A review on micropumps from the viewpoint of volumetric power density

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Abstract
Micropump is one of critical devices in composing high-performance micro-fluid systems like micro hydraulics, fluid-driven micro machines, micro liquid forced cooling of electrical components, μTAS(Micro total analysis systems), LOC(Lab-on a-chip), micro dosing system and so on. A lot of principles are proposed to develop micropumps in these 30 years. At the same time, many review papers on many kinds of micropumps were published in these 20 years, however, in these 8 years there are little review papers on micropumps, particularly from the point of power density view. Here, first, we survey some recent review articles on the progress of micropumps over the past 25 years. Secondly, we attempt to provide the review on latest trend on micropump researches in these 8 years. Finally, we introduce some powerful micropumps as a power source of micro hydraulics. From the point of view that the micropump can be power source as a micro hydraulics, the state of the art micropumps and their power densities are discussed. Much progress has been made, however, with micropumps suitable for primary applications still not available, it seems that this remains a developing and productive area for future research.

Key words: Micropumps, Hydraulics, Power density, Micromachine, EHD, ECF, Cooling, μTAS, LOC

1. Introduction

In micro systems from biology to micro fluid driven robotics and microelectronics cooling, micropumps are essential to compose the fluidic systems. Nowadays the application field of micropump rapidly expands and widen. In these 20 years, many kinds of micropumps have been proposed and fabricated for various applications. Micropumps can be classified into two groups, i.e., displacement type and dynamic type pumps by Laser (Laser and Santiago, 2004). In displacement-type, usually a membrane or a diaphragm is driven by micro actuator like PZT, SMA and so on. Valves are utilized to control fluid directions. The micropump generates a flow due to the change of positive displacement, therefore the pump usually has periodic fluctuations of flow. On the contrary, in dynamic-type, the pumping is based on the direct forces acted between electric field and fluids like Electrohydrodynamic (EHD) phenomena. Also, Turbo pumps are classified to dynamic-type and the pumping flow is aperiodic.

Many review articles on a lot of kinds of micropumps were published, however, there are little review papers on micropumps from the view point of the power density. Power density of micropump is considered to be one of important factors to fabricate a high-performance fluidic system. In this review, we attempt to evaluate and compare volumetric power density of micro pumps within 1 cubic-cm size. In the second section, we take an overview on recent 13 review papers on micropumps. Third section provides reviews of latest 8 years papers. In fourth section, high power density micropumps by the authors are briefly introduced and compared from the view point of power density.
2. Overviews on recent reviews

We have surveyed 13 latest review articles on the progress of micropumps over the past 25 years below. The review article of P. Gravesen (Gravesen, et al., 1993) ‘Microfluidics—a review’ mentioned micropumps as one of several components of microfluidic system and the review can be evaluated as a pathfinder on micropumps. The paper made a remark that research on membrane-type micropumps based on microvalves was initiated at Stanford University in 1980. The membrane-type pumps without check valves are focused. Some EHD pumps are introduced. In the article 129 papers are cited. 20 years ago, the authors of M. Esashi (Shoji and Esashi, 1994) : ‘Microflow devices and systems’ summarized a variety of micro actuators in detail. Particularly on the micro pumps, they mentioned mainly two groups of peristaltic micropumps and electrohydrodynamic micropumps. 48 papers are listed. The paper of N-T. Nguyen, (Nguyen, et al.,2002), ‘MEMS-Micropumps: A Review’ mentions microfluidics is essentially based on MEMS technology. As one of important components in microfluidics, some kinds of MEMS-micropumps are introduced, which are mainly membrane type. The authors stress that comparisons regarding pump size, flow rate, and backpressure will help readers to decide their proper design before starting a microfluidics project. 85 papers are cited.

