Energy conversion in microsystems: is there a role for micro/nanofluidics?

Introduction

Improving energy conversion efficiency has been a goal for decades, which is why it is not surprising that recent advances in microfabrication have led to the development of microenergy conversion devices. In this article, we will examine the developments of microscale novel energy conversion methods, focusing our efforts on devices utilizing micro and nanofluidics. First, we will look at the various types of energy conversion machines that can be developed with the aid of microfabrication. These devices include conventional devices that have been miniaturized (and perhaps improved) as well as microdevices that use completely novel methods of energy conversion. Next, we will focus on a particular type of mechanical to electrical energy conversion process where nanofluidics plays a direct and essential role, involving an electrokinetic phenomenon called streaming potential. Finally, we will discuss the issues that need to be overcome in order for micro- and nanofluidic devices to become a desirable solution in the energy conversion process.

Micro/nano "energy conversion machines"

Energy conversion efficiency is defined as the ratio between the useful input and output of an energy conversion machine. Conventional energy conversion machines include heat engines, fuel cells, hydroelectric dams, jet engines, nuclear reactors, solar cells, steam engines, windmills and piezoelectrics. Recent advances in microfabrication technology have not only allowed for miniaturization and improvement of conventional energy conversion machines, but also for truly novel methods of energy conversion. Examples of miniaturized conventional devices include micro reactors,[1] miniaturized gas turbines,[2–4] miniaturized heat engines,[5–10] micro batteries,[11–13] micro super capacitors,[14] and micro fuel cells.[15]

Examples of novel methods to convert energy using microscale fabrication include biologically inspired methods,[16–19] or creating a streaming potential through a nanochannel.[20–30] In this article, we will discuss the above examples in more detail, focusing our discussion on the role of micro- and nanofluidics.

Conventional miniaturized machines

In this section we will briefly describe conventional forms of energy conversion machines that have been miniaturized using microfabrication technology, focusing on those that use micro- and nanofluidics. However, we first note that microfabrication technology has also been instrumental in the *improvement* of macro-scale machines, for example, using nanocomposites with corrugated polymers to improve the efficiency of a solar cell.[31] However, micro- and nanofluidics is more often utilized in devices that are miniaturized versions of conventional devices, such as micro gas turbines, micro fuel cells, and micro reactors. A micro gas turbine converts heat energy from fuel into either electrical energy (*e.g.* to drive a load) or mechanical energy (*e.g.* to propel a micro air vehicle). These micro devices are advantageous over more conventional turbine engines because of their high power density. The microengines are able to generate up to 80 W of power, resulting in energy densities comparable to energy densities of large power plants. However, due to the complexity of fabrication, the difficulties associated with packaging, and the high costs of a device, these micro engines cannot currently be produced for large power applications. Instead, such a device is intended for small scale stand-alone portable applications such as laptop batteries, cell-phones and other mobile electronics. Micro fuel cells and microreactors are devices that are also aimed at achieving portable power for

mobile electronics. These devices can successfully convert chemical and biochemical energy into electrical energy. Micro fuel cells are advantageous because the structuring that can be designed and achieved at the micro-scale increases performance and efficiency. In general, all micro electrochemical energy systems, including microdevices that do not utilize microfluidics, such as micro-batteries and microsupercapacitors[11–14] have inherent advantages over other conversion systems. These advantages include high volumetric energy densities,[8] low-vibration, minimal or no air pollution and low-noise operation. Other interesting microfabricated devices that mimic conventional devices include MEMS piezoelectric,[32] thermoelectric and electromagnetic power generators.[7,8] These miniaturized conventional devices are summarized in Table 1, along with their typical power densities, efficiencies, and advantages.

Novel methods of energy conversion using microdevices

Another set of devices that can be fabricated at the micro- and nano-scale utilizes the unique properties of the small scale for successful functionality. For example, the nanometre-size of nano-structured materials allows heat to dissipate quickly, orders of magnitude faster than structures created with millimetre or larger dimensions, and therefore can be used for energy storage, thermal management, or other energy-related applications. Similarly, micro- and nano-scale catalysis, combustion, heat and mass transfer is limited by reaction time, instead of diffusion time. This phenomenon leads to novel forms of energy storage and transfer. For example, a novel type of micro fuel cell has been developed that uses multi-stream laminar flow to keep fuel and oxidant streams separated yet in diffusional contact.[38] The flow is parallel between two

