A novel alternating current multiple array electrothermal micropump for lab-on-a-chip applications

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The AC electrothermal technique is very promising for biofluid micropumping, due to its ability to pump high conductivity fluids. However, compared to electroosmotic micropumps, a lack of high fluid flow is a disadvantage. In this paper, a novel AC multiple array electrothermal (MAET) micropump, utilizing multiple microelectrode arrays placed on the side-walls of the fluidic channel of the micropump, is introduced. Asymmetric coplanar microelectrodes are placed on all sides of the microfluidic channel, and are actuated in different phases: one, two opposing, two adjacent, three, or all sides at the same time. Micropumps with different combinations of side electrodes and cross sections are numerically investigated in this paper. The effect of the governing parameters with respect to thermal, fluidic, and electrical properties are studied and discussed. To verify the simulations, the AC MAET concept was then fabricated and experimentally tested. The resulted fluid flow achieved by the experiments showed good agreement with the corresponding simulations. The number of side electrode arrays and the actuation patterns were also found to greatly influence the micropump performance. This study shows that the new multiple array electrothermal micropump design can be used in a wide range of applications such as drug delivery and lab-on-a-chip, where high flow rate and high precision micropumping devices for high conductivity fluids are needed. © 2015 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4907673>]

I. INTRODUCTION

Due to its relevance to the development of micro total analysis systems (μ TAS) for drug delivery, biological and chemical analysis, microscale manipulation of fluids and particles is receiving increasing attention from researchers in different fields.^{1,2} The developments in μ TAS include reduction of sample and reagent size, short reaction and analysis time, high throughput, and portability.³ AC electrothermal (ACET) has been shown to be very effective in high-conductivity fluids, and ACET micropumping has received attention for biological applications in the past few years,^{4–10} since ACET flow can operate in low voltages and at high frequencies. These two advantages lead to ACET micropumps being portable and cost effective.¹¹

The ACET effect arises from the interaction of temperature gradients and non-uniform electric fields in micro-scale fluid channels. Temperature gradients can be induced by Joule heating from electrodes or external sources, such as microheaters or lamps.^{3,12} Joule heating is the heat generated from electrodes upon applying an electric field. Since it is proportional to the inverse of electrode area, by decreasing the size of the electrodes (i.e., using microelectrodes), the amount of heat generated is increased. For fluidic channels with the height of <1 mm, the effect of illumination from the microscope lamp is not enough to interfere with the ACET flow.¹³ The temperature gradient in the fluid leads to gradients in the electric properties of fluid, i.e., conductivity and permittivity, which further induce free charge density. Free charges move in the non-uniform electric field and consequently induce microflows.^{8,9,14–17} As ACET flow depends on the thermal gradients in the fluid, the flows become stronger in fluids with medium to high ionic strength. As such, the ACET effect is the only electrokinetic mechanism capable

of pumping fluids at a biologically relevant ionic strength.¹⁸ ACET pumping has been demonstrated at low voltages ($<15 V_{rms}$) for fluid conductivity of 0.02–1 S/m with fluid velocity of 100–1000 $\mu\text{m/s}$.⁷

In order to generate high strength AC electric fields, microfabricated electrode arrays are commonly used for ACET devices.^{4,7,19} Symmetric electrodes, and therefore symmetric electric fields, have been used for mixing purposes, whereby fixed vortices are created above a set of electrodes. However, for pumping applications, it is essential to create asymmetry in the electric field to cause asymmetric vortices that generate a new fluid flow in one direction.²⁰ As commonly used by many groups,^{4,6,7,21} imposing geometry asymmetry to microelectrodes results in non-uniform electric fields. Such structures include interdigitated electrode pairs with unequal widths,²² T-shaped electrode arrays,⁷ concentric electrode design,²³ and 3D electrode structures.^{19,21,22} Using two opposing microelectrodes in a microchannel aimed for mixing and particle assembly have also been studied,^{14,24} as has applying a travelling wave on a group of symmetric microelectrodes.²⁵ In this paper, a novel AC-actuated multiple array electrothermal (MAET) micropump based on asymmetric coplanar microelectrode geometries is proposed, designed, numerically characterized, and experimentally investigated. The governing parameters, such as thermal, fluidic, and electrical properties are studied, and simulation and experimental procedure for different designs of AC MAET are discussed. The ideas investigated in this paper, which differ from other studies, are based on the use of multiple microelectrode arrays on multiple microchannel side-walls, which has not been previously reported.