The review of H. Andersson (Andersson and Berg, 2003): ‘Microfluidic devices for cellomics: a review’ presents the devices on biological cell treatment in the field of uTAS (Micro total analysis systems) or Lab-on-a-chip (LOC). As the pumping devices, hydrodynamic, electrokinetic, electroosmotic, and DEP (dielectrophoresis) forces are introduced. Also, in the review articles it has been demonstrated that a large variety of microfluidic devices is available for cell analysis. The large amount of very recent publications treated in this review indicates the rapidly growing interest in the exciting application area of LOC. 93 papers are referred. In the review of Y. Fu (Fu, et al.,2004) : ‘TiNi-based thin films in MEMS applications: a review’, they state MEMS based micropumps are attractive for many applications such as implantable drug delivery, chemical analysis and analytical instruments, etc. TiNi thin films are suitable for building pumps. In the review paper, some critical issues and problems in the development of TiNi thin films are discussed, including preparation and characterization considerations, residual stress and adhesion, frequency improvement, fatigue and stability, modeling of behavior as well as functionally graded or composite thin films.

The paper of D. J. Laser (Laser and Santiago, 2004): ‘A review of micropumps’ surveyed progress over the past 25 years in the development of micro-scale devices for pumping fluids. Here, micropumps are classified into two groups, displacement-type pumps and dynamic-type pumps. Electroosmotic micropumps exhibit favorable scaling and are promising for a variety of applications requiring high flow rates and pressures. Comparisons of reciprocating displacement micropumps and dynamic micropumps are carried out in detail. This review is considered to be ranked one very standard among reviews. 287 papers are referred. The review paper of P. Woias (Woias, 2005): ‘Micropumps - past, progress and future prospects’ takes an overview of microfluidics-based micropump. Microfluidics has provided a substantial stimulus for micropump research and development. Most micropumps found today can roughly be divided into two groups, so-called reciprocating micropumps and continuous flow micropumps, which is the same group as dynamic pumps. 75 papers are listed. In the paper of J. S. Yagoobi (Seyed-Yagoobi, 2005): ‘Electrohydrodynamic pumping of dielectric liquids’, Electrohydrodynamics (EHD) deal with the interaction between electric fields and fluid flow. Three kinds of electrohydrodynamics (EHD) pumping, i.e., ion-drag pumping, induction pumping, and conduction pumping based on so-called electrohydrodynamic (EHD) phenomena are introduced in detail and compared. 22 papers are listed. The review of C. Zhang (Zhang, et al., 2007): ‘Micropumps, microvalves, and micromixers within PCR microfluidic chips - Advances and trends’ surveys mechanical micropumps and non mechanical micropumps as one of components of microfluidic chips. Particularly, here treats the devices on polymerase chain reaction (PCR). The review also mentions that PCR is a key process in genetic analysis and has been playing an important role in modern biology and biochemistry research. 97 papers are listed.

In the review of N. C. Tsai (Tsai, and Sue, 2007): ‘Review of MEMS-based drug delivery and dosing systems’, Micropumps are sorted into two large groups, i.e., Mechanical micropumps and non-mechanical micropumps for drug delivery and dosing systems, which are required bio-compatibility. Their fabrications are mainly based on Micro-electro-mechanical Systems (MEMS) technology. Also, bio-compatibilities of MEMS materials are listed and
discussed. The review deals with 57 papers. The paper of B. D. Iverson (Iverson and Garimella, 2008): ‘Recent advances in microscale pumping technologies: a review and evaluation’ mentions that researches of micropumps are motivated in part by the need to develop pumping mechanisms for biological fluid handling such as for polymerase chain reaction (PCR) and lab-on-a chip (LOC) and micro total analysis systems (µTAS). The review builds upon a number of existing reviews of micropumping strategies by focusing on the large body of micropump advances reported in the latest literature. 144 reports are listed. In the review of L. Chen (Chen, et al., 2008): ‘Continuous dynamic flow micropumps for microfluid manipulation’, the focus will be on the pumping techniques used for delivery and control of liquids, especially those physical-chemical continuous dynamic flow micropumps. Electrokinetically-driven continuous flow pumps such as the electrophoretic pump and electroosmotic pump, surface chemistry based continuous flow micropumps such as the opto-electrowetting-based pump, optically-driven pump, electrochemical pump and constant gravity-driven pump, and combination-driven techniques such as hydrodynamic flow and electrokinetic/ gravity/magnetophoretic pumping are summarized. 138 papers are referred. The paper of A. Nisar (Nisar, et al., 2008), ‘Review, MEMS-based micropumps in drug delivery and biomedical applications’ takes an overview on the development of MEMS-based micropumps in the area of micro total analysis systems (µTAS), particularly on drug delivery. The focus of the review is to present key features of micropumps such as actuation methods, working principles, construction, fabrication methods, performance parameters and their medical applications. 111 papers are referred in the review.

