Sensors and Actuators A 194 (2013) 277–284

Contents lists available at SciVerse ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Experimental study of a novel Magneto Mercury Reciprocating (MMR) micropump, fabrication and operation

Mohsen Karmozdi[1], Alinaghi Salari[1], Mohammad Behshad Shafii*

Mechanical Engineering Department, Sharif University of Technology, Azadi Avenue, Postal Code: 11155-9567, Tehran, Iran

ARTICLE INFO

Article history:
Received 16 July 2012
Received in revised form 1 February 2013
Accepted 6 February 2013
Available online 27 February 2013

Keywords:
Micropump
Lorentz force
Reciprocating

ABSTRACT

Today, MEMS have wide applications in modern technologies. Magneto hydro dynamic (MHD) micropumps play an important role in the MEMS industry and have been thoroughly studied in the recent years. In this study, the idea of classic reciprocating micropumps was combined with magneto hydro dynamics (MHD) to develop a novel Magneto Mercury Reciprocating (MMR) micropump. To attain this goal, the Lorentz force, as the actuation mechanism, was used to move a conductive liquid (mercury) slug in a reciprocating manner in order to suck the working fluid (air) from the inlet and pump it to the outlet. The performance of the fabricated MMR micropump was examined in terms of parameters such as pressure difference, pumping frequency, and magnetic flux density. The maximum flow rate was achieved at a minimum backpressure of 9.5 mL/min. The maximum pressure head achieved in the experiments was 245 Pa. Furthermore, the results of these experiments were compared with other micropumps, which showed an improvement of 153% over the next best MHD micropump presented to date.

1. Introduction

The first attempts in the field of micropumps were commenced two decades ago by Smits in order to inject insulin to diabetic patients [1]. Many studies have developed novel applications of micropumps in a variety of fields such as chemistry, biology, and environmental monitoring systems. Today, terms such as micro total analytical systems (μTASs) and laboratory-on-a-chip (LOC) are well known among researchers. The main goal of these kinds of systems is displacement, reactions, recognition, and separation of fluid samples in a micro scale (chip-size) device.

The main anticipation of micropump usage in the aforementioned applications is their ability of reducing errors and costs as well as performance optimization and robustness. Micropumps have a wide range of application in many scientific and technological fields. Also, micropumps can be used in micro heat exchangers for pumping coolant fluids [2].

In general, micropumps can be categorized into two main groups: reciprocating micropumps and dynamic ones [3]. Reciprocating micropumps use the oscillatory or rotational movement of mechanical parts to generate a driving force which produces pressure in order to displace a fluid. Piston-like types, such as micro diaphragm pumps and peristaltic micropumps, are the first types of reciprocating micropumps that are still common in this class of MEMS [4,5]. These micropumps usually have poor performance due to some reasons such as pulsating flow and unwanted bubble formation inside channels. One type of diaphragm pumps is piezoelectric micropump which needs a high voltage for actuation. Another disadvantage of the prior micropumps is the possibility of clogging, which is caused by mechanical valves used for directing flow. Some efforts have been done to eliminate this problem [6]. Solving the clogging problem in piezoelectric micropumps by using non-mechanical moving valves may cause some other drawbacks such as a lower overall performance and the possibility of backflow when a micropump is switched off.

The most common dynamic micropumps (second group) fall into three main categories: magneto hydro dynamic (MHD), electro hydro dynamic (EHD), and electro-osmotic (EOP). MHDs have many advantages such as: omitting movable objects, ease fabrication, and continuing outflow.

However, the first MHD micropump was built less than a decade ago. This micropump was introduced by Jang and Lee [7] in 2000. In this micropump, a direct current (DC) was used, and seawater was used as the working fluid. At its best working condition, it was capable of generating a pressure difference of 180 Pa with a flow rate of 63 μL/min. However, this pump had major limitations due to electrolysis and bubble generation. Using an alternating current instead of DC, along with an alternating magnetic field, would be a solution for this problem if the current amplitude is kept limited to a proper value [8]. However, the performance of a micropump in this condition will be too low, because

---

* Corresponding author. Tel.: +98 21 66165675.
E-mail address: behshad@sharif.edu (M.B. Shafii).

[1] Tel.: +98 21 66165675.

0924-4247/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.sna.2013.02.012

of the limited current amplitude and the weak alternating magnetic field, which are produced by solenoids instead of permanent magnets. Fabricating a bypass channel for separating the bubbles from the main channel, which results in a higher current density in the electrodes and a higher performance, has also been proposed [9]. However, due to electrolysis and the separation of atoms from an electrode, this method is not a permanent solution, and the micropump will have a limited life span. To improve the performance of MHD micropumps, intensified magnetic field (7 T) was used in another study [10]. In this case, although the performance of the micropump was improved as the magnetic field was increased, but the bubble generation issue was still unsolved. Moreover, the application of this micropump was limited to strong magnetic field environments.

In all of these cases, only electroconductive working fluids (which are electrolytes in most cases) can be used. Furthermore, due to the high electrical resistance of electrolyte solutions, the current, and consequently, the pumping performance will be limited. This limitation is due to the fact that an unbounded increase in the current will generate too much heat, which will evaporate the working fluid. Moreover, the generation of bubbles in microchannels, which leads to viscosity changes, causes a nonlinear behavior in DC MHDs. Thus, the flow rate variation, with respect to the pressure difference or electric currents in these micropumps, is not easily predictable by analytical relations, specifically at high current densities.

