Microwave-induced water flows in microsystems

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Alternating current electric fields are of increasing importance for the development of microfluidic pumps. We report how microwave fields can induce water flow in microsystems, irrespective of saline concentration. A drop of water is placed on two parallel coplanar microelectrodes that are energized by a microwave generator. Fluid flow is observed and the fluid velocity is about the same for two electrolytes with very different saline concentrations. Electrically induced gradients of temperature produce spatial variations in mass density and dielectric permittivity leading, respectively, to buoyancy and dielectric forces in the liquid. The observed fluid flow patterns demonstrate that both effects are taking place at different length scales: the dielectric forces dominate at lengths of the order of 100 \( \mu m \) or smaller, while buoyancy dominates around 1 mm.

Control and manipulation of water is an important requirement for the lab-on-chip technology. Among the most promising techniques to handle small amounts of liquid are those that employ electrical forces directly applied to the liquid. Electrohydrodynamic (EHD) actuation presents the advantages of voltage-based control, dominance of electrical forces at the micrometer scale, and absence of moving parts. Therefore, several possible ways of EHD actuation in microsystems have been explored such as electro-osmosis, ac electro-osmosis, electrothermal induction pumping, and ion-drag pumping.

Microwave electric fields have recently been used in microsystems for controlled dielectric heating or for reagent detection within microchannels. In this letter, we experimentally demonstrate the use of microwave fields for electrothermal actuation of water in microsystems. The microwave fields heat the fluid generating gradients in mass density and dielectric permittivity. The fluid is then set into motion due to buoyancy \( \mathbf{f}_b = \Delta \rho g \) and dielectric forces \( \mathbf{f}_d = -\frac{1}{2} \nabla \mathbf{E} \cdot \epsilon \mathbf{E} \). The main advantage of this kind of EHD actuation is that water saline solutions can be pumped with almost no dependence on saline concentration since the heating is based on water dielectric loss at microwave frequencies. Other kinds of EHD pumping of water are suitable for certain ranges of conductivity: ac electro-osmosis is suitable for electrolytes with low ionic strength \((\sigma < 0.01 \text{ S/m})\), while ac electrothermal induction pumping is suitable for higher ionic strength \((\sigma > 0.01 \text{ S/m})\). The latter can be used for liquids with smaller conductivity but using external heating. In addition, the frequency of the signal must be changed depending on conductivity to achieve the best pumping performance in both kinds of actuation.

The power density dissipated as heat for an ac field \( \mathbf{E} \) of angular frequency \( \omega \) due to dielectric loss is

\[
P_{\text{dieel}} = \frac{1}{2} \epsilon'' \omega \mathbf{E}^2,
\]

and due to Ohmic currents is

\[
P_{\text{Ohm}} = \frac{1}{2} \sigma \mathbf{E}^2,
\]

where \( \epsilon'' \) is the imaginary part of the complex dielectric permittivity and \( \sigma \) is the electrical conductivity. Therefore, dielectric heating dominates over Joule heating for \( \epsilon'' \omega > \sigma \). For instance, the dielectric loss factor \( \epsilon'' \omega \) at 3 GHz and 20 °C results in an equivalent conductivity of 2.2 S/m. (The equivalent conductivity is 0.24 S/m for a frequency of 1 GHz at 20 °C.) The heating and the expected flow induced by ac electric fields at 3 GHz are about the same for water solutions with conductivities smaller than 2.2 S/m. Therefore, most biological fluids could be pumped with the same behavior using the same applied signal. For higher conductivity, the heating will increase but the effect would be similar. We propose that microwave water actuation can be of use for the lab-on-chip technology.

The experimental setup is shown in Fig. 1. A square fluid chamber was built with polydimethylsiloxane (soft polymer used in microfluidics). The bottom of the chamber is a planar glass substrate with two parallel platinum microelectrodes fabricated on it. The lid is a glass coverslip. The electrodes are 100 nm thick and 500 \( \mu m \) wide separated by a 10 \( \mu m \)

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gap. KCl water solutions were pipetted into the chamber. Fluorescent latex particles (500 nm diameter) were suspended in the solution and used as flow tracers. Fluid flow was observed after application of ac electric fields from 1 to 4 GHz. The microwave source comprises an Agilent PNA E8363B automatic vector network analyzer used as a microwave generator and connected to a microwave amplifier AR 5S164. The device was connected to the amplifier through a coaxial transmission line.