3. Latest papers on micropumps after 2007

Progresses all over the development of micropumps are fully mentioned in the above 13 reviews. Here, we take a glance at latest trends of the researches on micropumps. Following the paper of Laser (Laser and Santiago, 2004), micropumps are classified into two groups, i.e., displacement type and dynamic type pumps.

3.1 Displacement-type micropumps:

Displacement-type micropumps produces a flow due to the change of positive displacement of pumping parts like membranes, so the pump cannot avoid having moving parts. In fabricating displacement-type micropumps, 1) volume of moving parts, 2) miniaturization characteristics of output flow driving force are important factors. Also, in fabricating 1cm-cubic micro displacement pumps, valve characteristics are critical. The appropriate micro check valves are not available usually. In order to obtain high output power, actively driven valves are required because miniaturization makes the force of membrane driver difficult to maintain so strong. By employing the active valves, the volume becomes larger and the control method gets complicated. On the contrary employing Valveless diffusers has advantages, i.e., smaller size and easy to control, however, it results in very lower output power.

From the overview of latest articles, there can be seen comparatively many MEMS based silicon type (Dau, et al., 2009, Kang, et al., 2008, Lemke, et al., 2011, Spieth, et al., 2012, Yoon, et al., 2007), polymer membrane type (Fang and Tan, 2010, Doll, et al., 2007, Kim, et al., 2008, Liu, et al., 2011, Ni, et al., 2010), piezo-element type (Geipel, et al., 2008, Herz, et al., 2010, Izzo, et al., 2007, Kang and Auner, 2011, De Lima, et al., 2009, Ma, et al., 2011, Ogawa, et al., 2009, Tseng, et al., 2013, Wei, et al., 2014) and peristaltic type (Koch, et al., 2009, Cole, et al., 2011, Chia, et al., 2011, Lee, et al., 2012, Nakahara, et al., 2013) micropumps. Nowadays, it must be obvious that MEMS technology is a most powerful tool for realizing micro devices, and the process is often employed to fabricate devices in many researches. Another type of micropumps are SMA (Sassa, et al., 2012, Ishida, et al., 2007, Ullakko, et al., 2012), Ionic polymer (Santos, et al., 2010), IPMC (Nam and Ahn, 2012), Polymer (Tan, et al., 2010, Hansen, et al., 2007), Bubble (Chan, et al., 2010, Le and Hsu, 2010), Acoustic (Choe and Kim, 2013), Electrostatic (Yildirim, et al., 2012), Magnetic (Shen, et al., 2011, AI Halhouli, et al., 2012), Pneumatic (Jeong and Konishi, 2007), Metallic (Bodén, et al., 2008), Microplasma (Wang and Roy, 2009).

As a MEMS based silicon type, a micropump with PZT diaphragm and integrated hotwire is proposed and fabricated (Dau, et al., 2009). The diaphragm is driven at its resonant frequency. Diaphragm micropump with
piezoelectrically actuated check valves is fabricated on SOI wafers (Kang, et al., 2008). A micropump (Lemke, et al., 2011) fabricated by a multilayer piezo-actuator technology and a flexible and robust wafer-level bonding technology has succeeded decreasing the piezo driving voltage from formerly applied 360Vp–p down to 30Vp–p. Valveless diffuser type micropump is fabricated, in which a piezoelectric ceramic plate (PZT) and silicon membrane were used (Yoon, et al., 2007). It seems that Micropumps with PZT-driven membrane have comparatively better performance. Among polymer membrane types, a PZT membrane pump with active valves shows a better power density (Doll, et al., 2007). The interesting pump is fabricated for driving implant type artificial heart muscles and has four active membranes driven by piezo elements.

Excepting above types, little types are worthy of note due to the larger volume or the less power density.