Table 1 Different forms of micro-scale energy conversion devices

Machine	Energy input	Energy output	Typical Efficiency	Advantages	Ref.
Micro heat engine	Heat	Electrical	37%	High power density	4, 5, 8–10
Micro fuel cell	Chemical	Electrical	Up to 60%	High power density	15
MEMS piezoelectric	Vibration	Electrical	7%	More kT energy	32
Thermo-acoustics	Heat	Acoustical	3%	Can pump microchannels	33
Photovoltaic cells	Solar	Electrical	12%	Better engineered materials	34
Nanostructured materials	Heat, electrical, chemical	Electrical, chemical	N/A	Nanoscale only	31
Biologically inspired approaches	(Bio)chemical	(Bio)chemical, electrical	N/A	Nanoscale only	17–19, 35
Streaming potential	Pressure	Electrical	12%	Nanoscale only	20–27, 29, 36, 37

catalyst-covered electrodes on opposite sides. This novel fuel cell can be operated at room temperature and achieve a power density of up to 8 mA cm^{-2}. Microfabricated devices also allow for unconventional energy conversion. For example, using thermal energy to create an acoustic wave has been recently explored in microdevices by applying a temperature gradient along a system of plates parallel to a resonator axis in a gas-filled annular resonator. This method shows promise for pumping fluids in microscale channels and other applications benefiting from acoustical to mechanical energy conversion. Surface tension is another property of systems which, at the micro- and nano- scale, can be used to generate power. For example, researchers have developed a nano-electromechanical motor using surface tension between two liquid metal droplets along a surface as a driving force.[32] Additionally, biologically inspired approaches[18,19,35] for energy conversion have gained much attention recently. Biological systems as occurring in nature convert solar, mechanical, chemical, and biochemical energy to electrical, mechanical, chemical and biochemical energy. Although we are still in the early stages of the development of biologically inspired microdevices, many studies have been performed on the fundamental

understanding of biological systems and the energy that can be harnessed. For example, LaVan et al. have successfully shown that photosynthesis and light driven proton pumps can be emulated in the lab, the challenge being the transfer of the high level of performance seen in the lab into a more commercial device.[35] Additionally, there has been a plethora of studies using biomolecular motors such as kinesin, myosin, dynein, and F1-ATPase to power nano/micro-devices.[18,19,35] Again, although many of the results show promise, more research is required before we can successfully create commercial micro-devices to harness useful energy.

Nanofluidic energy conversion

One other method of energy conversion that in essence is nanofluidic involves the use of streaming current in a nanofluidic device to create electrical energy. This form of energy conversion is especially interesting because of the simplicity of the device: all that is needed is a nanometre sized channel, water, and a pressure gradient. The pressure gradient results in transport of the water through the nanochannel, creating streaming current of the charges in the electric double layer which can then be used to drive an external load (see Fig. 1). Both streaming

currents and streaming potentials have been widely studied in the context of lab-on-chip devices,[22,24–30,39–42] with the most recent studies theoretically determining maximum power efficiency of current systems at around 12% for 500 nm channels.[30] Experimental efficiencies of about 3% have also been achieved.[27] These results, albeit interesting, do not encourage future development of nanofluidics for energy conversion. However, combining these results with recent theoretical investigations indicating that liquid slip in nanochannels may increase streaming current effects[40,43] show promise towards a useful device. To further examine this opportunity, we theoretically calculate the increase of efficiency in a nanofluidic device due to a liquid slip length using a simple model that accounts for ionic conductance with overlapped double layers. The electrical conversion efficiency of a nanochannel can be calculated with the following relation:[44]

$$\varepsilon_{tot} = \frac{P_{ext}}{P_{hydro}} = \frac{I_{str} V_{str}}{\Delta P Q} \quad (1)$$

Where P_{hydro} is the hydrodynamic power, which is the pressure drop through the channel, ΔP, times the flow rate, Q through the channel. Q can be solved for by integrating the velocity profile, $u(r)$, that results from both
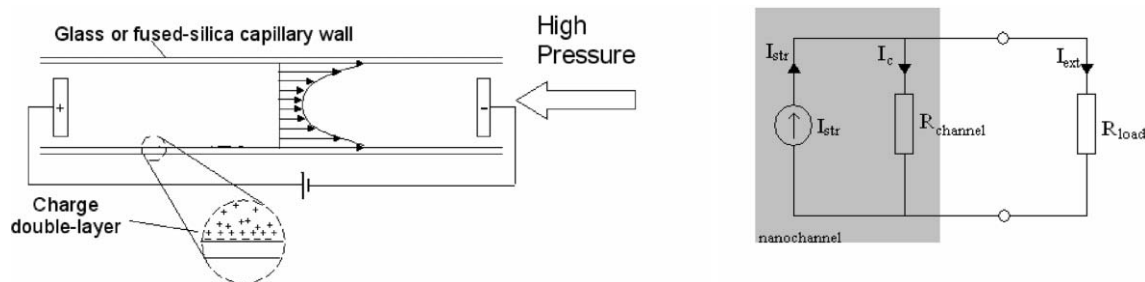

Fig. 1 (left) Schematic illustration showing nanochannel setup and electrokinetic effects. A pressure driven flow carries a net ionic charge thereby generating a streaming potential. This potential can then be harnessed to produce useful electrical energy. (right) Equivalent circuit diagram showing voltage-controlled current source network model of streaming current and potential.

