International Journal of Multiphysics
Volume 18, No. 3, 2024
ISSN: 1750-9548

# Optimal Design of an induction Annular Pump Using Cuckoo Search Approach

**Khadidja Bouali[1], Khelifa Moussa[2], Naima Benbouza[3], Nassima Bergoug[4], Fzohra kadid[5], Rachid abdessemed[6]**
[1,2,3] Department of Electrical Engineering, Faculty of Applied Science university of Kasdi Merbah Ouargla, Algeria.
[4,5,6] LEB Research Laboratory, Electrical Engineering, Department of Electrical Engineering, University of Batna, Algeria.

**Email:** bouali.khadidja@univ-ouargla.dz**,** khelifa.moussa@univ-Ouargla, benbouza.naima@univ-Ouargla.dz, bergoug_nassima@yahoo.fr, Fzohra_kadid@hotmail.com, rachid.abdessemed@gmail.com.

**Abstract**:
Magnetohydrodynamics (MHD) is a field that studies the behaviour of a fluid that conducts electric current, which can be a liquid, ionized gas, or plasma. It is a generalization of fluid mechanics, in the particular case where there is no electromagnetic field. This paper discusses a method for determining the dimensions of a pump in the shape of an annulus. The pump design issue is structured as a nonlinear optimization problem with constraints, aiming to minimize mass by utilizing the Cuckoo Search method. Both geometrical and electromagnetic constraints are applicable in this case. The results have been reported and are being discussed.

**Keywords:** Cuckoo Search. Design. Optimization. Objective Function. Magnetohydrodynamic. Annular pump.

## 1. INTRODUCTION

The magnetohydrodynamic pump (MHD) propulsion is widely utilized and studied in a variety of applications, including power generation, military submarines, and space ships. The magnetohydrodynamic pump is an attractive solution, in particular for biomedical applications [1- 2].

The MHD is the study of the interaction between an electromagnetic field and a conducting material. An MHD pump generates an electromagnetic force through a magnetic field application, resulting in fluid motion. These pumps have been crafted without any moving parts and offer numerous benefits compared to mechanical pumps, such as precise flow regulation and lower energy usage [3].

Figure 1 shows the geometry of an annular induction MHD pump. The annular type is more efficient than the rectangular type because the induced currents are always perpendicular to the flow direction. Thus, the Laplace force always has the same direction as the flow. On the other hand, in the case of a rectangular cross-section machine, the induced currents loop in a way that is less favorable for the conversion of mechanical energy into electrical energy and cause more Joule losses. The MHD pump principle is depicted in the figure 1. The working principle resembles that of an asynchronous motor. The inductor's power supply generates a magnetic field B that moves at the synchronous speed. This magnetic field induces electric currents in the liquid metal, leading to the creation of an electromagnetic force F. The flow of the fluid is then ensured by the instantaneous magnetic field. [4]

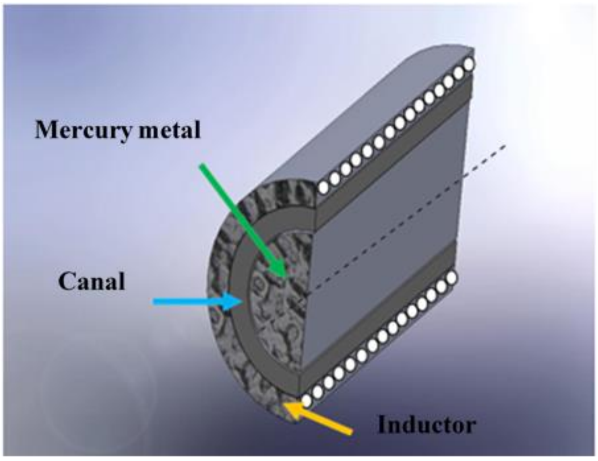


**Figure1** Schematic view of the Annular MHD pump

Optimal design methods in electrical engineering often use deterministic methods. Finding global minimums under convexity and differentiability hypotheses. If no knowledge about objective function behavior or local minima exists, stochastic methods are recommended.

