Enhanced heat transfer in a micro-scale heat exchanger using nano-particle laden electro-osmotic flow

Marwan F. Al-Rjoub a, Ajit K. Roy b, Sabyasachi Ganguli b, Rupak K. Banerjee a,

a Mechanical and Materials Engineering Department, University of Cincinnati, Cincinnati, OH, USA
b Nanoelectronic Materials Branch, Materials and Manufacturing Directorate, Air Force Research Laboratory, WPAFB, OH, USA

A R T I C L E   I N F O
Available online 1 October 2015
Keywords:
EOF
Micro-scale heat exchanger
Hot spot cooling
Al2O3 nano-particles

A B S T R A C T
This research presents a multi-channel micro-scale heat exchanger for thermal management of microelectronics hot spots. Electro-osmotic flow (EOF) was implemented to drive the cooling liquid through the micro-channels of the heat exchanger. Various cooling liquids including, deionized water, distilled water, borax buffer, and Al2O3 nano-particle solution, were tested and compared based on their flow rates and increase in cooling liquid temperature. The micro-scale heat exchanger was fabricated using a combination of polydimethylsiloxane (PDMS) and silicon dioxide-coated substrate. A constant heat flux heater was used to simulate the heat generated by microelectronic devices. The flow rate of the cooling liquid and its temperatures at the inlet and the outlet reservoirs were measured. Deionized water produced a flow rate of 30.1 μL/min and 2 °C increase between the inlet and the outlet reservoir temperatures at 1 W heating power and 400 V of EOF. The flow rate and the increase in temperature of distilled water at the same conditions were 22.7 μL/min and 3 °C, respectively. For the borax buffer the flow rate was 33.1 μL/min and the increase in temperature was 2.7 °C. Most notably, there was an increase in temperature of 2.4 °C with a lower flow rate of 20.4 μL/min when the Al2O3 nano-particle solution was used. Among all cooling liquids, the Al2O3 nano-particle solution showed the highest scaled specific heat energy removal with a maximum of ~69% increase compared to deionized water. Further, the current micro-scale heat exchanger device was able to produce higher electro-osmotic flow rates due to the use of PDMS on three sides of the micro-channel; thus providing smoother walls and higher zeta-potential while the silicon surface allowed heat transfer to the cooling liquid. The increased flow rate allowed enhanced heat removal from higher heat flux areas (hot spots) of microelectronic devices without the need for high-pressure pumping systems.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction
Modern microelectronic devices have higher computational power while their sizes are smaller than their predecessors. This leads to higher heat generation rates per unit area of the microchip (i.e., heat flux). A major concern that is associated with the increase in heat generation is the formation of hot spots that can lead to heat fluxes in the order of 2 kW/cm² [1]. These hot spots are usually linked to the logic blocks of the microchip that generate higher heat flux compared to memory blocks. In order to dissipate these high heat fluxes, new heat removal techniques are required instead of conventional low-capacity heat sinks. Different approaches have been implemented to increase the heat removal rates from microchips including: using improved fluid pumping techniques, introducing new designs of heat exchangers that are made of micro-channels, and implementing cooling liquids with higher thermal conductivity.

One of the new techniques to handle high heat flux hot spots is to use electro-osmotic flow (EOF) in micro-channels. In this case, the flow is maintained by applying an electric field across the liquid, thus eliminating the need for high pressure mechanical pumping systems. EOF is a phenomenon that occurs when an electrolyte solution is brought in contact with a surface, such as the walls of a micro-channel. The contact between the liquid and the surface leads to the formation of an electrical charge on the surface of the micro-channel. The electrical charge on the surface attracts counter ions from the bulk solution leading to the generation of the electric double layer (EDL). When an electric field is applied between two points across the liquid, charged ions in the EDL start to move in the direction of the electric field. The motion of these ions drags adjacent liquid volume and diffuses to the center of the micro-channel due to viscous forces. Further details of the theory and applications of EOF can be found in Probstein [2].

