International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 10, October- 2014

Drag Force Based Flowmeter Design for Conducting Fluids

Sapna.P. P
Department of Electronics and Communication
Mahatma Gandhi University College of Engineering,
Thodupuzha, Kerala, India

Abdul Hakeem M. A.
Department of Electronics and Communication
Mahatma Gandhi University College of Engineering,
Thodupuzha, Kerala, India

Abstract **–A force measurement based contactless flowmeter for measuring the flowrate of electrically conducting fluids can be obtained. This force is called drag force, and is due to the interaction of electrically conducting fluids with an externally applied magnetic field, which thereafter dragging the magnetic system along the flow direction. The force depends linearly on the mean velocity of the fluid flow and can be measured using force sensors. The flow rate can be obtained from this electromagnetic force. The main technological challenge occurs when the fluid to be evaluated is low conducting. Optimization of the magnetic system is required for generating a strong enough field for a measurable drag force. The aim of this project is to evaluate and design a basic flowmeter using the above principle by numerical modelling of the flowmeter scheme, optimizing the parameters for highest output at reasonably low computational cost. The numerical model has been developed using COMSOL Multiphysics software and for optimization of magnetic system optimization tool box in MATLAB has been used.**

Keywords— Magnetohydrodynamics, electromagnetic flow measurement, contactless measurement.

I. INTRODUCTION

Sometimes, fluids used in the heavy industry often are typically opaque, aggressive, or high temperature or cryogenic in nature and common flow measurement devices cannot be used. In recent times, there is great interest in flow measurement for liquid metals and semiconductor fluids. Chemical and pharmaceutical industry requires high purity fluids where measurements by non-contact non-intrusive methods become important. Acids or many kinds of fluids are aggressive and may corrode parts of flowmeter which in turn might affect fluid. In view of these problems, development of a non-intrusive method assumes significance. A novel flow measurement technique called Lorentz force velocimetry (LFV) is proposed and attempt to design such a flowmeter is made [1].

II. PRINCIPLE

A method by which the flow rate of electrically conducting fluids can be measured without any physical contact between the fluid and measurement system is called Lorentz Force Velocimetry (LFV). Measurement is based on the drag force on magnetic field lines which cross the fluid flow.

The fluid flow and constant transversal magnetic field interaction is what underlies the principle of LFV (see Fig.1).

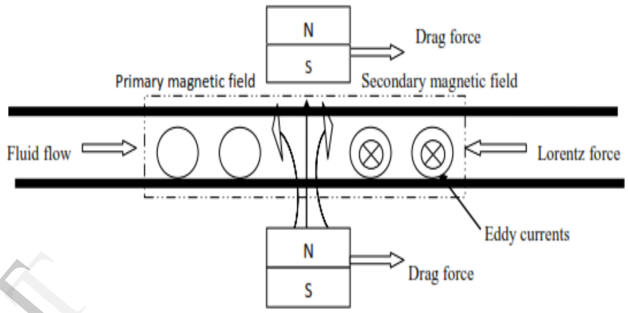

Fig.1. Principle of LFV

Fig 1 shows the magnetic field B, which is generated by permanent magnet at rest, interacting with the fluid flowing with a constant velocity v across. According to Faraday's law, the relative motion between the fluid flow and the primary magnetic field B gives rise to the eddy current j in the flow. This eddy current interacts with the magnetic field B and produces a force (Lorentz force F_L) which breaks the flow, slowing it down. As Newton's third law indicates, an opposite force, equal in magnitude, will be acting on the magnet system (MS) through which the stream is passing, so that there is measurable drag on the MS. The measure of drag force gives measure of the Lorentz force. The Lorentz force hence obtained will be proportional to the velocity v, the electrical conductivity of the fluid σ, and the square of the magnetic flux density B. Thus the Lorentz force density is roughly

$$F = \sigma \, v \, B^2 \quad (1)$$

Thus, by knowing these parameters, the flowrate can be derived from the Lorentz force as measured in the MS. The force F growing with second power of the magnetization is end result as the magnet acts as a source of the primary magnetic field and a sensor of the secondary magnetic field simultaneously. Thus by increasing the strength of the magnetic field, the sensitivity of the LFV can be increased. Due to this LFV is potentially suitable even for low conducting liquids like brine solutions, glass melts etc which are inaccessible to any other non-contact electromagnetic measurement method

III. NUMERICAL MODEL

The research initially models a two magnet system followed by a Halbach array, a set of permanent magnets which provides one-sided magnetic flux, and develops a numerical method to optimize the system. A small system was considered and a numerical procedure was devised with reduced number of optimization points which was later compared with turbulent model for accuracy. The AC/DC module and CFD module of the COMSOL Multiphysics were used to solve the electromagnetic equations in 2D and 3D. For obtaining maximum force subject to the constraint of keeping the magnet system below a given mass optimization of the magnet system was done. The iterative optimization technique sequential quadratic programming (SQP) was used which is contained in the MATLAB optimization toolbox.