Stochastic optimization techniques in the field of electrical engineering have become increasingly popular for their straightforwardness, reliable convergence, and strong likelihood of discovering targeted areas. An optimization algorithm involves an iterative process that begins with an initial estimation. After a considerable number of iterations, it may move towards a stable solution, ideally the optimal solution to the problem at hand. [5]

The Cuckoo Search Algorithm (CSA) appears as a recent intelligent optimization approach, offering notable advantages such as robust versatility, minimal control parameters, rapid algorithmic execution, etc. Currently, it has become a popular subject of study among researchers. Nevertheless, this algorithm has certain constraints, notably an unequal distribution between global exploration and local exploitation. This imbalance results in optimization towards local extremes, a slow search pace, and reduced convergence accuracy.[6]

The CSA algorithm, a modern nature-inspired meta-heuristic optimization technique, was presented by Yang and Deb in 2009 [5-6]. The CSA algorithm is inspired by the behavior of the cuckoo bird, known for depositing its eggs in the nests of other host birds. The primary objective of the cuckoo bird is to imitate the eggs of the host bird and evade detection. Thus, the optimization objective is achieved when the host bird is unable to detect the presence of the cuckoo egg. The CSA algorithm is commonly used by researchers to address a range of optimization issues, such as path planning challenges. CSA represents an advanced heuristic algorithm utilized in optimizing problem-solving processes. It's a gradual enhancement process that begins with any starting solution and aims to identify an improved solution.

The CSA is characterized as a metaheuristic optimization algorithm that has garnered considerable interest in the research community. Making adjustments to the original algorithm is necessary to enhance its performance, including reducing the population and implementing biased random walks. The algorithm is designed to help developers choose the most appropriate variation and parameters for specific types of problems, ultimately refining their solutions. It is now a well-established optimization approach that is quickly expanding into various new fields. Simulated annealing, along with other heuristic search algorithms like GA, has been identified as "highly promising" for addressing real-world applications in the future.

In this paper, we would like to demonstrate capabilities of the Cuckoo Search method in optimal design of MHD pumps.

## 2. MATHEMATICAL FORMULATION

The typical theoretical formulation of the magnetohydrodynamic model for electrically conductive and Newtonian incompressible fluids has been established by deriving it from Ohm's law for moving media, combined with the Navier-Stokes equations for smooth flow including the Lorentz force in the given equation:

$$\vec{F} = \vec{J} \times \vec{B} \tag{1}$$

Where:
$\vec{F}$: denotes the Lorentz force
$\vec{J}$: denotes the induced current density
$\vec{B}$: denotes the magnetic induction

### 2.1 Electromagnetic problem

The pump uses electromagnetic forces generated by the interaction of applied electrical currents and magnetic fields, which are derived from Lorentz forces. The MHD pump's electromagnetic model can be outlined as follows:

$$\overrightarrow{rot}\left(\frac{1}{\mu}\vec{A}\right) = \overrightarrow{J_{ex}} - \sigma\left(\frac{\partial\vec{A}}{\partial t} - \vec{\vartheta} \wedge \overrightarrow{rot}\vec{A}\right) \quad (2)$$

The magnetic induction is expressed as:

$$\vec{B} = \overrightarrow{rot}.\vec{A} \quad (3)$$

Where:
$\vec{A}$: denotes the magnetic vector Potential
$\overrightarrow{J_{ex}}$: denotes the current density excitation
$\vec{J}$: denotes the Induced current density
$\vec{\vartheta}$: denotes the kinematic viscosity
σ: denotes the electric conductivity
μ: denotes the magnetic permeability.

### 2.2 Hydrodynamic Problems

The MHD flow of an incompressible, viscous and electrically conducting fluid in a transient state condition is governed by the Navier-Stokes equations:

$$\frac{\partial V}{\partial t} + (\nabla.\vec{V})\vec{V} = -\frac{1}{\rho}\overrightarrow{grad}P + \vartheta\nabla\vec{V} + \frac{\vec{F}}{\rho} \quad (4)$$

$$div\vec{V} = 0 \quad (5)$$

Where:
**P:** denotes the pressure of the fluid,
$\vec{V}$: denotes the flow velocity,
ρ: denotes the fluid density.

### 2.3 Thermal problem

The thermal phenomena are exclusively analyzed within the MHD pump's channel. The thermal equation that governs the process is as follows:

$$\rho C_p\left(\frac{\partial T}{\partial t} + \vec{\vartheta}.\overrightarrow{grad}T\right) = div\left(K\overrightarrow{grad}T\right) + P_s \quad (6)$$

$$P_s = \frac{1}{2\sigma}J_i^2 \quad (7)$$

Where ρ is the density of the fluid, Cp the specific heat, K the thermal conductivity, T the temperature and Ps the thermal source (electric power density) induced by eddy current.

Simplified schema of the MHD model, channel length = 0.7m, height = 0.02 m and width of the inductor =0.15 m. Magnet length = 0.5 m.

In this study, where the model must represent an actual pump for mercury, working at different operating conditions, liquid mercury at 356.7°C is used as an electrically conductive fluid with density $\rho = 13.6 \times 10^3 Kg.m^3$, electric conductivity $\sigma = 1.06 \times 10^6 S/m$, relative permeability μr=1.55 and kinematic viscosity $\vartheta = 0.11 \times 10^{-6} m^2/s$.