II. THEORY

ACET effect refers to electrothermal flow induced by temperature gradients in the presence of AC electric fields. When an electric field is applied over the fluid with electrical conductivity σ , Joule heating of the fluid will take place according to the energy balance equation,^{14,16}

$$k\nabla^2 T + \frac{1}{2} \langle \sigma E^2 \rangle = 0, \quad (1)$$

where E is the magnitude of the electric field and σ and k are the electrical and thermal conductivity of the fluid, respectively. Laplace equation for a homogenous medium is

$$\nabla^2 V = 0, \quad (2)$$

where $E = -\nabla V$.

The resultant electrothermal force can be calculated as²⁶

$$\langle F_{et} \rangle = -0.5\epsilon \left(0.024 \nabla T \cdot \mathbf{E} \frac{E}{1 + (\omega\tau)^2} - 0.002 |E|^2 \cdot \nabla T \right). \quad (3)$$

For an incompressible fluid of low Reynolds number, the resulting steady fluid flow in a microchannel follows the Navier–Stokes equation,¹⁴

$$-\nabla p + \eta \nabla^2 \mathbf{u} + \langle F_{et} \rangle = 0, \quad \nabla \cdot \mathbf{u} = 0, \quad (4)$$

where $\mathbf{u}$ denotes the velocity field vector, η is the dynamic viscosity, and p is the pressure.

III. DESIGN

Generally, ACET is a multiphysics phenomenon that consists of heat transfer, electrostatics, and fluid mechanics, each of which contains related parameters which can affect the resultant ACET fluid flow. As a result, the concept of using multiple microelectrode arrays on microchannel walls can be studied in separate aspects, which are thermal, electrical, and fluidic, each of which is characterized in Secs. III A to III C. It should be noted that although different

combinations of the above mentioned aspects and their corresponding parameters can affect the ACET phenomenon uniquely, optimization and finding the best sets of parameters are not the goal of this paper. The purpose of this article is to characterize the significance of such parameters on the new concept of AC MAET micropump, and demonstrate the feasibility of them. Further optimization of the structure design and selection of parameters can vary significantly in different applications. Here, in order to study the ACET aspects individually, each corresponding parameter is studied separately, assuming other parameters remain unchanged.

A. Thermal aspect

Any change in the heat transfer rate from the ACET heat source, which is Joule heating, to the environment is expected to affect the resultant ACET fluid flow. Thus, substrate material and thickness, fluidic channel depth, ambient temperature, etc., are among the thermal parameters which need to be considered as thermal governing parameters. The effects of substrate characteristics and ambient temperature were investigated in our previous publications.^{27,28} Fluidic channel depth is studied in this paper.

Although the depth of the fluidic channel can affect the fluid flow regime inside the microchannel, it also affects the heat dissipation throughout the system. Therefore, a 2D simulation was performed for the MAET with different channel depths in the range of 50–1200 μm and constant substrate thickness of 100 μm . The range of channel depths less than 500 μm is a typical range used in the literature, as Refs. 3, 29, 25, 30, and 31 have used 50, 65, 150, 200, and 500 μm for their channel depths, respectively. Also, a parametric study performed by Ref. 21 showed that for asymmetric planar electrode configuration, increasing the depth to more than 500 μm , does not have a perceptible effect on mean velocity. In this section, MAET with two arrays of microelectrodes placed at the top and bottom of the microfluidic channel is compared to a conventional ACET micropump with a single microelectrode array at the bottom.

B. Fluidic aspect

The MAET design can include different fluidic channel cross sections. In order to compare the different geometries, all microchannel cross sections were set so that they have the same hydraulic diameter D_h which is defined as³²

$$D_h = \frac{4A}{P_w}, \quad (5)$$

where A and P_w are channel cross section and wetted perimeter, respectively. Rectangular,^{11,18,24,29,33} circular,^{34,35} and triangular³⁶ cross sections have been used in electrokinetics related designs, thus, fluidic microchannels with square, circular, and triangular cross sections were investigated, with multiple electrode arrays placed on the microchannel side walls.

