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Modeling and Optimization of the Magnetohydrodynamic Conduction Pump by Particle Swarm Method

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ABSTRACT

The paper is dedicated to the study and the optimization of a magnetohydrodynamic conduction pump. Electromagnetic pumps have several advantages to mechanical pumps, they do not use a moving mechanical part, unlike traditional electric motors, and they transform electromagnetic energy directly into kinetic energy. A fluid is set in motion in a magnetic field by an electric field supplying an electric current to the terminals of electrodes immersed in the fluid. The optimization procedure based on the particle swarm method uses a fitness function as the minimum of the mass. The electromagnetic model is carried out by the finite volume method and the steady fluid flow by COMSOL software. The optimized results of the performance characteristics of the electromagnetic pump are obtained.

Keywords: Fluid mechanics; Magnetohydrodynamic; Conduction pump; Particle swarm; Finite volume method; Fitness function; Constraints; Optimization.

NOMENCLATURE

$\vec{A}$	magnetic vector potential	β_i	projection function
$\vec{B}$	magnetic induction	σ	electric conductivity
$\vec{J}$	electric conduction current density	μ	magnetic permeability
$\overrightarrow{J_{ex}}$	induced current density	ρ	density of the fluid
$\overrightarrow{J_a}$	current density injected by electrodes	ϑ	kinematic viscosity
P	Pressure	V	flow velocity

1. INTRODUCTION

The general principle of electromagnetic pumps lies in the application a non-collinear magnetic induction $\vec{B}$ perpendicular to the current $\vec{I}$. The interaction between them produces a Laplace force which causes the movement of the conductive fluid in the channel.

These pumps have been designed without any moving parts and have many advantages over the mechanical pumps including precise flow control, reduced energy consumption (Ghassemi *et al*. 2008; Kandev *et al*. 2010; Kadid *et al*. 2004).

The fundamental concept of the flow of liquid metal under the influence of Laplace force in magnetohydrodynamic pumps is well explained in (Bahadir and Abbasov 2005; Shahidian and Ghassemi 2009).

Optimization with classic methods has been applied successfully over the last decades in all field engineering, including electrical engineering. These methods have shown their efficiency in finding suitable approximate solutions for a varied range of problems.

Particle swarm optimization (PSO), **t**his young method, inspired animal movements in swarms, has been a great success since its creation; her relative simplicity and competence make it one of the greatest used algorithms today**.**

PSO is a metaheuristic of optimization, invented by Russel Eberhart (electrical engineer) and James Kennedy (socio-psychologist) in 1995, Bai (2010).

This method of optimization is based on the collaboration of the individuals between them. It has similarities with the algorithms of ant colonies, which also rely on the concept of self-organization. This idea holds that a group of unintelligent individuals may possess a complex global organization. Thus, thanks to very simple displacement rules (in solution space), the particles can converge gradually towards a local minimum. However, this metaheuristic seems to work better for spaces in continuous variables. This algorithm has been applied successfully in several fields such as: electrical and It was applied to real world problems in both image segmentation and electronics fields, automation control systems, communication theory, operations research, mechanical engineering, fuel and energy, medicine, chemistry, and biology (Deh and Masehian (2009); El dor 2012; Ulker 2014 and Zhang *et al.* (2015).

In this paper, the design by optimization of the MHD pump by using particle swarm method is studied. In addition, the magnetohydrodynamic problem is studied using the finite volume method for the electromagnetic model and the finite element for the hydrodynamic problem.

2. DESCRIPTION OF THE CONDUCTION MHD PUMP

The structure of the MHD pump is shown in the Fig. 1. The currents of the coils generate the magnetic field which produces a current in the liquid metal. As a consequence a Laplace force acting on the fluid is obtained.