pressure-driven and electroosmotic flow in a cylindrical channel with radius a and slip length b:

$$u(r) = -\frac{(a+b)^2 \Delta P}{4\mu L}\left(1 - \frac{r^2}{(a+b)^2}\right) - \frac{\varepsilon\zeta V_{str}}{\mu L}\left(1 - \frac{\psi(r)}{\zeta}\right) \quad (2)$$

where μ is the coefficient of viscosity of the solution, ε is the dielectric constant, L is the length of the channel, ζ is the zeta potential, or the potential at the shear plane, $\psi(r)$ is the transverse potential distribution, and V_{str} is the streaming potential. Note when the slip length is 0, the equation reverts to the classic equation for Hagen–Poiseuille flow and electroosmotic flow in a cylindrical capillary.[42,45,46] The transverse potential distribution can be solved by Poisson's equation:[46]

$$\rho(r) = -\varepsilon \frac{1}{r}\frac{d}{dr}\left(r\frac{d\psi(r)}{dr}\right) = -2ezn_\infty \sinh\left(\frac{ze\psi(r)}{kT}\right) \quad (3)$$

To solve for the power dissipated in the external load, P_{ext}, we must solve for the streaming potential and current in the channel, since $P_{ext} = I_{tot}V_{str}$. Also, we must note that when a hydrodynamic flow is present in a channel with a finite charge distribution, the hydrodynamic flow will cause a current by the movement of the charge past the shear plane. The streaming current in the channel can be expressed by the following equation:

$$I_{str} = 2\pi \int_0^a u(r)\rho(r)\,dr \quad (4)$$

where the velocity and charge distributions have been defined by equations (2) and (3) above. For power conversion applications, this electrical current will be balanced by a conduction current that arises from the electric field created by the resulting polarization of charge along the plug axis:[44]

$$I_{em} = 2\pi \int_0^a [\sigma(r)V_{str}/L]r\,dr \quad (5)$$

The streaming potential can thus be found by equating the conduction current to the streaming current. These equations take into account the variation of conductivity throughout the channel due to the double layer. However, the layer of ions adsorbed to the wall (also known as the Stern layer) is not accounted for in this model, since it is not precisely known.[41,42,44,46] To account for slippage, we modify the zeta potential according to Joly as $\zeta = V_o(1 + b/\lambda_D)$, where λ_D is the Debye length.[40] Therefore, our boundary condition is one of a constant surface potential. As mentioned in previous work,[27,30] this sort of boundary condition may not be as accurate as modelling with a constant surface charge, but it allows us to see more clearly the effects of liquid slip. Additionally, continuum modelling may not be appropriate at such small length scales,[47] but nevertheless this simple model will help predict whether nanoscale channels will be useful as energy conversion devices.

Using this model, we have found that with a slip length of 6.5 nm in 100 nm cylindrical tubes the electrokinetic conversion efficiency increases by about 30%, and we can achieve up to a 35% efficiency at very high surface potentials in a 100 nm channel with 1 mM KCL as a background electrolyte.

However, even with a higher electrokinetic efficiency, we still face the challenge of creating a practical system. The conversion of ionic to electrical current requires the choice of electrodes to maximize efficiency, as well as a well-designed packaging system for efficiency and durability.

Applications and challenges for micro/nanofluidic energy conversion devices

The micro/nanofluidic energy conversion devices mentioned in this article, such as micro heat engines and nanofluidic streaming potential devices, all have the potential to power larger scale systems, such as power plants, cars, and household appliances due to their high power density and low weight. However, with current technology these devices are very costly, time-consuming to fabricate, hard to package, and it is highly questionable if mass production will ever reduce costs to such a level that they will become viable alternatives for present large-scale power generation methods. In another field, the current market need for small-scale portable power for mobile electronics is driving the technology towards smaller scale applications where the devices mentioned could be economically viable. However, regardless of application, micro- and nanofluidic energy devices still face many challenges before they can be commercially realized. First, an efficient, cost-effective packaging scheme must be devised that can practically and reliably re-direct harnessed energy to the electronic device. Next, large-scale MEMS fabrication must drive down the cost of such devices to ensure practicality for portable electronics. Finally, devices must be fabricated to be more robust, that is, to withstand the rugged conditions of the environment outside the laboratory.

Discussion and conclusion

There is a clear role for micro/nano-technologies in future power conversion systems. Apart from the more conventional MEMS-based approaches for such energy scavengers, there is also a role for micro/nanofluidics that is easily overlooked. In particular, we find that theoretically high-energy conversion efficiencies are possible using slip flow conditions in nanofluidic devices. Nevertheless, apart from practically demonstrating such extreme slip-flow conditions, it is also still unclear as to which type of microdevice will produce the best efficiency and maximum power density. More nanofluidic research and development will be needed to demonstrate the real potential of this form of energy conversion system.

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