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Development of a piezoelectric-driven miniature pump for biomedical applications

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ABSTRACT

Miniature pumping system is widely used in mechanical and bio-medical fields, and in this regard, extensive researches are being conducted in related applications. This paper reports a novel piezoelectric-driven miniature pump that can achieve high flow rate through a combination of piezoelectric-actuator and pumping chamber with internal rib structures. The major features of the proposed miniature pump are self-priming and high flow rate at low frequency range. Flow rates at different frequencies were measured under different piezoelectric-actuator thicknesses and fluid viscosities. In addition, the correlation between the actuator displacement and the pumping efficiency at different frequencies was investigated and discussed. High flow rates of up to 196 ml/min and 141 ml/min were achieved for water and blood mimicking fluid, respectively. It was achieved by using a piezoelectric actuator with a 0.2 mm thick piezoelectric layer and a 0.25 mm thick brass plate, and a pumping chamber with 0.05 mm embedded flow-guiding rib structures for pumping efficiency improvement.

1. Introduction

Miniature pumps are widely used in many fields, including biology, chemistry, medical treatment, and cooling systems. In general, miniature pumps can be categorized into two types, dynamic driven and mechanical displacement. Dynamic pumping, which usually utilizes interactions of fluid with an electric or magnetic field to exert driving forces on the fluid continuously, are typically represented by electro-hydrodynamic [1] and magneto-hydrodynamic [2] pumps. A displacement pump, on the other hand, uses a moving mechanical part to change the volume of a chamber to drive fluid within the chamber. Among various displacement pumps, reciprocating micropumps are typically designed with compact sizes and are thus suitable for integrating with various fluid systems.

Based on actuation mechanisms, the reciprocating micropumps can be categorized as follows—piezoelectric [3], electrostatic [4], pneumatic [5], electromagnetic [6], thermopneumatic [7], shape memory alloy (SMA) [8] and ultrasonic [9]. Among these actuation mechanisms, the piezoelectric-actuators have several advantages, such as large actuation force, short response time, high reliability, simple structure, small size and light weight, and have been widely developed and analyzed in the field of micro-electro-mechanical-systems (MEMS) [10–13]. Various studies have been conducted to investigate the characteristics of piezoelectric-actuated MEMS micropumps. For example, Kim and Jones [14] used a linear strain assumption to predict the optimal rectangular actuator-to-plate thickness ratio at different ratios of Young's modulus. The moment was optimized by a dual-layered piezoelectric actuator. Yoon and Washington [15] proposed a moment balance method to analyze a beam-shape piezoelectric actuator. Luo and Yin [16] designed and fabricated four types of micropumps with different bimorph piezoelectric actuators and check valves. Truong and Nguyen [17,18] presents a lamination technique by designing two micro check valves fabricated by using a 100 μm-thick SU-8 film. A flow rate of 1 to 1.6 ml/min was achieved. Sayar and Farouk [19] developed a piezoelectric valve-less micropump and applied it to transport water. The effects of inlet-outlet port angles and the overall pump size on the flow rate were investigated.

For bio-fluidics and cooling applications, a high flow rate is highly desirable. Cantwell et al. [20] proposed a low-cost, high flow rate electromagnetic micropump, achieving 170 ml/min. Ma et al. [21,22] interfaced one-sided piezoelectric micropumps with a heat-dissipation system and an optimal flow rate of 140 ml/min was achieved with a pump back pressure of 6.4 kPa. Despite of the high flow rate achieved by prior researches, so far there have