1. Square cross section

Square or generally rectangular cross sections are the most common type of fluidic microchannels especially in ACET fluid transport systems.^{11,18,24,29} All four walls are assumed to be able to hold electrode arrays. In this work, square with a side wall length/height of 300 μm is used. Using Eq. (5) this gives a hydraulic diameter of $D_h = 300 \mu\text{m}$.

2. Circular cross section

This type of microelectrode array is difficult to fabricate at the microscale, but in terms of fluid dynamics, it creates less resistivity for fluid flow. In this geometry, electrode arrays can be placed on one, two, or four quarters of the circular cross section. The diameter of the circular channel is 300 μm .

3. Triangular cross section

An equilateral triangle is another geometry that can be used in MAET devices; each of its sides has the length of $\sqrt{3}D_h = 519.6 \mu\text{m}$. Although fluidic channels with this cross sectional geometry are not common in the literature, it is beneficial to study an unconventional geometry, which can affect the electrothermal force due to the acute angles at its vertices that can introduce complex electric field distribution.

C. Electrical aspect

Typically, ACET micropumps employ an array of interdigitated microelectrodes, which are actuated either by single or multi-phase voltages.²⁶ Any change in the electric field distribution in the bulk of the fluid can dramatically affect the ACET fluid flow. The MAET design can be varied based on the actuation pattern of the microelectrodes, and the number of electrode arrays energized in the micropump.

1. Actuation pattern

Recent studies showed that ACET flow can efficiently be increased if different actuation patterns are used including single-phase,³⁷ two-phase,²⁶ and travelling-wave pattern.²⁴ In this paper, we focus on single-phase and different two-phase patterns, which are shown in Fig. 1 for a square cross section geometry, but they are conceptually the same for other geometries as well.

2. Number of side electrode arrays

Conventional ACET micropumps are based on one single array of microelectrode placed at the bottom of a microchannel.³³ Based on the design of the MAET, different configurations of one or multiple side electrode arrays can be considered. Depending on the cross section of the fluidic microchannel, microelectrode arrays can be placed in different ways, which are discussed separately (Fig. 2), and are as follows: electrode arrays on one side (Side5), two sides (Side1 and Side2), three sides (Side3), and all sides (Side4) of a microchannel.

FIG. 1. Different actuation voltage patterns investigated for the MAET. (a) Two-phase I (Pattern A), (b) two-phase II (Pattern B), (c) bi-planar single-phase (Pattern C), (d) single-phase (Pattern D), (e) two-phase III (Pattern E), and (f) two-phase IV (Pattern F). These actuation patterns are shown only for the case of two opposing side arrays in a square cross section fluidic channel, but the simulation was performed for MAETs with some or all side electrode arrays (except for (c)) being actuated and also for different fluidic cross section geometries. The pattern shown in (c) is only applicable for two opposing arrays, i.e., only the sides which are visible in the figure can be actuated. Note that the top surface of the fluidic channel and the substrates are not shown in the schematic. The fluidic channel has a $300 \times 300 \mu\text{m}^2$ cross section area and the substrate thickness is $200 \mu\text{m}$.

FIG. 2. Different actuation configurations of side electrode arrays. (a) Two opposing arrays (Side1), (b) two sidelong arrays (Side2), (c) three arrays (Side3), (d) all side arrays (Side4), and (e) conventional single array (Side5). The fluidic channel has a hydraulic diameter of $300\ \mu\text{m}$ and the substrate thickness is $200\ \mu\text{m}$.

IV. SIMULATION METHOD

To achieve a better understanding of how different microelectrode geometries affect ACET micropumping, 2D and 3D simulations were conducted using finite element software COMSOL Multiphysics (COMSOL, Inc., USA). The numerical solution consisted of three steps. First, the electric field was obtained by solving Eq. (2) for the entire fluidic channel domain. Then Eq. (1) was solved assuming heat generated with Joule heating as the heat source. This equation yields the temperature gradient in all domains, including the fluidic channel and the substrates. In the third step, Navier–Stokes and continuity equations (Eq. (4)) were solved for the fluidic domain considering ACET force (Eq. (3)) as an external force. The resultant velocity and temperature fields were used for calculating net flow rate and maximum temperature, as reported in Sec. VI. The universal boundary conditions (B.C.) remained constant in simulations and are shown in Fig. 3 for square cross section geometry, but they are conceptually the same for the other geometries as well. It also shows the B.C.s used in 2D simulations.