This research was performed for the following initial data: Electrolyte velocity v=5m/s, electrolyte electrical conductivity σ =4S/m, electrolyte cross-section area S=0.05m x 0.05m, remanence of the permanent magnets B = 1.445 T [2].

IV. MAGNET SYSTEM OPTIMIZATION

The magnetic system optimization for LFV of electrolytes took place in two steps: First, selection of the magnet system components; second, optimization of the magnetization directions and magnet dimensions.

The primary consideration was taken to answer whether to use permanent magnets or solenoidal coils to generate the magnetic field. PMs were chosen, after preliminary calculations and a literature survey, since the MS weight is restricted, and only PMs can generate a relatively high magnetic field with an operating weight of less than 1 kg [10].

The next question to be answered was whether an iron yoke is to be used in the LFV for electrolytes or not. To answer this question, two magnet systems were simulated with and without an iron yoke. The results showed that the magnet system without an iron yoke is much more efficient, efficiency being defined as the ratio between the drag forces.

For high conducting liquid metals we consider eutectic alloy GaInSn which is liquid at room temperature with electrical conductivity $\sigma=3.46\times10^{6}$ S/m and density 6.44kg/m^3. For a remanence of 1.445T the Lorentz force obtained, F=22.528N.

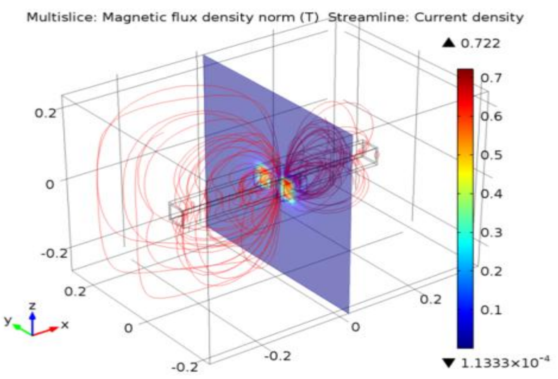

Fig. 2. Magnetic flux density and current density for a duct with liquid metal

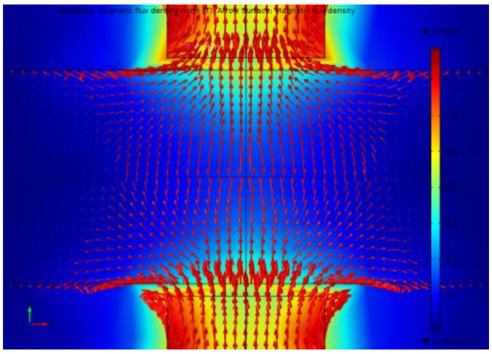

Fig.3. Magnetic flux density B (T) plot in the z = 0 symmetry plane in the electrolyte.

A. *Optimization Procedure*

For low conducting liquids, optimization of the magnet arrangement was done in order to maximize F_L, because our measurement system cannot measure forces lower than 10 μN. In other words, we would increase the resolution of the measurement system for lower flow velocities and lower electric conductivities, by achieving the highest possible Lorentz force [3].

To maximize the force obtained the channel should be made of conducting materials. On analysis we obtained force of 1.0352×10^{-5}N for a pipe material made of steel and this force decreased to 6.7007×10^{-7}N for PVC pipes which are insulating.

For better optimization a magnet system was made of two Halbach arrays were placed opposite to each other on either side of the channel. Each array consists of N rectangular magnets, with magnetization pointing alternatively in the x and y directions. The two arrays are designed so that opposite pairs of magnets is of the same dimension. All magnets have the same size x_2 and x_3 in the y and z direction but magnets with stream wise and upstream wise spins may have different dimensions x_4 from magnets with crosswise spins.

To solve the optimization problem, from the optimization toolbox in MATLAB, the fmincon function was used. It is convenient to consider the optimization problem with two design variables to illustrate the design space, the objective function, the nonlinear constraint and the optimal point [4]. To do so, the magnet system with two magnets can be considered as follows. The design variables chosen are linear dimensions of the magnets: length x_1 (along the x axis), width x_2 (along the y axis) and height x_3 (along the z axis). To deal with two design variables, we fixed x_2 = 0.0175 m. Consider a negative Lorentz force (objective function) which is minimized over design space 0.02 m $\leq x_1 \leq$0.03 m and 0.04m$\leq x_3 \leq$0.05 m and subject to the inequality constraint $G=2\times7500\times0.0175x_1x_3 - 0.32 \leq 0$, where m = 0.32 kg. The objective function was fixed with a polynomial of second order using Least Square Fit(LSF) and had the following structure: $F(x_1, x_3) = -(p_1x_2 + p_2x_1x_3 + p_3x_1 + p_4x_2 + p_5x_3 + p_6)$, where p_1 =−0.00689353, p_2 = 0.00672299, p_3=-0.000384385, p_4=−0.00457709, p_5=0.000420421, p_6=−0.0000130944 are coefficients of the polynomial. Using the fmincon function, the solution of this problem was found at point $x_1^{opt} = 0.028\text{m}, x_2^{opt} = 0.0104\text{m}, x_3^{opt} = 0.0467\text{m}$ in which F=-1.004×10^{-4}N.