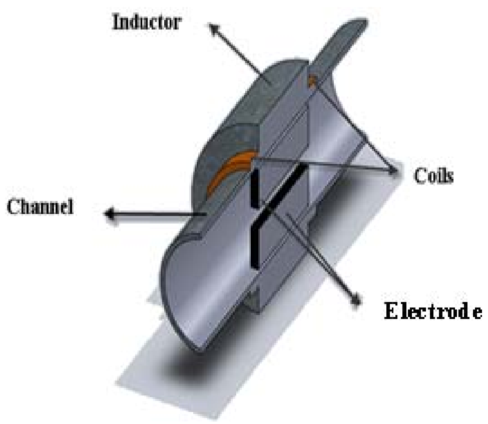

Fig. 1. MHD pump Geometry.

The fluid (mercury) considered is incompressible. The flow is supposed to be laminar and non-stationary.

The mercury's properties are summarized in table 1.

Table 1 Fluid properties

Parameters	Mercury fluid
Density ρ	13.6×10^{3} (kg/m^3)
Electric conductivity σ	1.06×10^{6} (S.m^{-1})
Viscosity ϑ	0.11×10^{-6} (m^2/s)
Relative permeability	1

3. ELECTROMAGNETIC AND HYDRODYNAMIC MODEL

The coils placed in the inductor are fed with a direct current creates a magnetic induction and induce currents in the channel. The interaction between the magnetic induction and these currents and the current injected by the electrodes develops the force of the place which makes it possible to move the fluid.

The dimensions and physical properties of a conduction MHD pump are given as follows:

Channel radius: 0,03m

Channel length: 0,18m

Electrode length: 0,1m

Electrical current: density coils J_{ex} : 2.10^6 A/m^2

Electrical current density injected by electrodes

J_a : 25.10^5 A/m^2.

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

$$\overrightarrow{rot}(\frac{1}{\mu}\overrightarrow{rot}\vec{A})-\sigma(\vec{\vartheta}\wedge\overrightarrow{rot}\vec{A})=\vec{J_a}+\vec{J_{ex}} \quad (1)$$

Using the 2D cylindrical coordinates; Eq. (1) is transformed as:

$$\frac{\partial}{\partial z}(\frac{1}{\mu}.\frac{\partial A_\varphi}{\partial z})+\frac{\partial}{\partial r}(\frac{1}{\mu}.\frac{\partial A_\varphi}{\partial r})-\sigma\vartheta\frac{\partial A_\varphi}{\partial z}=-J_a-J_{ex} \quad (2)$$

If we introduce the transformation

$$A=rA_\varphi \quad (3)$$

The Eq. (2) becomes:

$$\frac{\partial}{\partial z}(\frac{1}{\mu}.\frac{1}{r}\frac{\partial A}{\partial z})+\frac{\partial}{\partial r}(\frac{1}{\mu}.\frac{1}{r}\frac{\partial A}{\partial r})-\frac{\sigma}{r}\vartheta\frac{\partial A}{\partial z}=-J_a-J_{ex} \quad (4)$$

The integration of Eq. (4) on the control volume we obtain:

$$a_pA_p=a_eA_E+a_wA_W+a_sA_S-(a_n^{'}A_N-a_s^{'}A_S)\vartheta_z+d_0 \quad (5)$$

The equations describing the pumping process in the channel are the momentum conservation equation for laminar incompressible flows are:

$$div\vec{V} = 0 \quad (6)$$

$$\frac{\partial V}{\partial t} + (\vec{V}.\vec{\nabla})\vec{V} = -\frac{1}{\rho}\overrightarrow{grad}P + \vartheta\nabla\vec{V} + \frac{\vec{F}}{\rho} \quad (7)$$

Where

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

$$\vec{F} = (\overrightarrow{J_{in}} + \overrightarrow{J_a}) \wedge \vec{B} \quad (8)$$

The matrix of the equation system Eq. (5) is written as follows:

$$[M + jL][A] = [F] \quad (9)$$

Where:

$M + jL$: Matrix coefficients

A : Vector potential matrix;

F : Vector source matrix.

Applying the Dirichlet boundary $A = A_0$ and the Neumann conditions $\frac{\partial A}{\partial n} = 0$, the resolution is done using an iterative method.

The resolution of the electromagnetic and hydrodynamic equations makes it possible to determine the performances of the pump.

