


Fig. 2. Computation algorithm

Algorithm:

Step 1: Initial, boundary conditions and the pump data’s are given.
Step 2: First, magnetic potential and magnetic induction are evaluated.
Step 3: Computation of the eddy currents and the forces in channel.
Step 4: The forces are injected in the Navier-stokes equations as volumetric momentum sources.
Step 5: Computation of the velocity by resolution of the Navier-stokes equations.
Step 6: Test, if the time is less or equal the final time go to **Step 7**. If the time is great than the final time go to **Step 2**.
Step 7: End

As a convergence criterion, $\|e\| = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(V_i - V_i^{-1}\right)^2}$,

N is the total
number of nodes used by the FVM in the studied domain, V_i^{-1} is the past solution of each node and V_i is the present past solution.

The nodes numbers used for computation are 3000. The question of accuracy and stability of numerical methods is extremely important if our solution is to be reliable and useful. Accuracy has to do with the closeness of the approximate solution to exact solutions (assuming they exist). Stability is the requirement that the scheme does not increase the magnitude of the solution with increase in time, which implies that $\frac{\upsilon.\Delta t}{\Delta r^2} \leq 1$ for stability, where υ is the kinematic viscosity coefficient.

Table 1 presents pertinent tabulated material properties of seawater. In addition the geometric parameters and applied fields needed for the numerical simulations are listed in Table 2.

Table 1 Pertinent properties of seawater

	Seawater
Density, ρ	1000 (kg.m^{-3})
Conductivity, σ	50 (S/m)
Viscosity, μ	6.10^{-4} N.s.m^{-2}
Relative permeability	1

Owing to the geometric symmetry, only half domain was taken account. The Direchlet and Newmann boundary conditions are (V=0, $\frac{\partial V}{\partial z} = 0$ and $\frac{\partial V}{\partial n} = 0$).

Table 2 Parameters for numerical simulation

parameter	value
- Channel length L	0,14m
- Channel radius R	0,03m
- Electrode length l	0,08m
- Electrical current source density coils J_{ex}	0,2.10^7 A/m^2
- Electrical current density injected by electrodes J_a	0,25.10^7 A/m^2

Figures 3 and 4 show magnetic potential vector and its contours in the channel and on the level of each coil. The absolute value of the magnetic potential vector is less significant at the inlet than on the outlet side of the electrode and too weak along the electrode, this is explained by the equi-potential are very concentrated near the outlet of the electrode.

Therefore, as shown in Fig. 5, the axial MHD thrust become much greater increases in the outlet of the electrode leading to push the sea water.

Figures 6, 7 and 8, also show that the flow development is quicker. This is because driving forces of large magnitude are concentrated near the under and bottom electrode.

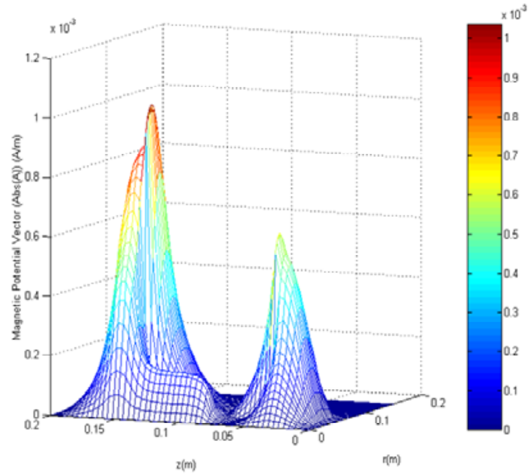


Fig. 3. Magnetic potential vector

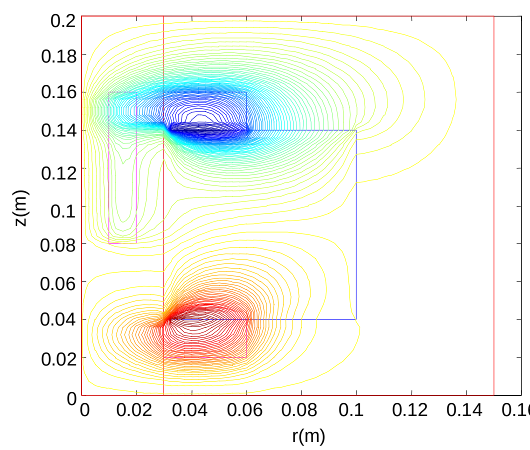


Fig. 4. Magnetic potential vector distribution in the DC pump MHD

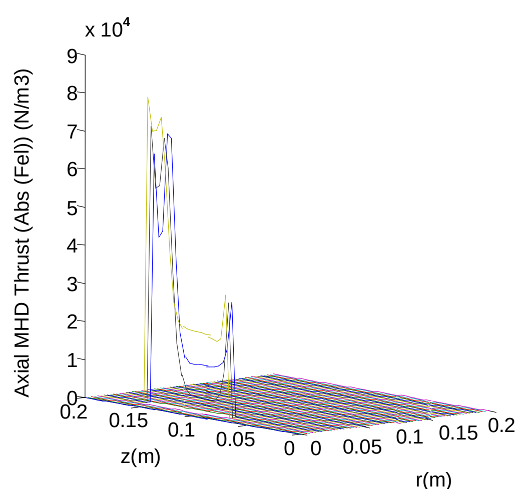


Fig. 5. MHD thrust

It should be noted also that for the various positions; at the entry of the channel (Fig. 6), the under and bottom electrode (Fig. 7) and the exit of the channel (Fig. 8), a transient state then velocity is stabilized.