To ensure that a sufficient discretization was employed in the simulations, different numbers of mesh sizes were examined. Satisfactory results were observed with an extra-fine mesh size, which contained more than 800 thousand elements in each 3D simulation design. Utilizing a finer mesh by 125% reduction in element number didn't show a significant difference in results. The simulations were conducted for six different actuation patterns (Fig. 1), and five different side electrode actuation configurations (Fig. 2) consuming in total more than 300 h of computational time.

Flow rate was calculated for each case by integrating the velocity field over the cross sectional area of the fluidic channel. For better comparability, maximum temperature was also

FIG. 3. Boundary conditions used in the simulations while solving (a) energy conservation equation, (b) Laplace equation, and (c) Navier–Stokes equations. (d) shows the boundary conditions used in 2D simulation. Note: For clarity, some surfaces are not shown in (b) and (c).

determined in the bulk of the fluid for each case. The following conditions remained constant in the simulations:

- As many different electrode geometries have been reported in the literature, we used a previously tested geometry throughout this paper, which contained a narrow electrode ($20\ \mu\text{m}$) and a wide electrode ($120\ \mu\text{m}$) separated by a $20\ \mu\text{m}$ gap; the pattern is repeated in each $300\ \mu\text{m}$ distance; this microelectrode geometry demonstrated desirable ACET velocity of $63\ \mu\text{m/s}$ (Ref. 33) and flow rate of $2.11 \times 10^7\ \mu\text{m}^3/\text{s}$.²⁶
- The working fluid was KCl solution ($\sigma = 0.224\ \text{S/m}$), to simulate a typical biofluid.
- Note that the simulation was also performed for phosphate buffered saline (PBS) ($\sigma = 3.2\ \text{S/m}$) only for the case of comparing the experimental and numerical results.
- The actuation frequency and voltage were $100\ \text{kHz}$ and $0\text{--}7\ V_{\text{rms}}$, which are typical values for electrothermal flow generation.¹⁸ Note that the simulation was also performed for a frequency of $200\ \text{kHz}$ only for the purpose of comparing the experimental and numerical results.
- Fluid viscosity was temperature dependent and was expressed for the temperature range of $273\text{--}643\ \text{K}$ as³⁸

$$\eta = 2.414 \times 10^{-5} \times 10^{247.8/(T-140)}. \quad (6)$$

- Conventional ACET micropump was considered as a single array of microelectrodes similar to Side5 design shown in Fig. 2. Also, the ambient temperature and pressure were $293.15\ \text{K}$ and $1\ \text{atm}$.

The parameters values used in the simulations are summarized in Table I. It should be noted that as ACET micropumps in the literature have many different physical, thermal,

TABLE I. Property values used in the numerical and experimental study.

Numerical			Experimental		
Property		Value	Property		Value
Substrate					
Thermal conductivity of material (K)	Silicon	131 W/mK	Thermal conductivity of material (K)	Silicon	131 W/mK
	Glass	1.1 W/mK		Glass	1.1 W/mK
	PDMS	0.16 W/mK		PDMS	0.16 W/mK
Thickness	100–1000 μm		Thickness	1 mm	
Ambient temperature (T_{amb})	293.15 K		Ambient temperature (T_{amb})	$\sim$ 293 K	
Channel dimensions					
Square side	300 μm			Conventional ACET	MAET
Circle diameter	300 μm			Depth	200 μm 800 μm
Triangle side	519.6 μm			Width	700 μm 700 μm
Depth	50–1200 μm				
Electrode properties					
Wide electrode width	120 μm			Wide electrode width	120 μm
Narrow electrode width	20 μm			Narrow electrode width	20 μm
Gap between electrodes	20 μm			Gap between electrodes	20 μm
Gap between electrode pairs	300 μm			Gap between electrode pairs	300 μm
Actuation properties					
Frequency	100, 200 kHz			Frequency	200 kHz
Voltage range	0–7 V_{rms}			Voltage range	0–4 V_{rms}
System properties					
Electrical conductivity (KCl and PBS)	0.224–3.2 S/m		Electrical conductivity of fluid (PBS)	3.2 S/m	
			Microsphere diameter	1 μm	

electrical, and fluidic parameters, it is difficult to directly compare them. For this reason, a conventional ACET micropump with a single row of electrodes on one side and all other parameters the same as the exactly MAET was also simulated in different sections of this paper.