## 3. NUMERICAL PROCEDURE

The finite volume method was selected for solving the electromagnetic, hydrodynamic, and thermal equations.

The study area is divided into a number of elements (Fig. 2) Each element is comprised of four interconnected mesh nodes. Each mesh node is enclosed by a finite volume. In this approach, every node P, positioned at the center of the control volume, is entoured by four nodes N, S, E, and W. These nodes serve as the centers' of neighboring control volumes situated to the north, south, east, and west of the central one. The equations (2), (4), and (6) are integrated across each volume.

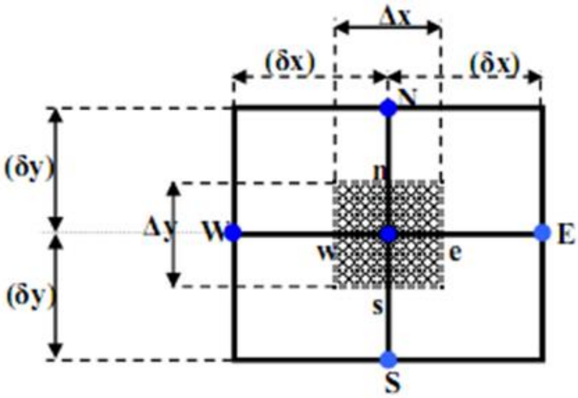


**Figure 2**. Discretization in finite volume method

## 4. OPTIMIZATION PROCEDURE

The complexity of MHD pump design led to the decision to approach it as an optimization problem. An optimization problem is a computational problem where the goal is to find the globally optimal solution (global minimum or global maximum) within a specified confined space of optimized parameters. Metaheuristic algorithms can be used to speed up the process of searching every point in a dataset, as it requires less computational power [7- 8- 9].

To formulate the optimization problems, it is necessary to define the objective function to be optimized. In this case, we have considered the mass of an annular induction MHD pump. The rest of the criteria of the schedule conditions will be used as constraints of equalities and inequalities.

The resolution of the design problem will be equivalent to the resolution of the optimization problem defined as follows: To determine the unknown vector X: X= (x1, x2... x6) which minimizes the objective function weight (X):

Min Mass (X) Subjugated with:

Constraints of inequalities:

$$B(X) \leq 1.5\ Tesla \quad (8)$$

$$J(X) \leq 6 \times 10^6\ {}^{A}/_{m^2} \quad (9)$$

Thrusts fixing the acceptable field:

$$X\ min \leq X \leq X\ max \quad (10)$$

$$X = (x_1, x_2. x_3, x_4, x_5, x_6). \quad (11)$$

The optimization problem with constraints, is transformed into a problem without constraints using the external penalties method [12].

The optimization problem becomes:

$$Min\ mass\ (X) = f(X) + r^m \left[max^2\left(0, \frac{B}{1.5} - 1\right) + max^2\left(0, \frac{J}{6\times10^6} - 1\right)\right] \quad (12)$$

Where:

f(x): The mass of the pump without constraints;

r=1, and m=0. 1.

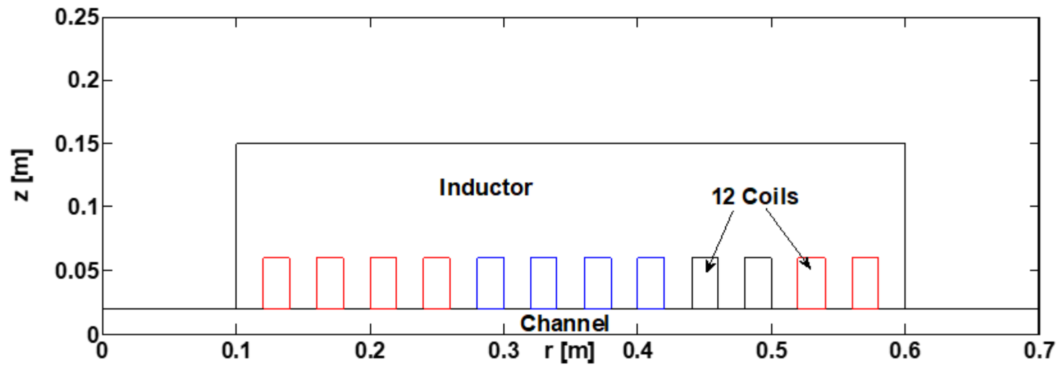


**Figure 3.** Geometrical model of annular MHD pump

Where:

$X_1$: channel length

$X_2$: channel width

$X_3$: inductor length

$X_4$: inductor width

$X_5$: coil width

$X_6$: coil length

## 5. CUCKOO SEARCH ALGORITHM (CSA)

Cuckoo research draws inspiration from nature, particularly from the interspecific brood parasitism observed in some cuckoo species that lay their eggs in the nests of other bird species to avoid parental responsibilities.