Fig. 1 The working principle of the AC electroosmosis (ACEO)

### 3.2 Dynamic-type micropumps

Turbine type pumps like centrifugal pumps are classified to dynamic-type and the pumping flow is aperiodic. Electrowetting type (Yun, et al., 2001) (Shabani and Cho, 2013) are also grouped into dynamic-type. Dynamic micropumps based on electrohydrodynamics (EHD) and magnetohydrodynamics (MHD) phenomena have been developed recently. In the dynamic-type, the pumping is based on interactions between either electric or magnetic field and the working fluid. This time, dynamic micropumps can be easily divided into two main groups, *i.e.*, EHD pumps (Seo, et al., 2007, Raghavan, et al., 2009, Iverson, et al., 2009, Iverson and Garimella, 2009, Singhal and Garimella, 2007) (Abe, et al., 2007, Takemura, et al., 2007, Kim, et al., 2012, Kim, et al., 2011, Kim, et al., 2013, Yokota, 2013) and Electroosmotic pumps (Guo, et al., 2011, Borowsky, et al., 2008, Rouabah, et al., 2011, Stoterau, et al., 2010, Yoshida, et al.,). Concerning papers of EHD pumps (Abe, et al., 2007, Takemura, et al., 2007, Kim, et al., 2012, Kim, et al., 2011, Kim, et al., 2013, Yokota, 2013), details are mentioned later in the next section.

Utilizing EHD phenomena micropumps, ECF-jet (refer to the next section) is employed to cool forcedly electronic devices (Seo, et al., 2007). The principle of the ECF-jet is tried to elucidate as Maxwell stress (Raghavan, et al., 2009). Traveling-wave electrohydrodynamic (EHD) micropumps can be incorporated into the package of an integrated circuit chip to provide active cooling (Iverson, et al., 2009). Through experiments, flowrate of 0.7cm$^3$/s is obtained and increase in flow rate of approximately 73.4% compared with a previous type is observed.

Electroosmotic pumping results from the interface charge between a liquid and a solid. It is called electrical double layer. When the externally electric field parallel to the layer is applied, ion drag of the interface charge forces a flow against pressure gradient. Figure 1 shows the working principle of the AC electroosmosis (ACEO) (Yoshida, et al., 2013). When AC voltages are applied to the electrodes, charged particles on the electrodes move due to the electric field at the slip velocity and cause total flow through viscous force. As both polarities of the particle charge and the
electric field change simultaneously, the flow directions on the electrodes are independent of the time. In electroosmotic pumps, recently, fabrications of 3D electrodes are topics.

A Micro pump with four three-dimensional (3D) micro-electrode arrays for pumping liquid by utilizing AC electro-osmosis (ACEO) mechanism (Guo, et al., 2011) is proposed and fabricated, and the velocity of 0.6mm/s is obtained through experiments. A high pressure electroosmotic flow (EOF) pump is fabricated within a glass substrate (Borowsky, et al., 2008), and measurements indicate a maximum pressure of 2.5MPa, a maximum measured flow rate of 1.4x10^{-3}mm^3/s, and power density is 0.32µW/cm^3. New electrodes with 3D structure of AC electro-osmosis (ACEO) pump are fabricated using carbon-MEMS technology based on the pyrolysis of the photo-patternable polymer SU-8 (Rouabah, et al., 2011) and the 3D micropump has a velocity of 120 μm s^{-1}, which is five times higher than previous one. Electroosmotic pumping is less power density compared other micropumps as it stands, however, in future it may be possible to obtain higher power density.

4. High power density micropumps
4.1 Displacement micropumps

When using EHD fluid for pumping, there are some limitations, e.g., limitation of kinds of liquids, however, for micro hydraulics and micro cooling, no problems are existed. From the reasons, we propose and develop high power output micropumps, using ECF-jets. ECF is a kind of dielectric and functional fluids, which generates strong jet between electrodes when a voltage is applied. Here, some micropumps with high power density using ECF-jets are introduced below.

1) An 1-cm-cubic-size SMA-Driven Micropump Using ECF Jet Cooling (Proc. ISFP 1999) (Yoshida, et al., 1999)
A 1cm-cubic-size SMA (shape memory alloy) wire-driven micropump using ECF jet cooling is proposed, fabricated and tested, as shown in Fig. 1. We employ very thin SMA wire with 70µm diameter to make bellows pushing axially as a pumping element. Fine wires are suitable for effective and fast cooling. Liquid forcibly cooling using ECF jet makes the fine SMA wire respond fast. ECF is considered a kind of EHD fluid and produce strong jet flow to apply voltage between electrodes in a vessel. The size of the fabricated micropump is 9mm in diameter, 10 mm in height. Effectiveness of the ECF jet forced cooling is verified and the basic characteristics and the optimal parameters for applying voltage to the ECF, applying electric power to the SMA and so on are obtained. The maximum output flowrate and pressure of 11mm^3/s and 0.18MPa are realized.