V. EXPERIMENTAL METHOD

The reliability and performance of the conducted simulations were compared to experimental data for one design of the novel AC MAET and a conventional ACET micropump. The experimental MAET design, shown in Fig. 4(a), has single-phase actuation pattern (Pattern D, Fig. 1(d)) and two-opposing electrode array configuration (Side1, Fig. 2(a)). The conventional ACET design has the following characteristics: Pattern D and Side5. Chrome/gold microelectrodes were fabricated onto 1 mm thick substrates using standard photolithography.³⁹ The electrode dimensions were 120 μm wide electrode, 20 μm gap, and 20 μm narrow electrode (Fig. 4(b)). The fluidic channels with a depth of 800 μm and width of 700 μm for the MAET, and a depth of 200 μm and width of 700 μm for the conventional ACET micropump were fabricated by Polydimethylsiloxane (PDMS) (Dow Corning, USA) using soft lithography. Finalizing the AC MAET micropump was performed by sandwiching and bonding the two electrode substrates to a PDMS channel using a corona bonding method⁴⁰ (BD-20AC, Electro-technic Products, USA). To assure the bonding mechanism and prevent leaks, the substrates were then clamped. Similarly, the ACET micropump was fabricated by attaching a PDMS channel onto the substrate. The AC actuation voltage and frequency were generated using a function generator (AFG 3102, Tektronix, USA), and amplified by a voltage amplifier (9400, Tabor Electronics, USA). Voltage and frequency were recorded by an oscilloscope (TDS 2004B, Tektronix, USA) while the electrothermal flow was captured using an optical microscope (VWR International, Canada). Phosphate buffered saline (PBS, $\sigma = 3.2 \text{ S/m}$) (Ward's Science, USA) containing 1 μm microspheres (Polysciences, Inc., USA) was employed as the electrolyte solution. Electrical conductivity was measured by conductivity meter (19601-03, Cole-Parmer, USA), which was calibrated with 1000 $\mu\text{S/cm}$ conductivity standard (VWR, USA). Each experiment was conducted at ambient temperature $T = 293 \text{ K}$ by tracing ten microspheres at different heights above the bottom electrode surface and 500 μm along the fluidic channel. The actuation voltage and frequency of $V_{rms} = 0\text{--}4$ and 200 kHz were used in experiments. All values used in the experiments are also shown in Table I.

FIG. 4. (a) A photograph of the experimental setup for AC MAET. It shows the two-opposing electrode arrays (Side1) fabricated on glass substrates, and the PDMS fluidic channel are bonded and clamped. Single-phase actuation pattern (Pattern D) was used. (b) Microscopic view of the fabricated microelectrode array. Three pairs of microelectrodes are shown here.

VI. RESULTS

The simulation and experimental results of the AC MAET micropump are presented in Secs. VIA to VID. To reduce the computational cost, the study of each effect is performed with constant predefined values for other parameters. Depending on the parameter investigated and again to reduce the computational time, some simulations were conducted in 2D and some in 3D structures.

A. Effect of fluidic channel depth

Changing the fluidic channel depth in an electrothermal micropump can affect the fluid flow in two ways, affecting the hydrodynamics of the microchannel and also the heat transfer throughout the system. As electrothermal flows are based on microvortices generated on top of the electrodes, the dimension of the fluidic microchannel can dramatically affect the formation and development of these vortices, especially if microelectrode arrays are used on two or more sides. Each microelectrode array is responsible for the vortices formed near its electrode surfaces, the center point position of which mostly depends on the electrode geometry, specifically electrode width.²⁹ Therefore, for each predetermined electrode geometry, the vortices are formed at a specific distance from the electrode surface, meaning that the fluidic microchannel length must be deep enough for the vortices to be able to develop. Figs. 5(a) and 5(b) show that there is no detectable velocity profile for fluidic channel depths $\leq 10 \mu\text{m}$, which is in agreement with the parametric study carried out by Ref. 21. It seems that for this range of fluidic depths the flow would be observed if the order of magnitude of the size of electrodes was reduced correspondingly. Also, it shows that increasing the fluidic depth from 10 to $150 \mu\text{m}$ makes a dramatic change in the velocity profile. This trend is similar to that of a conventional ACET flow (Fig. 5(b)), in which a one-peak velocity profile is created and remains almost constant for all channel depths. If the depth is increased more ($>150 \mu\text{m}$), the velocity profile of an AC MAET micropump (Fig. 5(a)) changes into a semi-flat and then two-peak profile. As a result, for depths $>150 \mu\text{m}$ and $<350 \mu\text{m}$ the distance between vortices caused by each side microelectrode array is small enough that the vortices can overlap and form a semi-flat velocity profile. Similarly, for depths $>350 \mu\text{m}$ the distance between vortices is farther than that required for them to overlap, meaning that each microelectrode array pumps independently (Fig. 5(c)). Fig. 5(d) shows the increase of flow rate by increasing the microfluidic depth. The figure depicts an increase of $\sim 600\%$ in flow rate for increasing the fluidic channel depth from 200 to $600 \mu\text{m}$ for both conventional and MAET micropumps.

