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A NOVEL MINIPUMP ACTUATED BY MAGNETIC PISTON

Radu Herţanu* ─ Radu Olaru*

This paper presents a novel and simple structure of a magnetically actuated mini/micro-pump for use in microfluidics. The pump of reciprocating type uses an externally actuated magnetic piston to develop pumping pressure. The piston, which slides inside a small main channel, is formed by a permanent magnet and two ferrofluid rings placed at the ends, ensuring both sealing and lubrication. The reciprocating movement of the piston is achieved using an oscillating magnetic field generated by an externally placed coil. The maximum backpressure attained when pumping atmospheric air was 21.6 mbar.

Keywords: ferrofluid, magnetic piston, micropump, passive valves

1. INTRODUCTION

Based on the constant request for new concepts and technologies for microfluidic applications, in recent years, magnetic actuation principles for use in micro pumping mechanisms or micro delivering systems began to be increasingly used.

A reason for the expansion of this research area consists in the involvement of miniaturization in biochemical analysis systems. Ever since the Lab-On-a-Chip concept was developed [1] it required micro manipulating structures able to vehicle small quantities of fluids, adaptable to various tasks and given characteristics. The aim is also to reduce the quantity of analyzed samples, to achieve a shorter analysis time, to automate the processes and to diminish the involved costs.

The most common principles in driving such micropump involve oscillating membranes actuated using the piezoelectric effect [2] or using micro coils and permanent magnets attached in order to develop reciprocating motion [3], [4].

In search for new concepts and technologies usual materials lose ground in favour of newer and more reliable ones. Ferrofluids represent an example of these kinds of materials which find their use in many technological applications. Because of their main characteristics, magnetic proprieties and flow capability, recently, ferrofluids raised a great interest in the field of microfluidics [5].

Since their first use in piston pumping systems [6], ferrofluids have shown a great potential. Ferrofluids conform to the channel shape providing very good seal and can be controlled by external magnetic fields for easy actuation offering advantages over other fluid pumping methods. The working principle of a micropump based on ferrofluids is to magnetically generate pumping pressure. Inside the micro channels and operated under the action of an external magnetic field, plugs of ferrofluids generate pumping motion. Involving this principle some different configurations were reported to generate linear motion of the ferrofluid plugs [7], [8]. Using the same principle, but operating inside a circular shaped tube, other concepts were developed, using either a permanent magnet in controlling the ferrofluid plug [9], [10] or a set of sequentially actuated coils, arranged in a circular shape, [11].

As described before, using ferrofluid plugs in pumping systems requests an external driving device, usually a permanent magnet, attached to a mobile shaft. Such an actuating mechanism complicates the system structure; therefore we propose a new concept of mini/micropump of reciprocating type without any external mechanical parts in motion.

2. OPERATING PRINCIPLE

The concept of our pump is based on a magnetic piston, externally actuated, used to develop a reciprocating motion in order to create pumping pressure. The piston, which slides inside a small main channel, is formed by a permanent magnet and two ferrofluid rings placed at the ends, ensuring both sealing and lubrication. The reciprocating movement of the piston is achieved using an oscillating magnetic field generated by an externally placed coil. The coil, positioned around the main channel, was designed with two identical windings, carrying currents in opposite directions. A view of the pump actuating system is presented in Fig. 1.

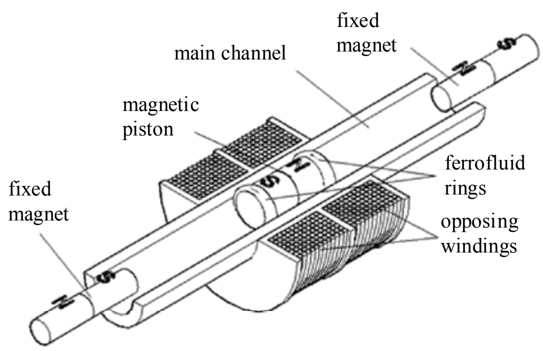

Fig.1. View of the magnetic driving system

* Faculty of Electrical Engineering, "Gh. Asachi" Technical University, 700050, Iasi, Romania, e-mail: radu.hertanu@yahoo.com, rolaru@ee.tuiasi.ro

In order to return to its initial position during operation and maintaining it in downtime mode, two extra permanent magnets are placed on the same axis with the magnetic piston to develop repulsive forces against it.