2) PZT resonantly-driven micropump (Actuator 2002) (Park, et al., 2002)
A 1cm-cubic-size resonantly-driven PZT micropump with check valves is proposed, fabricated and tested as shown in Fig. 2. A bellows is resonantly-driven by a frequency which mainly determined from bellows elasticity and mass using multilayered PZT, and the pressurized fluid is discharged from bellows. The pump is applicable to microfactory of micromachines using fluid power as a micro fluid power sources. The size of the fabricated micropump is 9mm in
3) A Micro Fluid Power Source Using Fluid Inertia Effect in a Pipe for High Viscosity Fluids (Proc. ICMDT 2007) (Yoshida, et al., 2007)
A novel piezoelectric micropump is proposed and fabricated, which utilizes the phenomena of fluid column separation in the relatively long pipeline element and generated inertia effect of fast outflow, instead of the outlet check valve as shown in Fig. 3. Through experiments on load characteristics using water as a working fluid, the newly devised micropump attained a higher fluid output power than 70mW and the volumetric efficiency of the pump exceeds 100% with the pump chamber diameter of 3mm. Furthermore, by measuring the internal pressure of the pump, the above-mentioned principle is confirmed based on the relation of the driving voltage of a multilayered piezoelectric element and the internal pressure of the pump. Maximum flow rate of 420mm$^3$/s, higher pumping pressure than 0.25MPa are obtained.

Fig. 4 A PZT Micropump utilizing Fluid Inertia Effect

Fig. 5 Needle-Ring electrodes pair

Fig. 6 TPS electrodes and its SEM picture

4.2 Dynamic type (ECF micropumps)

4) Concept of a micro finger using ECF micropump (J. SNA 2007) (Abe, et al., 2007)
Electro-conjugate fluid (ECF) is a kind of functional fluid, which generates jet flow (ECF jet) when applied to high DC voltage. It seems that this is an EHD phenomena and we have been trying to unveil how it works, however, the mechanism of jet generation is not yet well elucidated. It is ascertained that a strong ECF jet is generated under nonuniform electric field, for example, around a pair of a needle-electrode and a ring-electrode (a needle-ring electrode pair) as shown in Fig. 5. The size of the fabricated micropump is 2mm in diameter, 5 mm in height. This study proposes and develops a novel micro finger with two-DOF motion driven by ECF jet. Here, as a micropump, the pressure and flowrate characteristics of the needle-ring electrode pair are measured when the parameters are changed. Output pressure of 9kPa for one pair electrodes of ring and needle is obtained. Also, an artificial muscle cell using an electro-conjugate
fluid (ECF) as a built-in micropump and integration of the cells is proposed and fabricated (Takemura, et al., 2007). Tube-type ECF micropump using MEMS for micro hydraulics (J. SNA 2012) (Kim, et al., 2012) An ECF micropump is proposed and fabricated whose pumping sources are mounted on the inside of flow channels and are serially located through the flow channels. To combine easy fabrication for MEMS and high performance, a novel ECF-jet generator having 2.5 Dimensions that consists of a triangular prism electrode and a slit electrode for the tube-type ECF micropump, as shown in Fig. 6, is proposed. The size of the fabricated micropump is 5mm in width, 2 mm in height, and 8 mm in length. The maximum output pressure obtained is 64kPa and the maximum flow rate is 1.12 cm³/s at the applied voltage of 6 kV for 8 pairs in serial integration. The flow channel has 5mm in width, 5 mm in height, and 75 mm in length. The results describe that the proposed ECF-jet generator and whose tube-type ECF micropump can be a good candidate as a driving source for forced liquid cooling systems, new microactuators and so on.