4. NUMERICAL METHOD

The numerical modeling of the electromagnetic phenomena is done using the finite volume method and the hydrodynamic model by the finite element method with the COMSOL multiphysics.

The finite volume method is characterized by a control node P surrounded by four nodes north "n", south "s", east "e", and west "w"(Fig. 2).

The resulting resolution represents an algebraic equation connecting the unknown to the node principal "P" to unknowns at neighboring nodes.

5. FORMULATION OF THE OPTIMIZATION PROBLEM

The optimization problem is to determine the minimum of the mass of the pump as follows:

Min mass (X) subjected to:

Constraints of inequalities

$$B(X) \leq 1.5 \quad Tesla \quad (10)$$

$$J(X) \leq 6.10^6 \quad A/m^2 \quad (11)$$

$$X_{lower} \leq X \leq X_{upper} \quad (12)$$

where:

X_1 : electrode's width;

X_2 : electrode's length;

X_3 : channel's radius;

X_4 : channel's length;

X_5 : inductor's radius;

X_6 : inductor's length;

X_7 : coil's radius;

X_8 : coil's length.

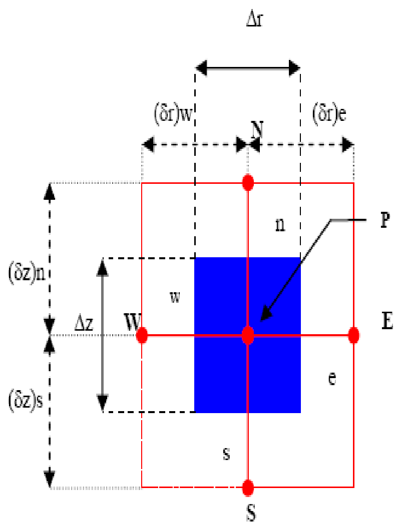

Fig. 2. Mesh domain.

6. BASIC PARTICLE SWARM OPTIMIZATION ALGORITHM

In the partial PSO, the speed and position of each particle change according the following equation Alloui and Fetha (2017).

$$V_i^k = \omega.V_i^k + c_1 r_1 (Pbest_i - x_i^k) + c_2 r_2 (Gbest - x_i^k) \quad (13)$$

$$x_i^{k+1} = x_i^k + V_i^{k+1} \quad (14)$$

where

c_1, c_2 : acceleration factors;

r_1, r_2 : random numbers in the range of 0.0 and 1.0;

ω inertia weight,

$Gbest$: gbest of the group,

$Pbest_i$: Pbest of the particle i

x_i^k : position of the particle i at iteration k.

x_i^{k+1} : position of the particle i at iteration k+1.

V_i^k : velocity of the particle i at iteration k.

V_i^{k+1} : velocity of agent i at iteration k+1.

ω : weighting function.

The flow chart represented by Fig. 3 groups together the steps of the PSO.

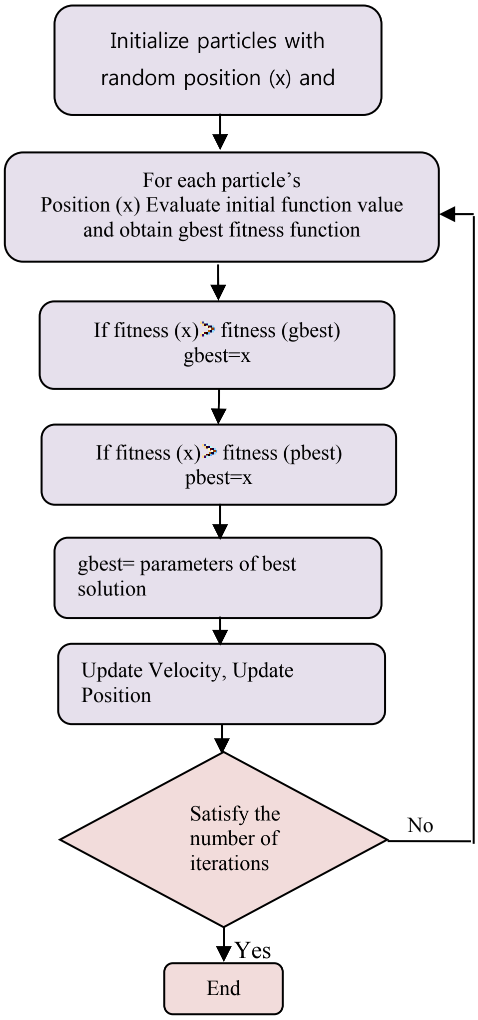

Fig. 3. PSO Flow chart.