This oscillatory movement of the piston is converted into fluid flow through a series of passive valves. Based on this, two distinctive configurations are available, the simple effect pump and the double effect one.

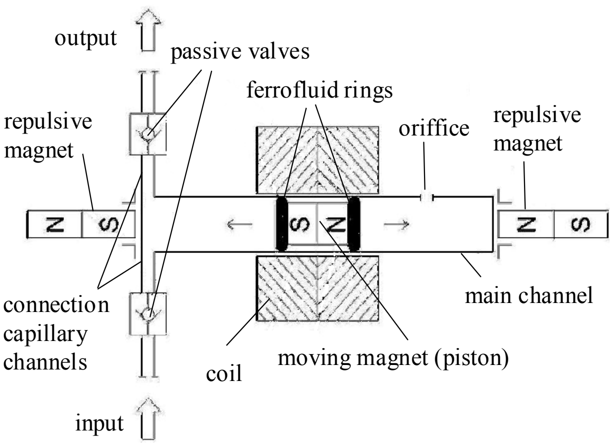

Fig. 2. Schematic view of the simple effect minipump

In the simple effect configuration (Fig. 2) the back and forth movement of the piston is converted into pumping function by two passive valves, in contrast with the double effect one which uses four valves.

The simple effect variant pumps fluid only within one alternation of the sinusoidal command voltage. Due to this fact the fluid flow driven through the pump is halved compared to the double effect configuration; however the double effect one requires a more complex structure. The orifice can be applied when the elastic effect of air on pump operation and/or the influence of ambient factors (temperature, for example) need to be eliminated.

An operating condition for this type of pump consists in the fact that the used ferrofluid must be immiscible with the working fluid, because of the direct contact during the working period.

A major advantage of this piston configuration, permanent magnet with ferrofluid sealing rings, compared to the use of only a ferrofluid plug, is a higher magnetic developed force. Reducing the response time and providing the piston with a raised rigidity are aspects which also improve the concept.

3. EXPERIMENTAL MODEL

The piston in this device is a cylindrical permanent magnet, 6 mm in length and 3 mm in diameter. At both ends the piston is provided with ferrofluid rings, so that sealing is ensured. The main channel, made of plastic, in which the piston operates, was designed with a 4 mm inner diameter and the capillary connection channels with a 1 mm inner diameter. The coil, built around the main channel, consists of two windings, each having 150 turns with ϕ 0.35 mm. The fixed magnets, also with cylindrical shape, 9 mm in length and 2 mm in diameter, were fixed inside a special housing at the ends of the main channel. In Fig. 3 the double effect configuration pump prototype

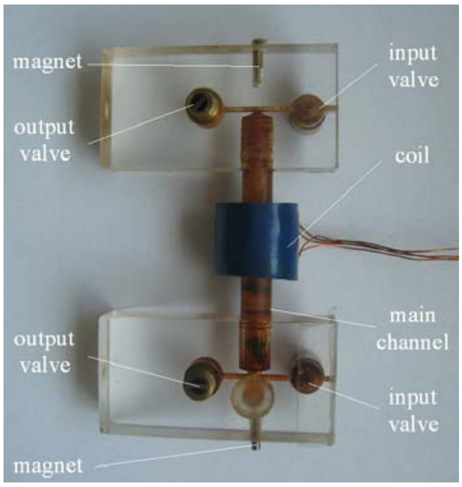

Fig. 3. Experimental model of the double effect minipump

using prefabricated passive valves is presented.

When using this type of configuration the piston degree of freedom is dictated by the distance at which the repulsive magnets are placed. The distance between the moving permanent magnet (piston) and the fixed ones during rest time, *r* (Fig.4), was set experimentally.