This strategy is also useful for minimizing the risk of egg loss, as cuckoos can distribute their eggs among a large number of different nests [10-11].

The cuckoo lays its eggs in the nests of other birds, a behavior called brood parasitism, which allows it to ensure the transmission of its offspring by using the natural insufficiencies of host birds to raise their young. To increase the probability of this, the female cuckoo often removes a host egg before laying her own.

However, some host birds may conflict with the intruding cuckoo, and have developed strategies to recognize and avoid this behavior [12].

Indeed, some host birds have evolved the ability to recognize cuckoo eggs in their nest, notably thanks to a sensitive, bare area of skin under their belly that allows them to detect differences in temperature and texture.

In some cases, they may reject or abandon the nest in response to the presence of a cuckoo egg.

However, some types of cuckoos, such as the Tapera, have evolved to mimic their hosts' eggs in terms of color and shape. This makes it more difficult for the host bird to detect the presence of the cuckoo egg, thereby increasing the chances of success of the cuckoo's brood parasitism strategy. This mimicry ability may vary depending on the cuckoo species and the host species involved [13].

### 5.1 Main components of cuckoo search

In cuckoo search, nest and egg are two important components of metaheuristic algorithm

**A. Nest**

The main characteristics of nests are:

- The number of nests is fixed and equal to the population size.
- Each nest represents a possible solution to the optimization problem.
- Nests are considered as individuals in a population.
- Nests can be replaced by new randomly generated solutions.
- Each egg in a nest represents an improved solution from the previous solution, obtained by applying the cuckoo search meta-heuristic.

**B. Eggs**

Egg is one of the main components of cuckoo search. In this optimization method, each egg in a nest represents a possible solution to an optimization problem.

Cuckoos deposit them in the nests of other birds in order to avoid raising their own offspring and minimize the risk of loss.

In cuckoo search, eggs deposited in nests represent different possible solutions.

New solutions are created by replacing existing eggs with new ones (cuckoo eggs) that result from modifications to previous solutions.

**C. Objective function**

The objective function (or fitness function) evaluates the quality of a solution in the search space by assigning it a numerical value.

In the case of cuckoo search, the quality of a nest is measured according to the egg it contains, because it is the latter that determines the ability of a cuckoo to reproduce and propagate in future generations [14].

Thus, the quality of the cuckoo egg is directly linked to its ability to generate a new generation of cuckoos.

**5.2. Lévy flight**

Lévy flight is a probability distribution used in probability theory and statistics, and is often used in cuckoo search. It is named after the French mathematician Paul Lévy, who introduced it in 1925 [14-15].

Lévy flight is characterized by random jumps of variable length, which allow the algorithm to cover large distances in the search space efficiently.

It is often used to simulate the movements of animals when they search for food, and is considered an alternative to the classical random walk, which is more limited in its scope [13].

In cuckoo search, Lévy flight is often used to model the movements of cuckoos when they search for nests to lay their eggs [14- 15].

It allows to diversify the proposed solutions and to explore the search space more efficiently.

## 6. PRINCIPLES OF CSA

The principle of CSA is to simulate the foraging and breeding behavior of cuckoos in nature to solve problems.

The breeding behavior of cuckoos consists of laying an egg in a nest belonging to another bird species and then leaving the parental nest.

The eggs are then incubated and fed by the adoptive parents until hatching.

## 7. CUCKOO SEARCH ALGORITHM

The CSA uses a set of nests (solutions) to perform the search. Each nest is represented by an n-dimensional vector xi, where i is the nest index. The total number of nests is set to N, which is the population size.

The CS algorithm works according to the following steps: [15]

1. Generate an initial population of n random host nests.
2. Evaluate the fitness of each nest using the objective function f(x).
3. Initialize the best solution as the solution of the first nest.
4. While the current generation is less than or equal to Max Generation:

**For each nest:**

1. Select a random neighboring nest.
2. Generate a new egg (new solution) by performing Lévy Flights.
3. Evaluate the quality/fitness of the cuckoo egg using the objective function f(x).
4. Compare the quality/fitness of the cuckoo egg with that of the current solution in the nest.
5. If the quality/fitness of the cuckoo egg is better, replace the solution in the nest with the cuckoo egg.
6. Abandon a fraction pa (probability of egg discovery by the host bird) of the worst nests (solutions) and build new random nests.
7. Select the best solution among all nests.
8. Update the best solution if the quality/fitness of the current best solution is improved.
9. Return the best solution found.