6) High Performance ECF Micropump by the In-plane Integration of MEMS-fabricated electrodes (Proc. ICMT2011) (Kim, et al., 2011) A high power ECF micropump composed of triangular prism and slit electrode (TPS) pairs is proposed and fabricated by MEMS technology based on photolithography with thick photoresist and nickel electroplating. In addition, we propose advanced ECF micropumps in which the electrode pairs are in-plane integrated for high performance in demand as shown in Fig. 6. The size of the fabricated micropump is 1.0mm in width, 0.4 mm in height, and 20.6 mm in length. The experimental results of the ECF micropumps denote that parallelizing the electrode pairs does not affect output pressure significantly and also prove that the flow rate is proportionally dependent on the number of parallelized electrodes. The output pressure of 73kPa, the maximum output power density of 159 mW/cm³ are obtained under the applied voltage of 4.0 kV, in the case of 3 pairs in parallel and 10 pairs in serial integration.

7) Flexible Micro gripper driven by ECF micropump (Proc. FLUCOME2013) (Kim, et al., 2013) On purpose to realize a micro novel flexible manipulator for biological and medical applications, the paper presents a major step forward in this direction by directly integrating a micropump into a balloon-type microactuator driven by the ECF jet. The ECF balloon-type microactuators (ECF-BMAs) is composed of an ECF micropump, a thin and flat layer of PDMS, and a thick and balloon-shaped layer of PDMS. The ECF micropump by 20 pairs in series and in plane of a triangular prism and slit electrodes (TPS), as shown in Fig. 7, produces maximum pressures of 76kPa and maximum flow rates of 39 mm³/s under the applied voltage of 3.5kV. The size of the fabricated micropump is 14.6mm in width, 12.1 mm in length, and 2.5 mm in height. The fabricated balloon-type microactuator (450mm³ in volume) had deformation up to 6mm and maximum output force of 0.9mN at the applied voltage of 3.5kV. By utilizing two ECF-BMAs, we proved the feasibility of a novel ECF microgripper.

4.3 Comparisons from the view point of volumetric power density

In micropumps, the volumetric power density is one of critical indices, particularly in micro hydraulics. It seems that micropumps used in the area of micro total analysis systems (µTAS) and drug delivery systems, it is not necessary to have high pressure capabilities. Forced cooling systems also do not require high pressure, however, it is necessary to have
enough pressure to overcome the pipeline resistance.

Figure 8 shows the relationship between volumetric power density of recent developed micropumps and the size. The power densities of micropumps are denoted from the data in the article. There are many papers in which due to the lack of the data on the power density are not able to calculate or estimate. It can be seen sometimes that Micropumps developed for µTAS are discussed flowrate only. In using µTAS, dosing, and forced cooling, high power density is not necessary, however, the author considers that to overcome the pipe resistance and the other obstacles in the system, certain power density is required. In microhydraulics, we consider that the power density of the micropump should be over a few hundred mW/cm$^3$.

![Fig. 8 Comparisons of power density of Micropumps](image)

5. Conclusions

We survey some recent review articles and latest papers, particularly from the view point of the power density. In microfluidic systems, micropump is an essential device, and it is required to build the micropump in the actuator or the system. Therefore, the size should be within 1cm-cubic. A lot of researches have been performed in these days, however, a micropump with high-performance is not developed yet. As for micro hydraulic system, situation is the same. In realizing high-performance micro hydraulic systems with high-power density, micropumps play an important role. Also, for applying to micro hydraulics, the volumetric power density should be over a few hundreds mW/cm$^3$. We focused ECF to obtain high power density as a micropump. Here, in order to realize micro hydraulic power sources with high enough power density for micro actuation, we propose a novel ECF micropump using ECF-jet as one promising candidate in micro hydraulic systems. The pressure due to the jet-flow is used as a pressure source.

From the view point of power density, integrated ECF micropumps are proposed and fabricated using MEMS process and the applications. Experimental results show using the ECF effect, ECF micropump by the integration can be a good candidate in micro hydraulic systems and the ECF-TPS micropump was proved to be a world top class in high output power density. In near future, the method to fabricate a micro pump with 3D arbitrary shape using MEMS process will be developed and established, which has higher enough power density and is driven by lower voltage like 1kV, and will apply to novel micro manipulators. Also it seems that this remains a developing area for future research, we expect that novel micropumps with appropriate power density will be proposed and developed in every applicable field.

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