PSO parameters used in our optimization of a conduction MHD pump are given in Table 2:

Table 2 PSO parameters

Parameters	Value
C1	1.2
C2	0.22
inertia weight	0.9
Size of the swarm	N=50
bird_ setp	50
Dimension of the problem	8

7. Establishment Of Objective Function

The accounting of the constraints in a method of optimization stochastic is often obtained by using a function of penalties associated with the objective function. Classically, we use a function of external penalty (Bouali *et al*. 2016), according to which the function to be minimized becomes equal to:

$$W(X)=f(X)+r\sum_{i=1}^{m}\left[\max\left[0,g_i(X)\right]\right]^2 \quad (15)$$

where:

$W(X)$ Objective function;

$f(X)$ Objective function without constraints;

$g_i(X)$ Constraints function;

r : Penalty coefficient.

8. Results And Discussion

The obtained results after the optimization are given in table 3.

Table 3 Results obtained by PSO method

Parameters	before optimization	After optimization
X_1 (m)	0.01	0.01
X_2 (m)	0.1	0.097
X_3 (m)	0.03	0.029
X_4 (m)	0.18	0.176
X_5 (m)	0.03	0.029
X_6 (m)	0.1	0.096
X_7 (m)	0.03	0.029
X_8 (m)	0.02	0.02
Iron mass (Kg)	20.18	18.55
Coil's mass (Kg)	1.5	1.47
Electrode's mass (Kg)	0.34	0.33
Mercury's mass (Kg)	3.33	3.04
Pump's mass (Kg)	25.35	23.39

Taking into account the results obtained, we see that the PSO method still proves its capabilities and its reliability of exploration of the field of research and gives the best optimum.

The performance of the optimized pump is represented by the figures below.

The Fig. 4 represents the conduction MHD pump in the plan (r, z).

The Figs. 5 and 6 show, respectively, the equipotential lines, the magnetic vector potential and the magnetic induction in the pump.

On each of equipotential lines and the vector potential figures, it is clear that the maximum values are located in the vicinities of the two coils.

The vector potential is less significant to the input of the electrode and it is too low along the electrode.

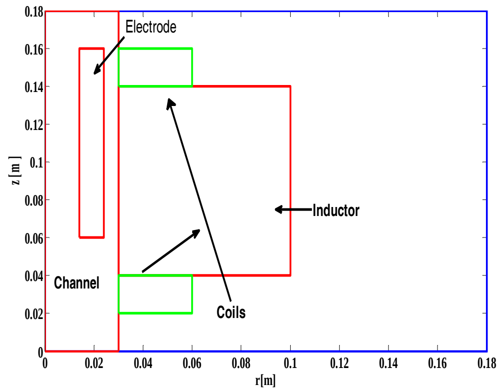

Fig. 4. Geometrical model of the conduction MHD pump.

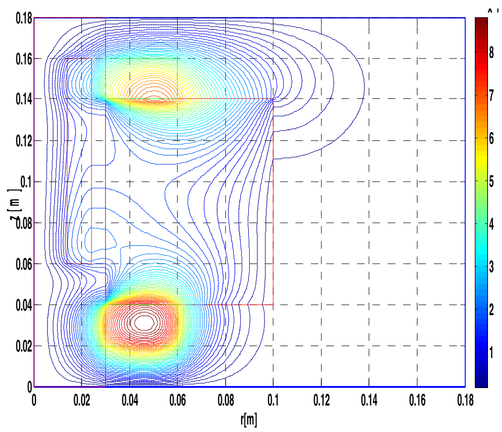

Fig. 5. Equipotential lines in the pump.