Figure 4 illustrates the flowchart of the cuckoo search approach

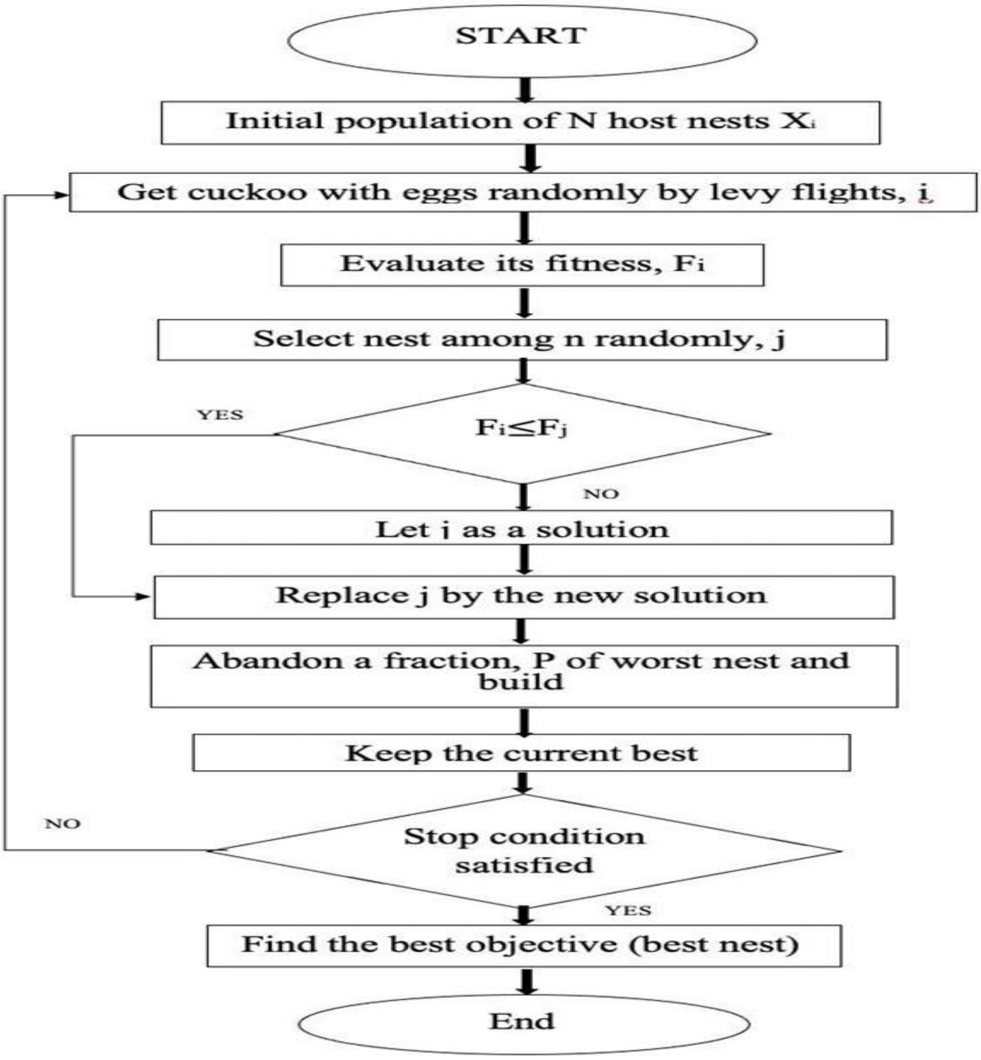


**Figure4.** Cuckoo algorithm flowchart [15]

The Cuckoo search algorithm can be represented using the following pseudo code: [15].

**begin**
Objective function f(x), x = $(x1,.,xd)^T$
Generate initial population of n host nests xi (i = 1, 2,.,n)
**while** (t < Max Generation) or (stop criterion)
Get a cuckoo randomly by Levy flights
evaluate its quality / fitness Fi
Choose a nest among n (say, j) randomly
**if (Fi > Fj),**
replace j by the new solution;
**end**
A fraction (pa) of worse nests
are abandoned and new ones are built;
Keep the best solutions
(or nests with quality solutions);
Rank the solutions and find the current best
**end while**
Postprocess results and visualization
**End**

## 8. CUCKOO SEARCH OPTIMIZATION RESULTS

Tables 1 and 2 show the results obtained by Cuckoo Search approach.