A rotary MHD (RMHD) was proposed by Esmaily and Shafii which took advantage of MHD micropumps while eliminating the mentioned limitations [11]. This micropump pumped air by driving a mercury slug inside a microchannel. To maintain continuous pumping, the microchannel was arranged in a loop consisting of a valve capable of allowing the mercury slug to pass through while preventing the air from passing [11].

Using a ferrofluid plug [12] for pushing the fluid, and also, placing ferromagnetic particles in magnetic field gradient [13] are examples of micropumps actuated by magnetic fields. These micropumps have some exclusive properties such as controlling the particles inside a microchannel indirectly. Moreover, these devices are not sensitive to the temperature, pH, and ionic concentration of a fluid [14].

In this paper, a novel micropump is introduced which can be categorized into both reciprocating and dynamic (MHDs) ones. The proposed design employs an electroconductive liquid (e.g. mercury), in a role of a reciprocating piston, to pump the working fluid (e.g. air). In this new reciprocating micropump, the general reciprocating pump advantages are upgraded, and its disadvantages in comparison with dynamic micropumps are diminished. Moreover, the advantages of MHD micropumps by means of this innovative micropump are almost achieved. Continuous pumping, working at relatively low voltages, simple fabrication and implementation, and low cost manufacturing are the main additional advantages of our micropump. The reciprocating mechanism is prepared by an electric current going through the mercury slug in a magnetic field. The generated Lorentz force moves the mercury slug. By setting a particular sequence for the movement of mercury slugs in microcavities, the air is pumped through a microchannel. Because of the mechanisms of both actuation and pumping system, the novel micropump can be called Magneto Mercury Reciprocating (MMR) micropump.

2. Theory

The micropump manufactured in this research is a mercury actuated valveless pump. The main part of the MMR micropump is an actuation force which is the Lorentz force generated by the movement of electric charges in a magnetic field. The Lorentz force is proportional to a vector which is the cross product of electric current $\dot{I}$ and magnetic field density $\dot{B}$ vectors.

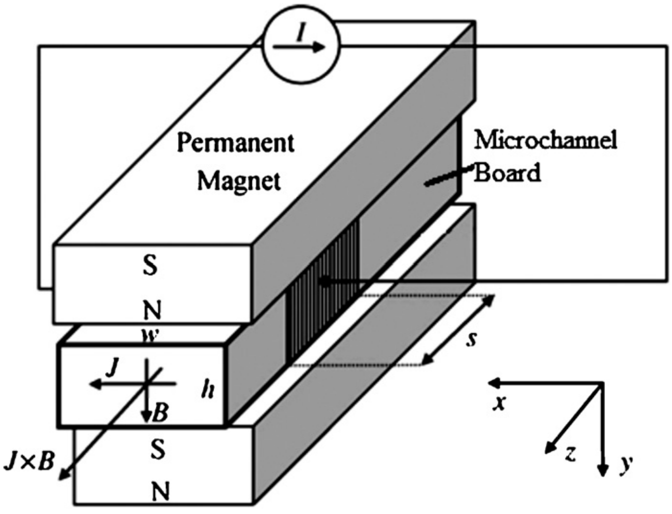

Fig. 1. Schematic of MMR micropump from outside view.

As it is illustrated in Fig. 1, two permanent magnets are located at the top and bottom of the microchannel, generating a magnetic field along the *y* axis. There is an electroconductive liquid inside the microchannel. If there is an electric current through the *x* axis, a force will be exerted on the liquid along the *z* axis causing the liquid to move. The force magnitude per unit volume of the liquid is obtained as the following:

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

where *F* is the Lorentz force, *w* is the width of the microchannel or the distance between the electrodes, *h* is the height of the microchannel, and *s* is the length of the electrodes.

Per definition, the electric current is obtained by multiplying electric current flux by the area, from which the current passes through. Therefore, the Lorentz force is calculated as follows:

$$\vec{F} = w\vec{I} \times \vec{B} \tag{2}$$

An electroconductive liquid is used to fill the microcavities positioned on the microchannel membrane (Fig. 1). Mercury is the first choice for the liquid material which is needed to move through the microcavities and microchannel like a piston due to its high surface tension. Although, mercury is a toxic material and cannot be used in biological applications, it is still applicable for non-biological systems such as microspacecrafts [15]. In this instance, the delivery of compressed gas at a high flow rate is required. Replacing mercury with nontoxic materials, such as Galinstan, would be an open area of research in the future. In this experiment, the electrodes are permanently in contact with mercury and are made of austenitic stainless steel which has a long life span. It should be emphasized that the goal of this experiment is not to use mercury as an element of the micropump, because it can simply be substituted by any other conductive liquid.

The efficiency of the micropump can be defined as the quotient of the output power and input electrical power.

$$\eta = \frac{\Delta PQ}{VI} \tag{3}$$

where ΔP, Q, V and I are pressure difference, flow rate, electric voltage, and electric current of the micropump, respectively.