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Design And Multi-Objective Optimization Of A Magnetohydrodynamic Drug Delivery Infusion Micropump

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ABSTRACT: Continuous drug infusion plays an important role in drug effectiveness. However, in most cases, the size, weight and power consumption of the conventional pumps are among the most important factors that cause a lot of problems for the patient comfort. The present work aims to design and optimize a Magneto hydrodynamic micro pump for continuous drug infusion. A mathematical model of Magneto hydrodynamic micro pump is proposed and solved analytically to investigate its feasibility for drug infusion. For the patient's comfort, the micro pump is optimized using non-dominated sorting genetic algorithm II. The number of channel rows and columns, channel height and width, and driving voltage are chosen as decision variables for multi-objective optimization. The Pareto front of the optimization result is presented. Six possible cases that meet the desired specifications are selected using a fuzzy decision-making approach. A computational fluid dynamic model is adopted to predict bubble formation due to the electrolysis phenomena. With higher reliability without any mechanical part, the present design can deliver drug flow 48 times while its driving voltage is 3 times lower than a conventional micro pump. In addition, it provides potentially better reliability and a simple fabrication process without any mechanical part.

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1. INTRODUCTION

Drug delivery systems are pharmaceutical formulations or devices that are used for controlled delivery of a therapeutic substance to the human body. Over the last couple of decades, much attention has been devoted to controlling the drug delivery by using micropumps. The latter has been actuated with the use of piezoelectric materials, electromagnetic forces, thermal phase-change peristaltic and so on. For a given drug flow rate, a well-designed micropump should have characteristics such as a small size, light weight, low power consumption, high reliability, long lifetime and biocompatibility. Also driving voltage levels due to its contacts with the human body have to be limited (less than 12v).

The main objective of the present work is to achieve a micropump configuration which can deliver a continuous flow rate (< 3 cc/min) while its driving voltage, as well as its weight and size, is lower than the other available micropumps. Therefore, a micropump for pumping a drug (aqueous salt solution) is designed and then optimized. Three objective functions are chosen for the optimization procedure. Minimizing the power consumption and the micropump physical size and maximizing the flow rate to meet the required drug dosage. On the other hand, to avoid bubble generation, the maximum driving voltage must be limited. A case study is conducted to well address the continuous infusion of drug solution as a special application of the drug delivery system.

2. MATHEMATICAL MODELING

A DC-MHD micropump for the pumping of aqueous salt solution is designed for pumping less than 3 cc/min. The cross-section of the micropump is schematically illustrated in Fig. 1. It is composed of an array of nr × nc straight rectangular channels. Each channel has two electrodes located at the opposite side walls. They connect to a DC voltage source (V_0). Neodymium permanent magnets with a flux density of 100 Gauss are considered for providing a magnetic field (B_0). The aqueous salt solution is considered to be a single-phase incompressible Newtonian fluid. The flow regime assumes to be a fully developed, steady-state laminar flow. Uniform magnetic and electric fields are assumed. The aqueous solution of drugs often solves in normal saline; thus, salt water is considered as the operating fluid with constant properties.

The MHD flow is mathematically introduced by the governing equations including conservation of mass, momentum, energy, and species, and Ohm's law, Maxwell's equations and continuity of electric current.