B. Effect of actuation patterns

Fig. 6 illustrates the resultant flow rate and maximum temperature values for the application of different actuation patterns (Fig. 1). A comparison between these values shows the following order:

$$\text{Pattern A} = \text{Pattern B} > \text{Pattern F} > \text{Pattern E} > \text{Pattern D} > \text{Pattern C}$$

and in each pattern:

$$\text{Square} > \text{Circle}$$

As stated above, Patterns A and B are capable of providing the highest flow rates due to the highest temperatures. Also, both patterns indicate identical results which are in agreement with the corresponding data reported by Ref. 26 for conventional two-phase ACET micropump. The reason that there is a noticeable difference between the results of Patterns A and B, and other patterns is that the generated electric field in these two patterns are much stronger than other patterns, for instance, it is twice as strong as what Pattern D generates, because each electrode pair in Pattern A and B has $2 V_{rms}$ voltage difference whereas Pattern D has V_{rms} . Moreover, Pattern F can generate higher flow rates than Pattern E which is dissimilar to what

FIG. 5. 2D simulation results showing the velocity profile for (a) AC MAET, (b) conventional ACET, and (c) both conventional and MAET micropumps with 1200 μm fluidic channel. In (a), the electrode arrays are placed on the top and bottom of the fluidic channel, while in (b) only one array is used at the bottom. The corresponding flow rates of the two micropumps are compared in (d). Pattern D, silicon substrates, and $V_{rms} = 7$ were used.

was reported by Ref. 26 for the two configurations of conventional two-phase ACET. This means that the results are also dependent on the number of side electrode arrays used, but the trend remains constant. In other words, the effect of actuation patterns variation on electrothermal flow in conventional ACET, which is similar to Side5, can be different from that in a MAET (Side1, Side2, etc).

FIG. 6. (a) Flow rate and (b) maximum temperature in the bulk of the fluid versus actuation voltage. Side4 was used and all sides are made of glass. Data is shown for two cross section geometries, square and circle. As shown, Patterns A and B generate the highest flow rates and temperatures in the micropump.

C. Effect of side electrodes

Fig. 7 depicts the flow rate and temperature variations versus actuation voltage for different side electrode array configurations. Data taken from this figure can be ordered as follows:

Flow rate:

$$\left\{ \begin{array}{l} \text{Triangle: Side4} > \text{Side2} > \text{Side5} \\ \text{Square: Side4} > \text{Side3} > \text{Side1} > \text{Side2} > \text{Side5} \\ \text{Circle: Side4} > \text{Side3} > \text{Side1} > \text{Side2} > \text{Side5} \\ \text{Side1: square} > \text{circle} \\ \text{Side2: triangle} > \text{square} > \text{circle} \\ \text{Side3: square} > \text{circle} \\ \text{Side4: triangle} > \text{square} > \text{circle} \\ \text{Side5: triangle} > \text{square} > \text{circle} \end{array} \right.$$

Maximum temperature:

$$\left\{ \begin{array}{l} \text{Triangle: Side4} > \text{Side2} > \text{Side5} \\ \text{Square: Side4} > \text{Side3} > \text{Side2} > \text{Side1} > \text{Side5} \\ \text{Circle: Side4} > \text{Side3} > \text{Side2} > \text{Side1} > \text{Side5} \\ \text{Side1: square} > \text{circle} \\ \text{Side2: triangle} > \text{square} > \text{circle} \\ \text{Side3: square} > \text{circle} \\ \text{Side4: triangle} > \text{square} > \text{circle} \\ \text{Side5: triangle} > \text{square} > \text{circle} \end{array} \right.$$