Figure 2(a) presents the measured velocity against frequency for constant power $P_m=0.16$ W of the incident wave for two saline solutions. The height of the channel is 737 $\mu$m, sufficiently high to consider that the fluid motion is mainly due to buoyancy (see below). Typically, two symmetric rolls were observed on top of electrodes. For $f > 1.5$ GHz, the velocity is roughly the same for the two water solutions. At frequencies from 1 to 4 GHz, microwave wavelengths are of the order of 10 cm, much greater than the dimensions of the device ($\sim 2$ mm). Therefore, simple circuit theory is valid for the analysis of the microdevice and a voltage difference can be assumed to be applied between the parallel electrodes. The variation in fluid velocity with frequency can be understood from the frequency variation of the voltage between electrodes. Our device will behave as a load impedance $Z$ connected to the end of the transmission line, which has a characteristic impedance of $Z_0=50$ $\Omega$. At microwave frequencies the connection pads behave mainly as an inductor (of inductance $L$), which is connected to the two coplanar microelectrodes that, with the water drop on top, behave as a leaky capacitor (with resistance $R$ and capacitance $C$ in parallel). The resistance $R$ is not a constant (it is inversely proportional to $\epsilon''/\epsilon$). The device impedance is given by $Z=\mathrm{i}a L+R/(1+\mathrm{i}a CR)$. The voltage $V=V_+V_-$ and the electrical current $I=(V_+-V_-)/Z_0$ at the end of the transmission line are related by $V=ZI$, where $V_+$ is the amplitude of the incident wave provided by the source and $V_-$ is the amplitude of the wave reflected by the device. The voltage at the electrodes relative to $V_+$ is then $V_{CR}/V_+ =2Z_{CR}(Z+Z_0)$, with $Z_{CR}=R/(1+\mathrm{i}aCR)$ the impedance of the leaky capacitor. Figure 2(b) shows the voltage at the electrodes as a function of frequency for reasonable values of $L$, $R$, and $C$, computed with finite elements for the actual device. It also shows the theoretical voltage required to generate the measured velocities by buoyancy. The agreement is satisfactory.

Figure 2 can be used as a calibration curve to infer the voltage at the electrodes as a function of frequency for a given incident power $P_m=V_+^2/2Z_0$. Figure 3 shows the experimental fluid velocity as a function of estimated dissipated power $P_{\text{dis}}=P_m\left(V_+^2/V_-ight)^2(Z_0/R)$ for two channels with different heights (287 and 737 $\mu$m). The experimental velocities were obtained varying the incident power ($0$–$3$ W) for given frequencies ($1$, $2$, and $3$ GHz) and saline concentrations (de-ionized water and KCl solution of conductivity $128$ mS/m). We can see that the experimental velocities have collapsed into a single curve, independent of frequency. Computations for the velocity using finite elements are also shown. The difference between experimental and numerical results at low powers for the 287 $\mu$m channel height can be attributed to the fact that the calibration curve was obtained from the 737 $\mu$m channel height measurements.

For the computations, we have solved the electric, temperature, and velocity fields in the chamber. Because the wavelength is much greater than microdevice dimensions, the electric potential is solved. Complex permittivity in different domains (water, glass) are used in order to account for the dielectric response at microwaves,

$$\nabla \cdot \left[ (\sigma + \mathrm{i}\epsilon \omega) \nabla \phi \right] = 0, \quad \epsilon(\omega) = \epsilon'(\omega) - \mathrm{i}\epsilon''(\omega).$$

At 20 $^\circ$C, the real part $\epsilon'$ is approximately $80\epsilon_0$ for frequencies below 5 GHz (relative variation <5%). On the other hand, the imaginary part $\epsilon''$ depends on frequency in the range of our experiments (1–4 GHz). The temperature field is governed by

$$k \nabla^2 T + \frac{1}{2}(\sigma + \omega \epsilon')E^2 = 0,$$

neglecting convection of heat. Finally, the fluid velocity is obtained from Stokes equations for an incompressible fluid,

$$\eta \nabla^2 \mathbf{u} - \nabla p + \mathbf{g}_F + (f_\tau) = 0, \quad \nabla \cdot \mathbf{u} = 0,$$

where $p$ is the pressure and $\eta$ is the viscosity. The dielectric force expression is usually obtained from thermodynamic arguments with static fields. We have assumed that the dielectric force expression is valid with $\epsilon = \epsilon'$ since $\frac{1}{2}\epsilon'\epsilon E^2$ accounts for the electrical energy stored in the dielectric. For simplification, the dielectric energy is neglected. The results at low powers for the 287 $\mu$m channel height can be attributed to the fact that the calibration curve was obtained from the 737 $\mu$m channel height measurements.
The theory for small temperature increments predicts that fluid velocity due to buoyancy should be proportional to the dissipated power, while the velocity due to the dielectric force should be proportional to the dissipated power squared. For a channel with height 287 μm, Fig. 3 shows that the velocity increases more than linearly with dissipated power for \( P_{\text{dis}} > 0.02 \) W.

In conclusion, we have demonstrated the pumping of water in a microdevice by the electrothermal action of microwave electric fields. Buoyancy and dielectric forces set the liquid into motion. We have shown semiquantitative agreement between experiment and theory in terms of frequency and voltage dependence. The ability to pump water solutions with different conductivities (including biofluids) in a microsystem has many potential applications in the lab-on-chip technology.

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11See EPAPS Document No. E-APPLAB-94-006903 for a video showing the fluid motion at two different heights above the electrodes. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.