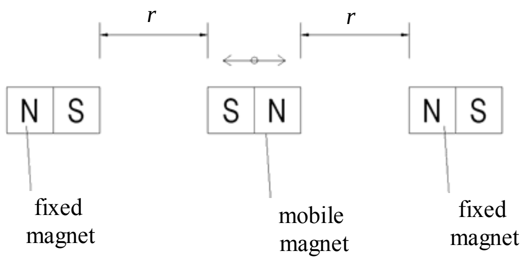

Fig .4. Expressing the distance between moving and fixed permanent magnets

This length intervenes in the expression of the repulsive magnetic force. It is considered that the repulsive force of two axial magnets can be expressed as [12]

$$F = k\left(\frac{1}{(r+h)^2} + \frac{1}{(r+2d)^2} - \frac{2}{(r+d)^2}\right) \tag{1}$$

where *k* and *h* are constants, *r* is the distance between the two magnet faces, and *d* is the axial length of the magnets. As in (1) one can observe that the repulsive magnetic force between two permanent magnets is strongly dependent with distance. The repulsive force presents higher values at smaller distances between magnets and decreases for increasing values of *r*. Initially the value of *r* was set to 17 mm and the pump was tested when pumping atmospheric air, with the backpressure being measured. Gradually the value of *r* was reduced, measurements being made for 15, 13 and 11 mm, respectively. As a result, an increased backpressure is reached when decreasing the distance between repulsive magnets, however from 11 mm limitation occurs, the value of the repulsive force reaching a much higher value and disrupting the movement of the piston. Although a higher repulsive force is pushing against the piston, limiting its movement, a better position control in the oscillating magnetic field during operation is achieved, so that a 13 mm distance between the piston and the fixed magnets was chosen.

Two types of ball type passive valves were evaluated during the experimental setup, prefabricated and laboratory made. The requirements for the used valves are mainly two: a lower response time, in order to enlarge the optimal frequency interval of operation, and a high capacity in maintaining backpressure, lowering as much as possible the valves leakage. Although easily available, the prefabricated valve presented the main disadvantage of operating only in vertical position, involving positioning restraints for the pumping system.

A second type of valves, made in our laboratory, was developed and tested in order to remove any positioning restraints and to achieve a pumping system able to be fabricated in an integrated structure. Using a multilayer manufacturing process the valve was fabricated from two thin Plexiglas boards bound together with an epoxy adhesive (Fig. 5).

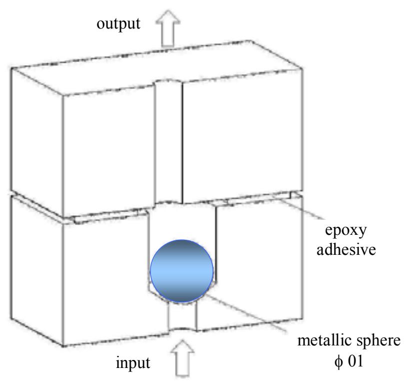

Fig. 5. Multilayer structure valve in section view

The lower plate acts as a valve chair, being provided with a truncated conic shape drilled orifice, 1.2 mm - the diameter of the large base and 0.6 mm that of the small base, in which the light metallic ball, 1 mm in diameter, operates under the pressure gradient. Acting as a stopper the upper plate is provided with a connection channel, 0.6 mm in diameter, drilled eccentrically.

4. EXPERIMENTAL RESULTS

For the experimental stage the coil was connected to a variable frequency power generator, measurements being made in the frequency rage 1 – 40 Hz. Also the amplitude of the piston during operation was varied using several r.m.s. values for the supply voltage.

The first measurements were made with prefabricated passive valves when atmospheric air is pumped. Backpressure was measured using a Meriam M2 Series manometer both for the single and double effect configurations. The characteristic backpressure versus command voltage frequency is illustrated in Fig. 6 and 7, for the simple and double effect case, respectively.