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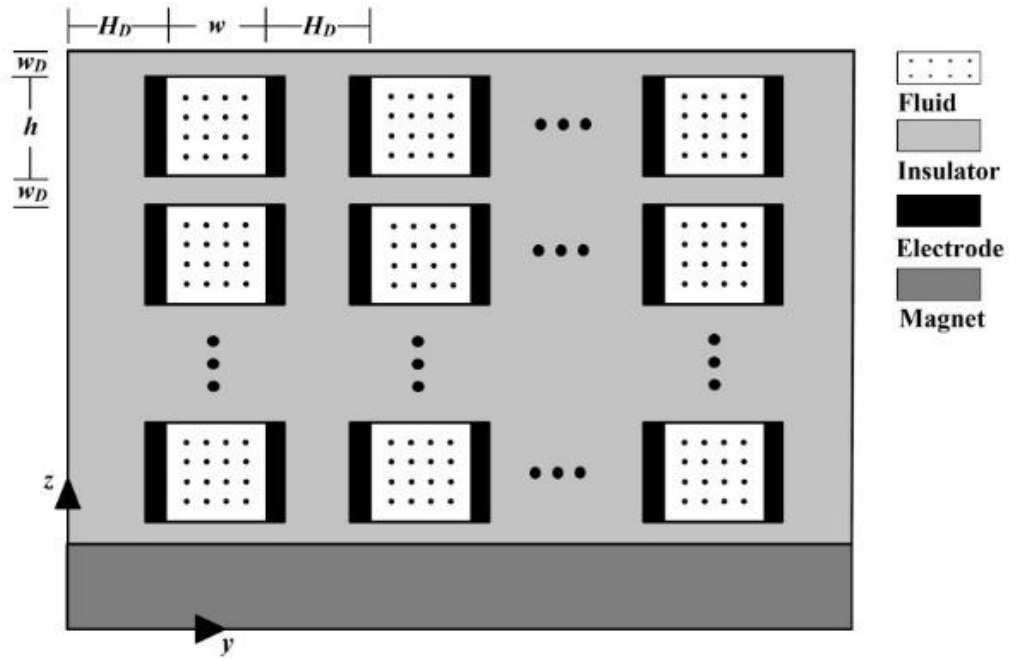

Fig. 1. Micropump cross-section

3. ANALYTICAL AND NUMERICAL SOLUTION

Following equations are solved by using both analytical and numerical methods. The analytical solution is used for the micropump optimization while the numerical solution is adopted to give detailed information on the bubbles generation throughout the micropump channels.

4. OPTIMIZATION

In order to achieve a suitable design configuration, hydrodynamic performance of the designed MHD micropump must be studied and optimized. Three objective functions are chosen for the optimization procedure. Minimizing power consumption and micropump physical size for the patient comfort and maximizing flow rate to meet the required drug dosage. Thus the geometry and driving parameters of the micropump are optimized to meet the desired performance. Therefore, a multi-objective optimization with NSGAII algorithm is used to obtain the optimal design parameters.

5. RESULTS AND DISCUSSION

After obtaining of Pareto front for each pair of objective functions separately, based on the desired application, the optimum parameters and conditions should be selected among all optimal points. As a case study, a micropump for drug infusion is considered. To find the optimal points that can well address the desired micropump characteristics, a fuzzy decision-making approach is adopted. Six different designs with various desired levels for each objective function are obtained from the Pareto front.

In order to select the best design among these six cases for the mentioned application, the performance of the mentioned cases is studied. For a better comparison between pumping performances of these cases, two operating criteria are defined as follows:

· Pumping frequency:

$$f_{sp} = \frac{Q_{max}}{V_{pump}} \tag{1}$$

· and thermodynamic efficiency:

$$\eta_t = \frac{Q\,\Delta p}{P_{cons}} = \frac{Q_{max}\,\Delta p_{max}}{4P_{cons}} \tag{2}$$

These two criteria are calculated for the selected optimum cases and represented in Fig. 2. As seen, cases I, II, IV and VI have a low pumping frequency while the other two cases are suitable for the higher pumping frequency applications. Thus for a given drug infusion rate, higher pumping frequency results in a smaller size. In view of thermodynamic efficiency, for a given infusion rate and pressure drop, lower power consumption micropump results higher thermodynamic efficiency.