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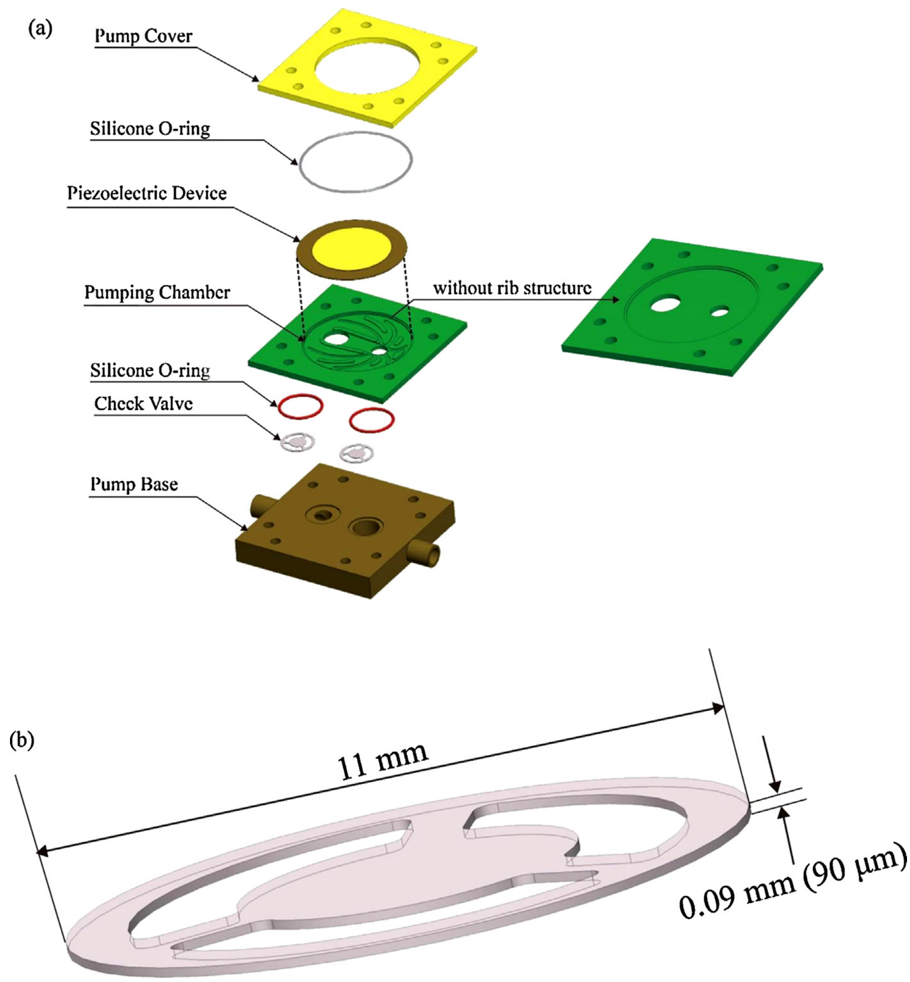

Fig. 1. Structure of (a) the miniature pump assembly (b) the check valve.

been no commercialized, high flow-rate micropumps suitable for integrating with bio-medical or cooling systems.

The aim of the present study is to develop and characterize a high flow rate miniature pump suitable for commercial use in bio-medical and warming/cooling applications. Typical commercially available blood transfer devices have flow rates ranging from 80 ml/min to 200 ml/min. For example, Belmont Buddy® Lite™ AC provides 80 ml/min flow rate, 3 M™ Ranger™ System (model 245) has a standard flow rate of 150 ml/min, and GE Healthcare enFlow system offers a standard flow rate is 200 ml/min. Our proposed miniature pumps can meet the standard flow rate for this kind of blood transfer applications. For the biomedical applications, a circular chamber structure was chosen to achieve easy assembly of the miniature pumps. Both water and blood-mimicking fluid were used to investigate the influence of fluid viscosity on flow rate. To optimize the performance of the miniature pump, a series of rib structures were designed based on flow-field simulation within the miniature pump chamber and the effects of the rib structures on the flow rate were also investigated. Three types of miniature pumps with different chamber structures and piezoelectric-actuator thicknesses were designed, fabricated and measured at different frequencies. The miniature pump performance was evaluated and discussed based on the measured flow rates under different pumping structures and settings.

2. Development of the piezoelectric-driven pump

2.1. Miniature pump structure and flow mechanism design

The basic structure of the circular piezoelectric miniature pump is shown in Fig. 1(a). The external dimension of the pump is 50 mm × 50 mm × 12 mm. The case of the miniature pump was made by machining a Poly-methyl-methacrylate (PMMA) block with a computer numerical controlled (CNC) milling machine. Commercially available piezoelectric coated brass disks were used in this study. Lead zirconate titanate (PZT) was used to serve as the piezoelectric layer. Two check valves were made out of a 0.09 mm thick silicone film, and it was cut out by using a Nd:YAG laser cutting machine. The assembly was done by placing all pieces together layer-by-layer and then clamped together with 4 screws and silicone O-rings between layers. The space between the piezoelectric actuator and the lower case formed the miniature pump chamber, with a diameter of 34 mm and a chamber depth $d = 0.45$ mm. A circular piezoelectric-actuator with a diameter of 35 mm covered the chamber to form a tight seal. This piezoelectric-actuator drove fluids in and out the chamber through check valves fabricated on the lower case. To further optimize the flow rate, a series of rib structures were designed within the chamber. Fig. 2 shows different rib structure designs within the chamber. The gap p, defined as the space between the piezoelectric-actuator and the rib structure, was one key feature of the rib structure design. Two types