Many researchers used EOF to remove the heat generated by micro-electronic devices and tested different cooling liquids that were mostly water-based. One of the earlier designs of EOF micro-channel heat exchangers was presented by Laser et al. [3]. In their design, multiple deep micro-channels that were arranged parallelly transported the cooling liquid between the inlet and the outlet reservoirs to reduce...
the temperature of the high power density hot spots. [4] tested a two-phase closed-loop micro-channel cooling system. In that system an external EOF pump was used to circulate the cooling liquid between the heat exchanger and the heat rejection unit, maintaining the microchip temperature at less than 120 °C. [5] studied the differences between nanofluids and pure water using a single micro-channel and compared the convection heat transfer coefficient as well as the friction factor for both cases. [6] designed a silicon-based heat spreader using EOF to pump the cooling liquid; a reduction of 4 °C in the device temperature was achieved. A recent study by our group [7] reported that EOF-driven flow in micro-channels can achieve higher heat transfer compared to pressure-driven flow. In this study, it was shown that there was an increase of 10% in the value of Nusselt number (Nu) when EOF was used compared to other pressure-driven flows.

Most recent studies with regard to the thermal management of micro-chip devices using EOF were mainly either analytical or numerical. To the best of the authors’ knowledge there were no experimental studies to test EOF driven microchip cooling systems in the recent past. [8] presented a numerical and theoretical analysis of cascade EOF micro-pumps for the cooling of microchips. They reported an increase of 13% in the value of Nu number when EOF was used compared to pressure driven flow. A numerical study by [9] presented EOF in micro-channels having an elliptical cross section with a constant wall heat flux. Their study showed that the increase in the electro-kinetic diameter of the elliptical micro-channels increased Nu number. Another numerical study involving thermally fully-developed EOF flow through rectangular micro-channels was presented by [10]. The study investigated the effects of the microchannel aspect ratio, the ratio of Joule heating to heat flux, and the ratio of the characteristic length of the micro-channel to Debye length on the temperature distribution inside the micro-channel. They found that the temperature profiles were significantly dependent on the ratio of Joule heating to heat flux when the ratio of the characteristic length to Debye length is small. An experimental study of heat transfer and pressure drop in micron-sized tubes was presented by [11]. In their study a comparison between micro-scale and macro-scale Nu number showed that there was 1.89–5.82 increase in the value of Nu number in micron-sized tubes. The above mentioned study didn’t implement EOF; however they investigated developing and fully-developed pressure driven flow.

The current study introduces a new concept of micro-scale heat exchanger design based on new and combinations of different materials while testing different types of cooling liquids. A schematic of the heat exchanger is presented in Fig. 1 showing its major components. The micro-scale heat exchanger was made using a combination of polydimethylsiloxane (PDMS) and silicon dioxide surfaces. The PDMS surfaces enclosed three sides of the micro-channel and the silicon dioxide surface was the fourth surface that sealed the micro-channels and conducted heat to the cooling liquid inside them. Choosing PDMS on the three surfaces increased the zeta-potential of the micro-channels and produced better quality surfaces (less roughness) compared to silicon etching [12,13]. Increasing the value of zeta potential increased the EOF velocity leading to an increase in the flow rate of the cooling liquid. This increase in the flow rate can enhance the heat transfer from the silicon substrate to the cooling liquid leading to improved micro-heat exchangers with higher heat-removal capacity.

The current micro-scale heat exchanger design was based on a multi-channel Si-PDMS micro-pump that was recently designed by our group [14]. The micro-pump has inlet and outlet reservoirs that were connected by twenty micro-channels arranged in parallel. The micro-channels have a rectangular cross section of 150 μm × 100 μm and a length of 20 mm. The micro-pump was able to produce flow rates that were orders of magnitudes higher than other EOF micro-pumps of similar size. It was anticipated that the micro-pump will enhance the performance of heat removal from localized hot spots. In order to test and quantify the performance of the micro-pump in thermal management applications, a heater was attached to the silicon surface to simulate the heat flux generated by hot spots in the microchip surface. The heat was carried by the cooling liquid as its temperature increased between the inlet and the outlet reservoirs. To quantify the heat removed by the cooling liquid, measurements of the cooling-liquid flow rate and the difference between inlet and outlet reservoir temperatures were acquired using a data acquisition system. Further analysis of the micro-scale heat exchanger heat transfer and a comparison between different cooling liquids were performed.

The performance of different cooling liquids, including nano-particle laden liquids, was tested using the micro-scale heat exchanger. Aluminum oxide nano-particle solution, deionized (DI) water, distilled (DS) water, and borax buffer were used as cooling liquids. The amount of heat carried by these liquids was quantified and compared at the same heating power. A comparison of the scaled specific heat energy carried by the cooling liquids is presented in the results section.