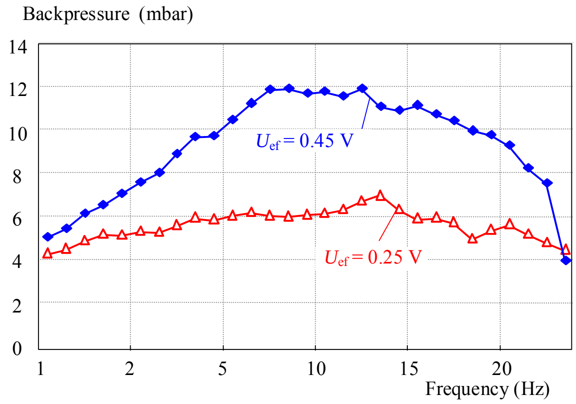

Fig. 6. Backpressure versus command voltage frequency for the simple effect configuration

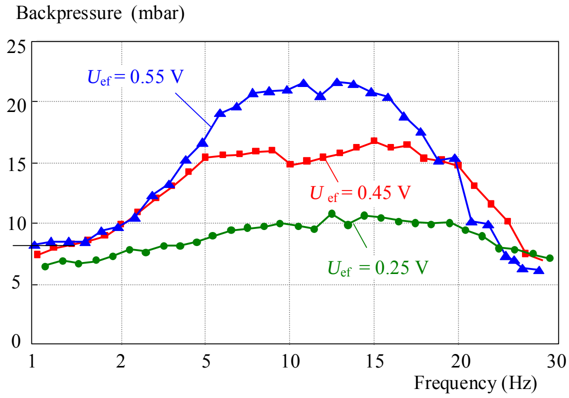

Fig. 7. Backpressure versus command voltage frequency for the double effect configuration

As expected the double effect configuration developed a higher backpressure compared to the single effect one, air being pumped on both alternations of the command voltage. An optimal operation interval is considered to be 10 – 15 Hz when the system proved a higher stability. When frequency exceeds 30 Hz, valves limitations intervene, being unable to operate at the imposed speed. The effect is observed in the drastic backpressure drop. The maximum attained backpressure was 21.6 mbar at 14 Hz and 0.55 V, r.m.s. value of the command voltage, when the double effect configuration was used.

For a complete characterization of the pump, the simple effect configuration was also tested when pumping water. At a voltage of 0.63 V and 14 Hz the measured flow rate was 1.86 ml/min and a 6.57 mbar pressure was generated.

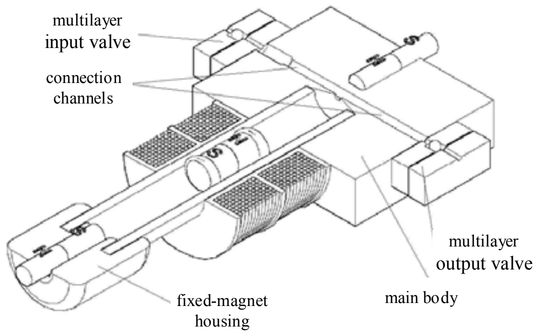

Fig. 8. Simple effect pump with multilayer passive valves, in transversal section view

Using the multilayer structure valves led to an integrated structure pumping system presented schematically in Fig. 8. The prototype was evaluated when pumping air both for the single and double effect configurations , see Fig. 9.

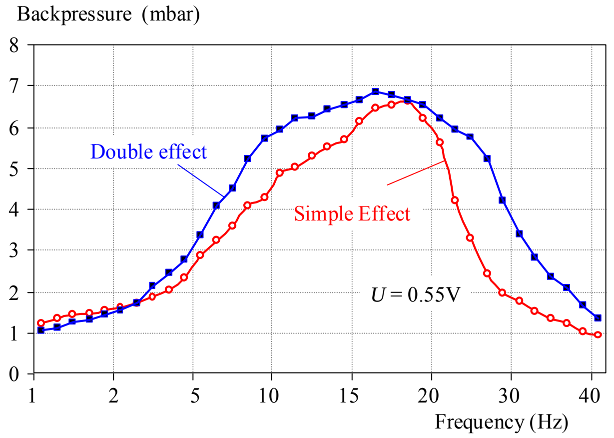

Fig. 9. Backpressure dependence on frequency for both simple and double effect configuration

Due to the fact that the valve chair interior was processed using usual drilling methods, a surface with superficial imperfections results, preventing the valve in achieving superior sealing. As a result the maximum achieved backpressure is considerable lower when compared with the use of prefabricated valves, however using multilayer valves the positioning restrains are removed and the pumping system becomes a more compact one.