The optimization problem could be then written as:

$$\text{Minimize} \quad (-1) \cdot F(x_1, x_2, x_3)$$
$$\text{Subject to} \quad 2 \cdot \rho \cdot x_1 \cdot x_2 \cdot x_3 - m \leq 0$$
$$x_i^{low} \leq x_i \leq x_i^{up}, i = 1,2,3 \quad (2)$$

First, the design space is initialized, i.e. for each design variable the lower, middle and upper values and the step size are defined: $x_i = x_i^{low}\, x_i^{mid}\, x_i^{up}$, $\Delta x_i = x_i^{up}\, x_i^{mid} = x_i^{mid}\, x_i^{low}$, Second, the objective function is calculated for the given values of variables using the numerical model described previously. The polynomial expression of F(x) is obtained using the least square fit. It includes ten terms up to second order.

$$F(x_1, x_2, x_3) = p_1x_2 + p_2x_1x_2 + p_3x_1x_3 + p_4x_1 + p_5x_2 + p_6x_2x_3 + p_7x_2 + p_8x_2 + p_9x_3 + p_{10}. \quad (3)$$

Here, c_i i=1... 10 are the coefficients of the polynomial. Once the polynomial has been obtained for the magnet system with its particular parameters, the optimization problem Eqn. (4.15) can be formulated and solved. After that the step size Δx_i is refined around the optimizer x^{opt}. The new step size is $\Delta x_i^{new} = \Delta x_i/3$. Then steps 1-3 of the optimization flow chart are repeated to obtain more accurate results.

B. Magnet System Containing Halbach Array

Replacing a two-magnet system with any Halbach array typically doubles or triples the efficiency of the system. Optimal dimensions and aspect ratios of the magnets for N = 1, 3, 7 and 9 are plotted against the maximum magnet system's weight.

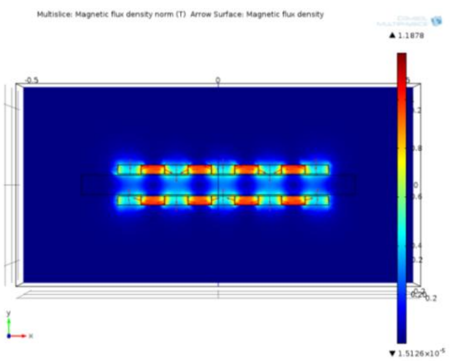

Fig.4. Magnetic flux density norm (T) of magnetic system with Halbach array (N=9).

Here there are four design variables to deal with [5]. The optimization algorithm is as discussed before. The optimization problem changes to:

$$\text{Minimize } (-1) \cdot f(x1, x2, x3, x4)$$
$$\text{subject to} \quad 2 \cdot \rho \cdot x2 \cdot x3\,(n1 \cdot x1 + n2 \cdot x4) - m \leq 0$$
$$x_i^{low} \leq x_i \leq x_i^{up}, i = 1,2,3,4 \quad (4)$$

Here, n1 and n2 are the amounts of odd and even magnets in Halbach arrays, respectively. The polynomial expression for the objective function is changed to:

$$f(x_1, x_2, x_3, x_4) = p_1 x_2 + p_2 x_1 x_2 + p_3 x_1 x_3 + p_4 x_1 x_4 + p_5 x_1 + p_6 x_2 + p_7 x_2 x_3 + p_8 x_2 x_4 + p_9 x_2 + p_{10} x_2 + p_{11} x_3 x_4 + p_{12} x_3 + p_{13} x_2 + p_{14} x_4 + p_{15} \quad (5)$$

Here, c_i, i=1,..., 15 are the coefficients of the polynomial. Once the polynomial has been obtained, the optimization problem can be formulated and solved. After that the step size Δx_i is refined around the minimiser and steps 2, 3, and 4 are repeated to obtain more accurate results.

Table 1.Optimized results of the magnet system with two Halbach arrays:(a) N=3, (b) N=5, (c) N=7, and (d) N=9 magnets in each array.