Note that as shown in Fig. 2, Side1 and Side3 actuation patterns do not apply to triangular cross section designs. The results show that although the maximum temperature in a triangular cross section micropump reaches higher values unwantedly, but that the corresponding flow rates are much higher. For instance, as shown in Fig. 7, an increase of 1% in temperature corresponds with a 180% flow rate increase for $V_{rms}=7$ when Side5 design is changed to Side4. The reason appears to be the higher local gradients of electric field that occur in the bulk of the fluid in the vicinity of the triangular cross section vertices. It can be concluded that cross sections with more acute angles at their vertices can generate higher temperatures and flow rates. Micropumps with Side4 and Side5 configurations provide the highest and lowest flow rates, respectively, and micropumps with more electrode arrays can generate higher flow rates. Those with a two opposing microelectrode configuration (Side1) have less flow rate than the ones

FIG. 7. The effect of different side electrode configurations versus actuation voltage on (a) flow rate and (b) maximum temperature in the bulk of the fluid. Pattern D and three cross section geometries were used. All sides of the micropump are made of glass. As shown, the micropump with Side4 and triangular cross section generates the highest flow rates and temperatures.

with two side-by-side electrode arrays (Side2), which should be due to higher local gradient of electric field generation near the vertices of the cross section geometries.

It should be noted that comparison between three cross section geometries while studying the effect of the parameters discussed in this paper can be problematic, due to the electrode length on each side of the micropump having a different value based on which cross section geometry was being used. As designed, circle, square, and triangular fluidic channels contain arrays of 235.6, 300, and 519.6 μm length microelectrodes, respectively, which can affect the magnitude of electrothermal force in the following order: triangular > square > circle. This can be one explanation to the results shown in Figs. 6 and 7 that demonstrated the same order between geometries. To have a better understanding of the temperature distribution in these geometries, Fig. 8 shows the temperature along a closed curve consisting of the internal edge-line of the narrow microelectrode in each geometry. It shows that the maximum temperature occurs in the middle of the actuated microelectrodes. Also, it depicts that the highest temperature gradient occurs at the geometry vertices for the triangular cross section, which can cause higher conductivity and permittivity gradients in these areas. The same order of triangular > square > circle can be inferred from the figure in terms of temperature gradients at the vertices, which can be another reason for order of flow rate observed in Figs. 6 and 7.

D. Experimental results

Electrothermal velocities were measured for both conventional ACET and AC MAET. The corresponding flow rates were calculated assuming a semi-flat velocity profile (similar to Fig. 5(c)) for MAET, and a quasi-parabolic profile using the following equation:^{41,42}

$$Q = \frac{HWU}{2}, \quad (7)$$

where H , W , and U are channel height, channel width, and average velocity, respectively. In Fig. 9, the experimental flow rates are compared to 2D simulation data, which were specifically performed for the corresponding geometries. The experimental and simulated flow rates show very good agreement for $V_{rms} < 3.5$ in MAET and $V_{rms} < 5.5$ in conventional ACET micropumps. However, the experiments showed that the electrodes cannot sustain higher voltages, as electrode deterioration occurs, due to the high local electric fields generated at the electrode edges. According to Eqs. (3) and (4), $u \propto (\nabla TE^2)$ which explains the quasi-parabolic shape of the flow rate-voltage curve of the experimental trend which was also observed in the simulation results shown in Secs. VIB and VIC (Figs. 6(a) and 7(a)).³³ The experimental data obeys the simulation curve until it reaches the maximum value of $16 \times 10^6 \mu\text{m}^3/\text{s}$ for MAET and $4.5 \times 10^6 \mu\text{m}^3/\text{s}$ for conventional ACET, at this point electrode deterioration begins to occur,

FIG. 8. (a) Temperature distribution along a perimeter closed curve consisting of the edge-line of the narrow electrodes. (b) The curve length has 942.4, 1200, and 1558.8 μm for circular, square, and triangular cross sections, respectively. Side4, Pattern D, and $V_{rms} = 7$ were used and all sides are made of glass. As shown, the maximum temperature on the perimeters of the three micropumps has the following order: Triangle > square > circle.