TABLE 1. Pump performances

| Performance | Cuckoo Search |
|---|---|
| Best function (kg) | 13.744 |
| Number of iterations | 100 |

TABLE 2. Pump dimensions obtained by Cuckoo Search approach

| Parameters | Dimension without optimization | Dimension with optimization Cuckoo Search |
|---|---|---|
| Channel's width (m) | 0.02 | 0.0184 |
| Channel's length (m) | 0.7 | 0.6930 |
| Inductor's length (m) | 0.5 | 0.49 |
| Inductor's width (m) | 0.13 | 0.1281 |
| Coil's length (m) | 0.02 | 0.02 |
| Coil's width (m) | 0.04 | 0.035 |
| Pump's masse (Kg) | 14.8649 | 13.744 |

## 9. APPLICATION AND RESULTS

The resolution of the electromagnetic, thermic and the hydrodynamic equations makes it possible to determine the magnetic potential vector $\vec{A}$, magnetic induction$\vec{B}$ and the Electromagnetic force $\vec{F}$, velocity and the temperature in the channel of the induction pump.

With this optimal vector dimension, we have presented the 2D numerical modelling of the coupling electromagnetic- hydrodynamic– thermic phenomena using the finite volume method in cylindrical coordinate. Figures (5) and (6) present respectively, the distribution of the magnetic vector potential $\vec{A}$ and the Magnetic induction in the MHD pump.

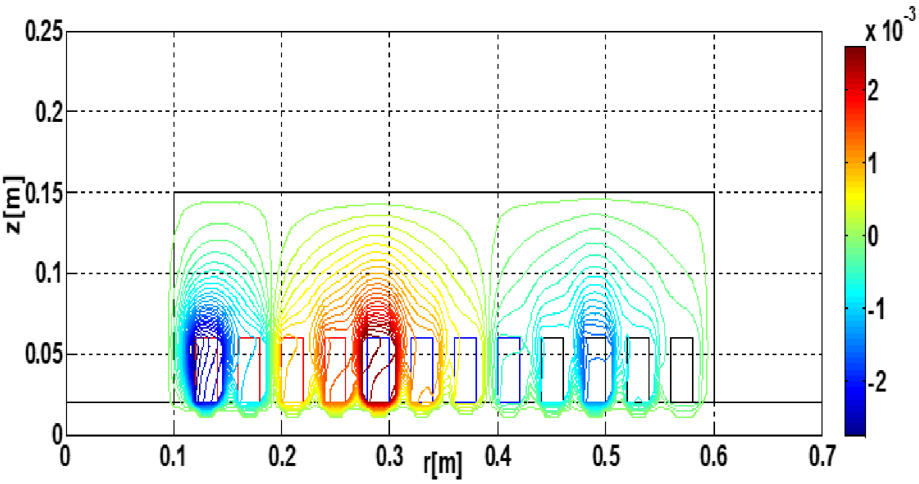


**Figure 5** Distribution of magnetic vector potential in the MHD Pump

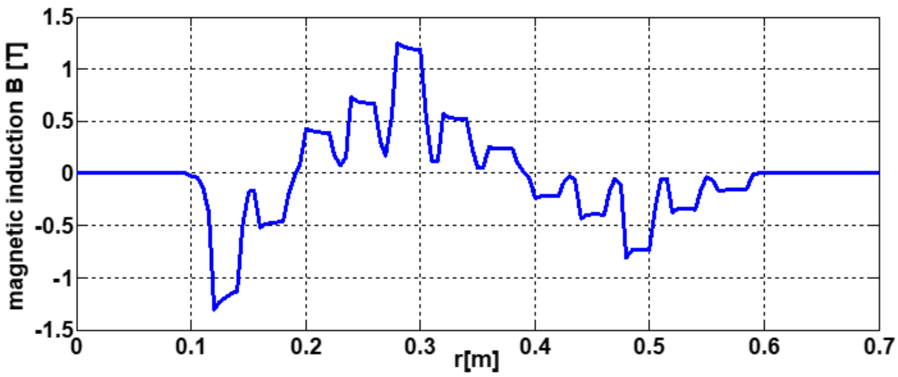


**Figure 6.** Magnetic induction in the MHD pump

It is clear that the magnetic induction B reaches its limit value at the inductor and decreases as one moves away from the field.

Figures 7 and 8, present respectively, the current density and electromagnetic force in the channel of the MHD pump.