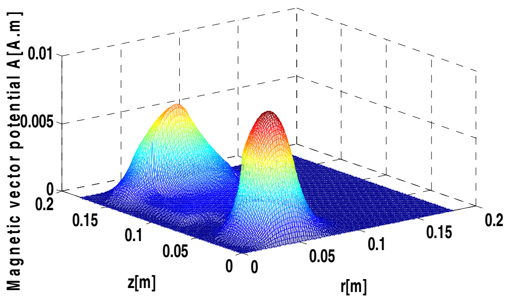

Fig. 6. Magnetic potential vector in the pump.

Figure 7 represents the magnetic induction pump; it has peaks to places of arrangement of the coils. Figure 8 shows the variation of the current density induced in the channel of the pump. It is found that the maximum value of the current density is in the coil.

Therefore, as shown in Fig. 9, the MHD thrust become much greater increases in the outlet of the electrode leading to push the mercury.

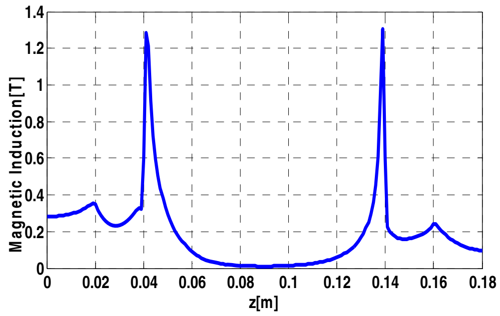

Fig. 7. Magnetic induction in pump.

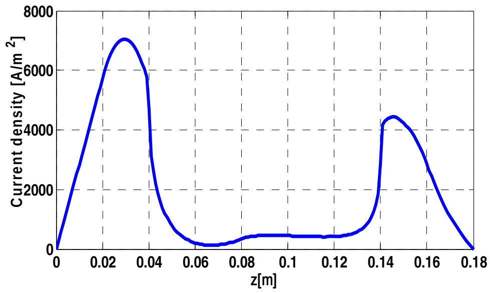

Fig. 8. Current Density in the pump.

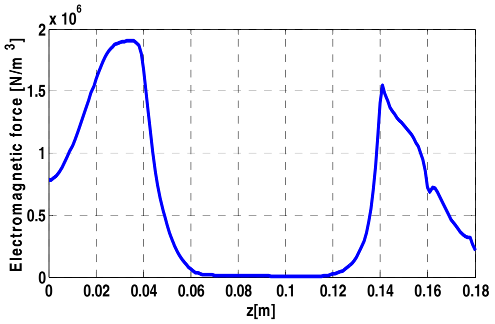

Fig. 9. MHD thrust.

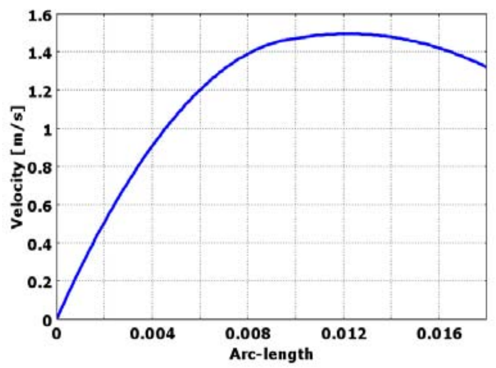

Fig. 10. Velocity in the channel.

As shown in Fig. 10, the velocity of the fluid. passes through a transient state, then it reaches a steady state as in the electrical machines.

9. CONCLUSION

This paper is aimed at the conception by optimization of the magnetohydrodynamic pump. The optimization design procedure is applied successfully by PSO method.

PSO is a powerful algorithm approach that has been applied with great success. It has a limited number of parameters to adjust.

The electromagnetic problem using the 2D finite volume method is also presented. Various characteristics are given.

The result from the CONSOL is exploited to represent the velocity in the channel of the DC MHD conduction pump.

The obtained results, regarding to the magnetic induction and current density values, show to be more suitable to create a good enough electromagnetic force in MHD pump.

It is worth to mention that the electromagnetic force becomes much greater in the outlet of the electrode leading to push back mercury further.

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