5. CONCLUSIONS

This paper presents a concept of micro/minipump with magnetic piston. The novelty of the concept lies on the use of permanent magnets in configuration with ferrofluid rings in order to achieve a magnetic piston structure. A main advantage is brought by the lack of any mechanical parts in motion to actuate the piston, the reciprocating movement being induced by an externally generated, oscillating, magnetic field.

This concept was practically tested and proved its functionality, both for the single and double effect coniguration. During the tests two types of ball type passive valves were evaluated, one prefabricated and one made in the laboratory. A maximum backpressure of 21.6 mbar was attained when using the prefabricated valves at 0.55 V rms value of the command voltage, for the double effect configuration. Although less effective, the multilayer valves led to a more compact, easy to minify, pumping system. The double effect minipump, presented a higher stability during operation, the fluid being pumped on both alternations of the command voltage. A wider frequency interval, corresponding to the maximum attained backpressure, was also obtained in this case.

REFERENCES

[1] MANZ, A. – GRABER, N. – WIDMER, H. M.: Miniaturized total chemical analysis systems: a novel concept for chemical sensing, Sens. Actuators B, Chem. **1** (1990), 244–248.

[2] VAN LINTEL, H. T. G. – VAN DE POL, F. C. M. – BOUWSTRA, S.: A piezoelectric micropump based on micromachining of silicon, Sens. Actuators, Vol. **15** (1988), 153–167.

[3] MAO, L. – KOSER, H.: Towards ferrofluidics for μ-TAS and lab on-a-chip applications, Institute Of Physics Publishing, Nanotechnology, Vol. **17** (2006), 34–47.

[4] PAN, T. – MCDONALD, S. J. – KAI, E. M. – ZIAIE, B.: A magnetically driven PDMS micropump with ball check-valves, Journal of Micromechanics and Microengineering, Vol. **15** No. 5 (2005), 1021–1026.

[5] SHEN, M. –YAMAHATA, C. – GIJS, M. A. M.: Miniaturized PMMA ball-valve micropump with cylindrical electromagnetic actuator, Microelectronic Engineering Vol. **85** Issues 5-6 (2008), 1104–1107.

[6] LELAND, J. E.: Ferrofluid piston pump for use with heat pipes or the like, US Patent no. 5005639 (1991).

[7] YAMAHATA, C. – CHASTELLAIN, M. – PARASHAR, V. K. – PETRI, A. – HOFMANN, H. – GIJS, M. A. M.: Plastic micropump with ferrofluidic actuation, Journal of Microelectromechanical Systems Vol. **14** No. 1 (2005), 96-101.

[8] HARTSHORNE, H. – BACKHOUSE, C. J. – LEE, W. E.: Ferrofluid-based microchip pump and valve, Sensors and actuators B Vol. **99** Issues 2-3 (2004), 592-600, 2004.

[9] HATCH, A. – KAMHOLZ, A. E. – HOLMAN, G. – YAGER, P. – BÖHRINGER, K. F.: A Ferrofluidic Magnetic Micropump, Journal of Microelectromechanical Systems Vol. **10** No. 2 (2001), 215-221.

[10] KIM, E. G. – OH, J. G. – CHOI, B.: A study on the development of a continuous peristaltic micropump using magnetic fluids, Sensors and Actuators A Vol. **128** Issue 1 (2006), 43-51.

[11] NGUYEN, N. T. – CHAI, M. F.: A Stepper Micropump for Ferrofluid Driven Microfluidic Systems, Micro and Nanosystems Vol. **1** No. 1(2009), 17-21.

[12] DEFRANCESCO, S. – ZANETTI, V.: Experiments on magnetic repulsion, American Journal of Physics Vol. **51** (1983), 1023.

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Radu Hertanu was born in Iasi, Romania, in 1983. He received the Electrical Engineering and MS degrees from the Technical University of Iasi, Romania in 2007, and 2008 respectively. He is currently working toward the Ph.D degree at the Department of Energy Utilization, Electrical Drives and Industrial Automation, Faculty of Electrical Engineering from this university. His research interest is in the area of actuators based on magnetic fluids

Radu Olaru, for biography see page 147 of this issue.