N	x1(m)	x2 (m)	x3 (m)	x4 (m)	f_{opt} (N)	m(kg)
1	0.0208	0.0104	0.0467	-	1.004e-4	0.32
3	0.0153	0.0125	0.0491	0.0163	1.967e-4	0.32
5	0.0133	0.0113	0.0489	0.0134	4.237e-4	0.6
7	0.0134	0.0123	0.0343	0.0123	5.162e-4	0.7
9	0.0175	0.0104	0.0382	0.0156	6.738e-4	0.9

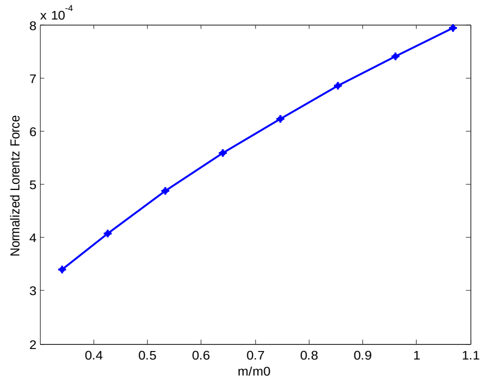

Fig.5. Normalized drag force and MS weight.

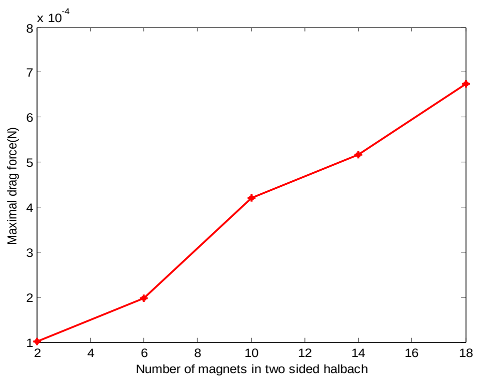

Fig.6. Maximum Lorentz drag force plotted against the maximum weight of the magnet system.

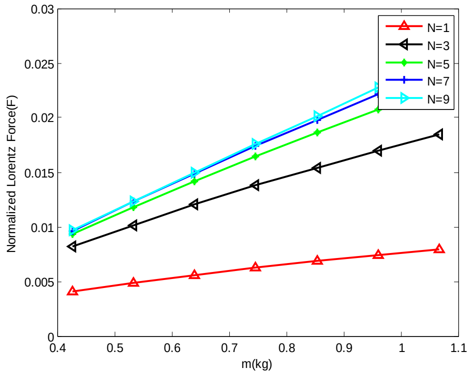

Fig.7. Maximum Lorentz drag force plotted against the maximum weight of the magnet system.

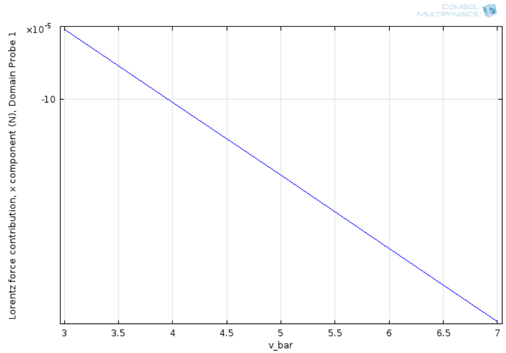

Fig.8. Lorentz force contribution of the magnet system plotted against the velocity

V. CONCLUSIONS

The use of drag force for conducting material has been investigated numerically. A numerical model was developed using commercially available COMSOL Multiphysics software. The maximum drag force increases with the mass of the magnet system, regardless of the chosen magnet configuration. For a given mass, the Lorentz force increases with increase in N but later saturates. When a low mass system is considered, N = 3 already produces almost the maximum drag force, N = 7 is the best choice for optimal drag force and simplicity, as the force is practically the same as for N = 9.

REFERENCES

[1] Thess, E. Votyakov, B. Knaepen, and O. Zikanov, "Theory of the Lorentz force flowmeter," *New J. Phys.* vol. 9, pp. 299–326, 2007

[2] C. Stelian, A. Alferenok, U.L¨udtke, Yu. Kolesnikov and A.Thess, "Optimization Of A Lorentz Force Flow Meter By Using Numerical Modeling", Magnetohydrodynamics Vol. 47, No. 3, pp. 273–282, 2011.

[3] Marek Ziolkowski and Hartmut Brauer "Fast Computation Technique of Forces Acting on Moving Permanent Magnet", IEEE Transactions On Magnetics, Vol. 46, NO. 8, 2927-2930, 2010.

[4] A. Alferenok, M. Werner, M. Gramss, U. Luedtke, and B. Halbedel, " Numerical optimization of the magnet system for the Lorentz Force Velocimetry of electrolytes" International Journal of Applied Electromagnetics and Mechanics 38 pp. 79-92.,2012.

[5] M. Werner, B. Halbedel, E. Rädlein, "Numerical study of magnet systems for Lorentz force velocimetry in electrically low conducting fluids", International Scientific Colloquium Modelling for Material Processing Riga, September 16-17, 2010

[6] COMSOL Multiphysics. User's Guide.

[7] MATLAB documentation.