The CFD results show that in the cases I, IV and VI, there is no sign of the electrolyze. However, in the other three cases (cases II, III, and V), the bubbles are formed by electrolyze. Therefore, cases I, IV and VI are suitable with no bubble formation throughout the micropump. However, considering the thermodynamic efficiency, case VI is the best choice among the other two optimum cases. Driving voltage for such an application should be below 12 volts while the maximum required injection flow rate is 1 cc/min. These desired operating conditions are marked by a gray color in Fig. 3. As seen, micropump case VI meets the required conditions for

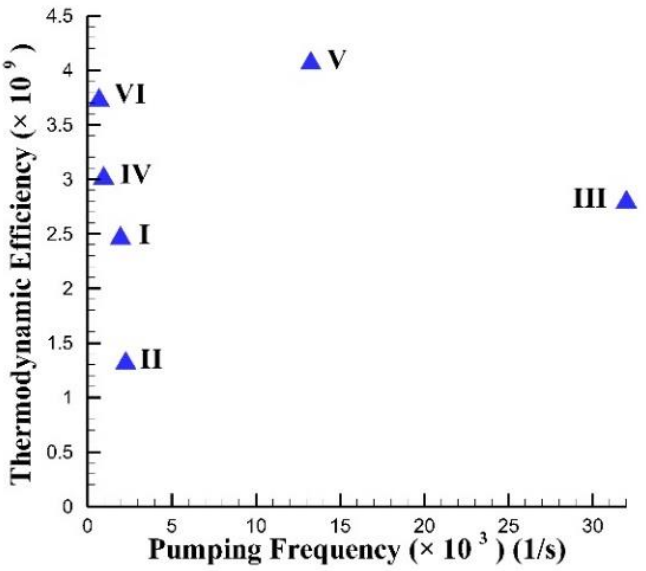

Fig. 2. Pumping frequency versus thermodynamic efficiency of selected optimum cases

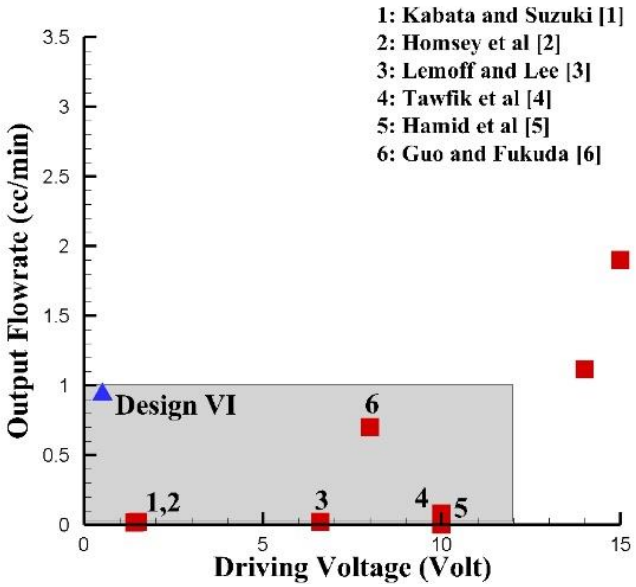

Fig. 3. Comparison between optimized cases and other micropumps for drug delivery systems

the drug infusion. By the comparison between cases VI (the present design) and other micropumps (literature), it is seen that the present design needs much lower driving voltage (or lower power consumption) for operating while pumping higher drug flow rate.

This comparison shows that the driving voltage reduces 3 times while the flow rate augments 48 times (compared to the lowest required voltage Kabata and Suzuki [1]). The comparison with the work of Guo and Fukuda [6] shows that the present optimal design delivers 33% higher drug solution while the driving voltage is 16 times lower. Thus with the present optimal design a micropump with higher performance and without any mechanical part is obtained. In addition, it provides potentially better reliability and simple fabrication process.

6. CONCLUSION

An MHD micropump for drug infusion is designed and optimized with NSGAII multi-objective genetic algorithm to maximize the drug flow rate while the physical volume and power consumption of the micropump are minimized.

It is shown that the present optimal design delivers 33% higher drug solution while the driving voltage is 16 times lower. The latter well addresses the following important concerns; bubble formation and energy consumption.

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