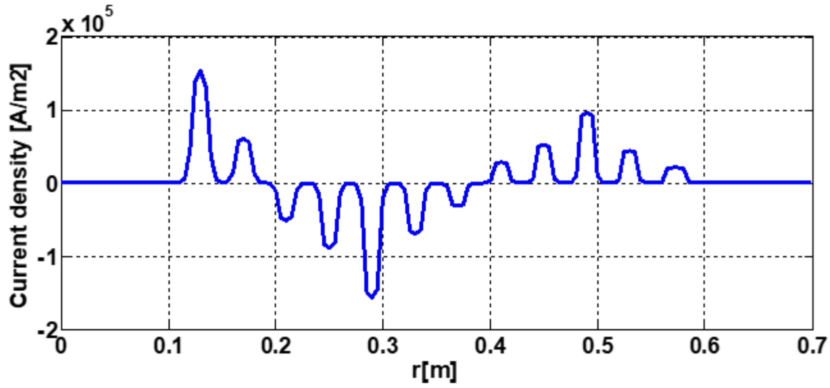


**Figure 7.** Current density in the MHD pump

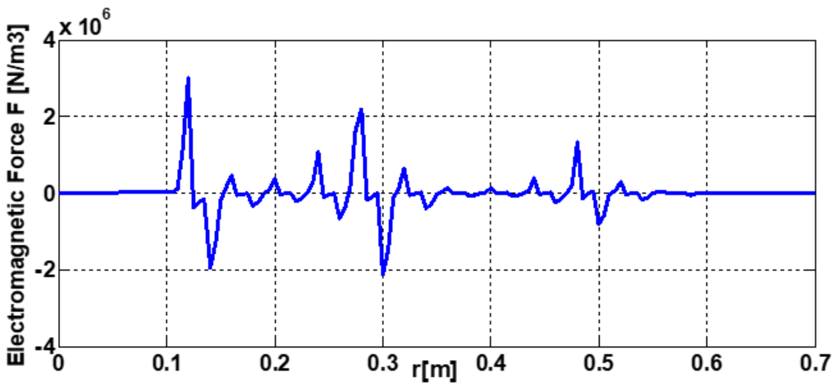


**Figure 8** Electromagnetic Force in the MHD pump

The hydrodynamic model of the MHD pump is based on the Navier-Stokes equation. The solution of the flow equations allows the determination of the velocity in the channel of the MHD pump.

Figure 9 presents the variation of the velocity in the pump channel. We note that the velocity of the fluid passes through a transitional period and then stabilizes as in all the electrical machines. The velocity increases as we advance in the channel.

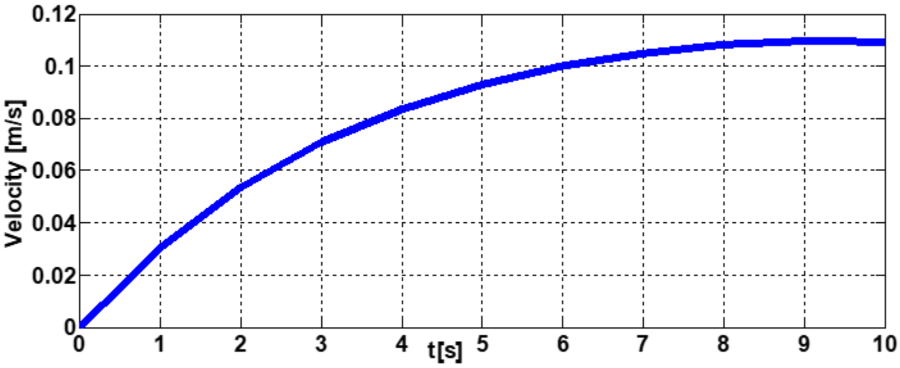


**Figure 9.** Variation of the velocity in the pump's channel

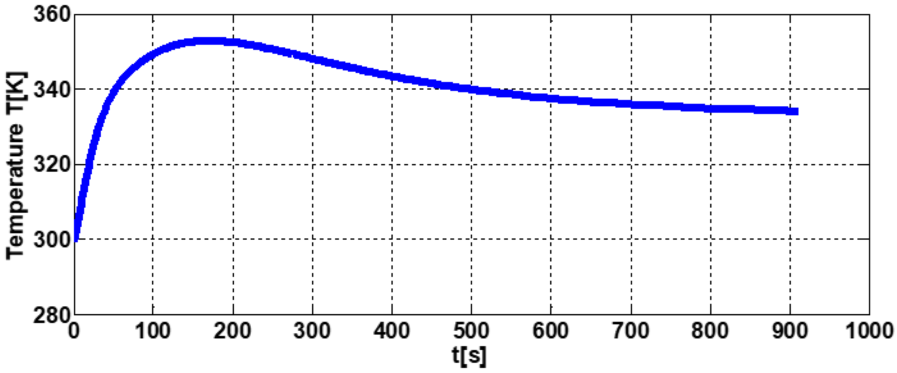


**Figure10.** The temperature in the channel of the MHD pump

The figure **10** shows the distribution of the temperature in the channel of the MHD pump. It is noticed that the temperature passes by a transitory mode then is stabilized.