FIG. 9. Experimental result and the corresponding 2D simulation data for AC MAET (blue circle: experimental; blue solid line: simulation) and conventional ACET (black square: experimental; black solid line: simulation) micropumps. The error bars show the maximum and minimum values. By increasing the actuation voltage, the experimental result follows the simulation curves until electrode deterioration occurs.

causing a weaker electric field which in turn reduces the flow rate dramatically. Although several governing parameters are different in the two micropumps, comparing the two micropumps from an experimental point of view indicates that, as shown in the literature, maximum temperature caused by using glass substrates is higher than when silicon is the substrate material, which makes the electrodes more vulnerable to damage.²⁸ This is the reason for failure of the two micropumps at different voltages, i.e., $V_{rms} \approx 3.5$ for MAET and $V_{rms} \approx 5$ for conventional ACET. Moreover, higher flow rates are achieved in the MAET micropump compared to the conventional ACET micropump.

As can be seen in Fig. 9, by increasing the voltage, in both AC MAET and conventional micropump, the flow rate increases. But at a certain point in the conventional micropump ($\sim 5 V_{rms}$), the flow rate plateaus and then starts to decrease gradually. This change happens in an abrupt manner at $\sim 3.5 V_{rms}$ for the case of AC MAET. The important reason behind this change may be electrode deterioration which gives rise to other problems.

Other studies showed that the highest temperature increase occurs near the narrow electrode, which is where the highest local electric field is produced.^{28,33} This significant increase is the result of high voltage and low surface area of the electrode. As previously reported in the literature, while working with fluid of conductivity in the vicinity of 1 S/m, in the voltage range of below 7 V_{rms} and with frequency greater than 10 kHz, there is small possibility of any electrochemical reaction.¹⁸ However, the fluid used in our experiments is of high conductivity of 3.2 S/m, which may cause the aforementioned range of voltages to decrease. Therefore, the electrochemical reactions may occur at lower voltages, causing the narrow electrode to be damaged. This electrode deterioration causes the pattern of electric field to be no longer predictable or reliable. Thus local perturbations in flow pattern (e.g., flow reversal) may cause the decrease in flow rate. Besides, at high temperatures (due to increased voltage or even the heat emitted from the microscope lamp), the characteristics of fluid may also change.

The abrupt decrease of flow rate in MAET micropump, compared to the conventional ACET one, may be because of the impact of temperature increase and voltage drop over two rows of electrode arrays, compared to a less severe effect for the conventional single array only case. This causes the sudden 80% decrease of flow rate, while in the conventional ACET micropump there is a gradual 30% decrease. Furthermore, any uncontrolled temperature rise may also cause the buoyancy effect to be no longer negligible.²³ A combination of some or all of the reasons mentioned above can be responsible for the flow rate drop.

VII. CONCLUSION

In this paper, a novel idea of using multiple arrays of asymmetric coplanar microelectrodes on multiple surfaces of the microfluidic channel walls of an ACET micropump was numerically and experimentally investigated. The results showed that the electrothermal flow rate can be increased by increasing the number of electrode arrays used in the micropump. Although the fabrication of micropumps with three (Side3) and four (Side4) electrode arrays can be more challenging, devices with two arrays (Side1) can be easily fabricated using the same technology as for conventional single array (Side5) devices. The number of side electrode configurations and their corresponding patterns has been shown to be effective in increasing the electrothermal flow. Additionally, it was shown that acute angles in fluidic channel geometries, such as triangular cross sections, can give rise to highly localized temperature gradients, and consequently higher electrothermal force. However, the temperature increase can be challenging, but it appeared to be safe for biofluid applications ($<40^{\circ}\text{C}$) if relatively low actuation voltage $V_{rms} < 5$ are used.

The results also showed that the best MAET micropump configuration can be obtained if Side4 and Pattern A or B as the actuation mechanism, and glass substrates with a triangular cross section geometry are used.

For future work, a thorough investigation to optimize the discussed parameters can be performed to design a more robust electrothermal micropump with even higher flow rates. The proposed MAET micropump can be used in a wide range of applications such as drug delivery and lab-on-a-chip, in which high flow rate and high precision micropumping devices are needed.

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