2. Methods

The micro-pump design presented in our recent publication [14] was modified for testing as a micro-scale heat exchanger. The micro-pump consisted of a PDMS block with micro-channels cast on it along with an oxidized silicon substrate on one surface. The first step for the manufacturing of the micro-pump was to fabricate an SU-8 master for PDMS casting. For that reason, a 3″ silicon substrate was cleaned and SU-8 2075 (MicroChem Corp., Newton, MA) was spun-coated to achieve a 150 μm thickness. The substrate was then soft baked at 60 °C for 10 min. After that, the substrate was aligned with a mask that has a pattern identical to the desired micro-channels and was exposed to UV light. After exposure, the substrate was hard baked over a hot plate at 90 °C for 20 min. Since SU-8 is a negative photoresist, UV-exposed areas of the substrate remained while unexposed areas were washed away in the SU-8 developer (MicroChem Corp., Newton, MA).

The SU-8 master was used to cast the micro-channels in a petri-dish. For that, PDMS (sylgard 184, Dow Corning Corp., Midland, MI) was mixed and degassed in a vacuum desiccator. PDMS was poured over the SU-8 master in a petri-dish and then degassed until all air bubbles were extracted. The petri-dish was then placed over a hot plate at 80 °C for 2 h for PDMS to cure. After curing, PDMS was cut to the desired shape and the reservoirs at the inlet and the outlet were created. The PDMS block, with twenty micro-channels cast into it, and an oxidized silicon substrate were bonded together. Fig. 2 presents the various processes used to fabricate the device having rectangular micro-channels with three PDMS and one silicon surfaces. By the end of these processes a silicon-PDMS (Si-PDMS) test section was obtained and used as an EOF-driven micro-scale heat exchanger.

The micro-channels served as EOF driving conduits having a heat exchange interface between the cooling liquid and the silicon surface. The cooling liquid was in contact with the silicon substrate surface where heat flux was applied. The transport of the cooling liquid between the

---

**Fig. 1.** Schematics of the micro-scale heat exchanger showing its major components; the PDMS micro-channels and the Si substrate.
inlet and the outlet reservoirs of the micro-pump allowed removal of heat from the target device (microchip or heat generation source). The PDMS surfaces were smooth and their roughness was much less than silicon-etched micro-channels (Fig. 3). The reduced roughness and the higher value of zeta-potential of PDMS led to an increase in the flow rate [12] in the micro-pump that was modified for use as a micro-scale heat exchanger. In this study, for transforming the micro-pump to a micro-heat exchanger, the modifications included adding a heat generating source and temperature probes for the measurement of heat transfer.

To simulate the heat generated by a micro-electronic device a DC-powered heater was used. The dimensions for the heater were 64 mm × 64 mm (Part #: HK5565R10.0L12E, Minco, Inc., Minneapolis, MN). The heater was attached to the silicon substrate in its middle section. The heater and the central section of the micro-channels overlapped at the middle of the substrate. A surface-mounted thermocouple was used to measure the substrate temperature (Part #: SA1XL-T, Omega Engineering, Inc.). A PDMS layer was used to cover the heater. This layer provided thermal insulation to prevent heat loss to surroundings from the heater and the silicon substrate.

The temperatures at the inlet and the outlet reservoirs of the micro-scale heat exchanger were measured using two T-type thermocouples (Part #: HYP1-30-1/2-T-G-60-SMWPW-M, Omega Engineering, Inc.). These thermocouples were inserted through the PDMS cover and were in contact with the cooling liquid in the inlet and the outlet reservoirs.

The modifications introduced to the micro-pump are shown in Fig. 4, where the heater and the thermocouples are shown inside the dotted boxes. The micro-scale heat exchanger was integrated within the flow loop where a micro-flow-meter (ASL-1600, Sensirion Inc., Westlake Village, CA) and an EOF power supply were connected. The micro-flow-meter measured the flow rate of the cooling-liquid through the micro-scale heat exchanger. The thermocouples were connected to a DAQ system (NI cDAQ-9174, NI 9213 module, National Instruments Corporation, Austin, TX) where temperature data was gathered.

The EOF power supply was used to maintain the EOF in the flow loop. The voltage was in the 100 to 400 V range. More details on the micro-pump are provided in our earlier publication [14].

3. Results

The increase in temperature values with variable flow rates of different cooling-liquids within the micro-channels of the micro-scale heat exchanger is presented in this section. The increase in temperature and the flow rates are presented, on the same graph, as a function of the EOF voltages. Electro-osmotic flow voltages of 100 V, 200 V, 300 V, and 400 V were used to drive the different cooling liquids. In addition,
results for variable heating powers are presented including 0.5 W, 0.75 W, and 1.0 W cases.