## 10. CONCLUSION

The main characteristics of CS algorithm is its simplicity. The applications of CS into engineering optimization problems have shown its encouraging efficiency. For example, the optimal design of an annular induction MHD pump studied in this paper for assumes the minimum of mass as the objective function. This method has several advantages as a good quality solution where the constraints can be easily introduced.

The modelling of MHD problems for incompressible fluids is approached by a coupling of numerical methods. The choice of the methods used was made according to the main characteristics of the physical phenomena.

The finite volume method was thus chosen to treat the three electromagnetic-hydrodynamic and thermal problems. The associated principal algorithm is presented in the form of an iterative process composed of an electromagnetic calculation, a flow calculation and a thermal calculation. Convergence is reached when the speed and the temperature no longer vary between two successive iterations.

The obtained results show that the optimized pump has a good performance. According to the obtained results, we see the strong capacity of the Cuckoo Search method in obtaining the optimum of the pump mass.

## REFERENCES

1. Bergoug, N., Kadid, F. Z., & Abdessemed, R. (2013). numerical modelling of the coupling electromagnetic hydrodynamic equations of an annular induction MHD pump. *U.P.B.Sci Bull*, *75*.
2. Borghi, C. A., Cristofolini, A., & Fabbri, M. (1998). Study of the Design Model of a iquid Metal Induction Pump. *IEEE Transaction on Magnetics*, *October*. https://doi.org/10.1109/20.717690.

3. Dhivya, M., Sundarambal, M., Anand, L. N., & Al, E. T. (2011). Energy Efficient Computation of Data Fusion in Wireless Sensor Networks Using Cuckoo Based Particle Approach ( CBPA ). *Int.J. Communications, Network and System Sciences*, *2011*(April), 249–255. https://doi.org/10.4236/ijcns.2011.44030.
4. Gherboudj, A., Abdesslem Layeb and Salim Chikhi. (2012). Solving 0-1 knapsack problems by a discrete binary version of cuckoo search algorithm Solving 0-1 knapsack problems by a discrete binary version of cuckoo search algorithm *Int.J. Bio-Inspired Computation*, *May*. https://doi.org/10.1504/IJBIC.2012.048063.
5. Gherboudj, A. (2013). *methodes de resolution de problemes difficiles academiques*. constantine 2.
6. Layeb, A. (2012). A Novel Quantum Inspired Cuckoo Search Algorithm for Bin Packing Problem. *I.J.Information Technology and Computer Science*, *May*, 58–67. https://doi.org/10.5815/ijitcs.2012.05.08.
7. Liu, P., & Zhang, S. (2021). A Novel Cuckoo Search Algorithm and Its Application. *Open Journal of Applied Sciences*, 1071–1081. https://doi.org/10.4236/ojapps.2021.119079
8. Mareli, M., & Twala, B. (2018). Applied Computing and Informatics An adaptive Cuckoo search algorithm for optimisation. *Applied Computing and Informatics*, *14*(2), 107–115. https://doi.org/10.1016/j.aci.2017.09.001
9. Merdj, F., & Drid, S. (2022). Electromagnetic Forces Effects of MHD Micropump on the Blood Movement. *Journal Europeen Des Systemes Automatises*, *55*(1), 147–153.
10. Pandya, K., Universiy, P., & Joshi, S. K. (2016). *Reactive Power Optimization in Wind Power Plants Using Cuckoo Search Algorithm Reactive Power Optimization in wind power plants using Cuckoo Search Algorithm*. *December*. https://doi.org/10.1007/978-3-319-26245-1.
11. Ramli, R. (2010). Recent Advancements of Nurse Scheduling Models and A Potential Path Recent Advancements of Nurse Scheduling Models and A Potential Path. *Proceedings of the 6th IMT-GT Conference on Mathematics Statistics and Its Applications*, *May*.
12. Reda, M., Onsy, A., Haikal, A. Y., & Ghanbari, A. (2024). Path planning algorithms in the autonomous driving system : A comprehensive review. *Robotics and Autonomous Systems*, *174*(January), 104630. https://doi.org/10.1016/j.robot.2024.104630.
13. Safi, M., & Khater, T. A. (2016). Review of magnetohydrodynamic pump applications. *Alexandria Engineering Journal*, *March*. https://doi.org/10.1016/j.aej.2016.03.001.
14. Shiralkar, S., Bahulekar, A., & Jawade, S. (2022). The Cuckoo Search Algorithm : A review . *Internatinal Research Journal of Engineering and Technology*, 1238–1246.
15. Yang, X., & Deb, S. (2009). *Engineering Optimisation by Cuckoo Search*. 1–17.