Figure 9 depicts that the negative velocity will occur at a negative magnitude of MHD thrust for (r=0.013m, z=0.15m); this change of sign velocity causing the system to act as a brake.

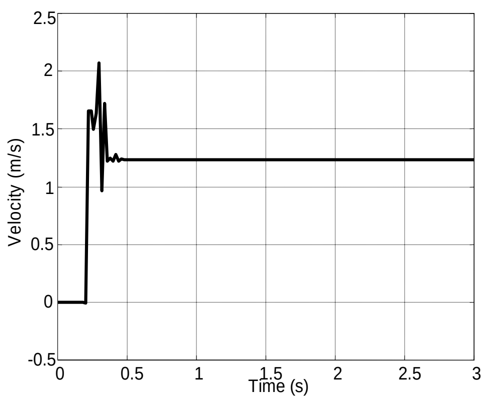


Fig. 6. Velocity at various times in the entry of the channel

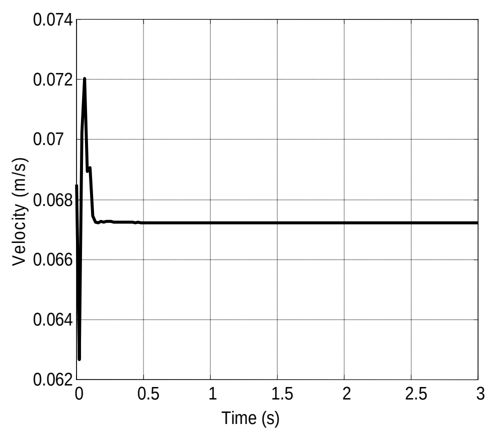


Fig. 7. Velocity at various times near the under and bottom electrode

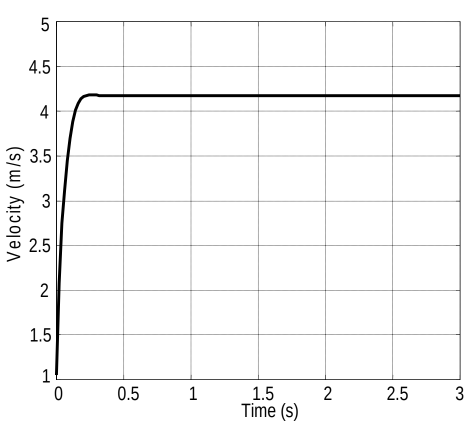


Fig. 8. Velocity at various times in the outlet of the channel

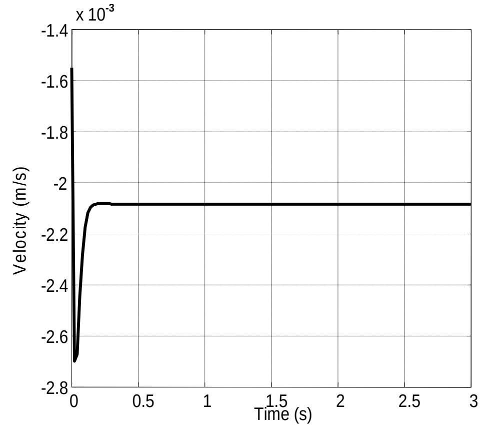


Fig. 9. Velocity at various times for (r=0.013m, z=0.15m)

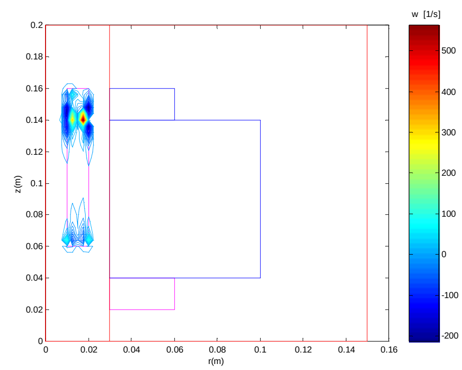


Fig. 10. Distribution of vorticity

The vorticity distribution in the duct is shown in Fig. 10. It is confirmed that the vorticity can be created by MHD forces

Figure 11 shows the velocity various times in direct and inverse mode. The velocity changed at 0.5 sec according with the electrodes current direction.

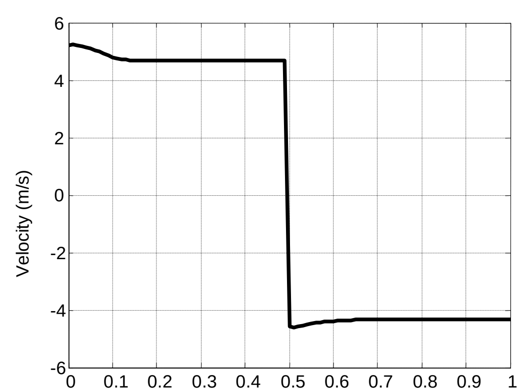


Fig. 11. Velocity various times in direct and inverse mode

4. Conclusion

It is suggested that the basic effects of the theory of propulsion MHD, which are usually concerned as special properties of pumping fluids, can also be found for the DC pump MHD.

The configuration proposed for the DC pump MHD largely simplifies the consideration. In particularly, it becomes worth noting that the new design can be employed in other application like MHD engine.

There is a need for an electromagnetic pump that works without any moving parts and produces large thrust. The results obtained are in perfect agreement with what was expected on the basis of theoretical considerations and also of results reported by other authors but obtained in different working conditions Hughes et al. (1995); Wang et al. (2004) and Takeda, Yasuaki (2005).

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