It was evident that there was an overall increase in the bulk temperature of the outlet reservoir compared to the bulk temperature of the inlet reservoir. This increase was due to the heat transfer from the higher temperature silicon surface to the cooling liquid flowing within the micro-channels.

3.1. Deionized water

When DI water was tested as a cooling liquid in the micro-scale heat exchanger, there was a maximum increase of 0.9 °C between the inlet and the outlet reservoirs’ bulk temperatures at 400 V and 0.5 W of heating power (Fig. 5A). The average flow rate at 400 V was 29.4 μL/min. For 0.75 W of heating power, the increase between reservoirs’ temperatures was 1.4 °C and the flow rate was similar (32.9 μL/min) at 400 V (Fig. 5B). There was a 2 °C increase between the reservoirs’ temperatures for the 1.0 W case with similar flow rate of 30.1 μL/min at 400 V (Fig. 5C).

The increase in temperature was linear in relation to EOF voltages (Fig. 5). R² values of ΔT–voltage curves for the three powers were approximately equal to 1. Flow rates versus EOF voltages were also linear with R² values ranging from 0.97 to 1.00. The linearity of the flow rate–voltage agrees with our previously published experimental results [14].

3.2. Distilled water

The increase in the temperature of distilled water and its flow rates are presented in Fig. 6. For the 0.5 W heating power case, the increase in temperature was 1.3 °C at 400 V (Fig. 6A). At 0.75 W of heating power and 400 V, the increase in temperature was 1.8 °C (Fig. 6B). When the heating power was increased to 1 W, the increase in temperature was 3 °C (Fig. 6C). The ΔT–voltage relationship was linear for all powers with R² values ranging from 0.93 to 1.00. Average flow rates at 400 V were similar, i.e., 20.5 μL/min, 28.8 μL/min, and 22.7 μL/min for 0.5 W, 0.75 W, and 1.0 W heating powers, respectively.

3.3. Borax buffer

The increase in temperature of the borax buffer and its flow rates at different voltages are shown in Fig. 7. The increase in temperature for the borax buffer cooling liquid at 400 V was 1.1 °C, 1.8 °C and 2.6 °C, for heating powers of 0.5 W, 0.75 W and 1.0 W, respectively. The ΔT–voltage curves are highly linear with an R² value of approximately equal to 1. Flow rate for the 0.5 W case was 30.0 μL/min at 400 V whereas it was 33.1 μL/min and 31.0 μL/min for the 0.75 W case and 1.0 W case, respectively.

3.4. Al₂O₃ nano-particle solution

Results of the increase in temperature and the corresponding flow rates at a fixed voltage for the Al₂O₃ nano-particle solution are shown in Fig. 8. In the case of the 0.5 W heating power, the increase in temperature was 1.2 °C with a lower flow rate of 13.3 μL/min at 400 V (Fig. 8A). The increase in temperature was 1.7 °C for the 0.75 W heating power with a maximum flow of 14.4 μL/min (Fig. 8B). For 1 W of heating power and 400 V, the increase in temperature was 2.6 °C with a flow of 20.4 μL/min (Fig. 8C). In general, when compared with all other liquids, the Al₂O₃ nano-particle solution showed a similar temperature rise under reduced flow rates.

3.5. Scaled specific heat energy of the cooling liquids

The flow rates of the Al₂O₃ nano-particles cooling liquid were lower than other cooling liquids at the same voltage. In order to better compare the performance of heat removal of the different cooling liquids, the heat transferred by the cooling liquids was scaled with respect to the maximum flow rate, Q_L (flow rate of borax buffer). The heat removal rate for an individual fluid was evaluated using Eq. (1).

\[ q = \rho c_p \Delta Q_L \]  

where \( q \) is the heat removal rate of the cooling liquid (W), \( \rho \) is the density of the cooling liquid (kg/m³), \( c_p \) is the specific heat of the cooling liquid (J/kg·K), \( Q_L \) is the volumetric flow rate of the cooling liquid (m³/s), and
\[ \Delta T \text{ is the difference between the cooling liquid temperatures measured at the outlet and inlet reservoirs.} \]

Eq. (1) was scaled by multiplying both sides of the equation by \( \left( \frac{Q_H}{Q_L} \right)^2 \). This resulted in the following equation:

\[
q \left( \frac{Q_H}{Q_L} \right) = \rho c_p \Delta T Q_L \left( \frac{Q_H}{Q_L} \right).
\]  \quad (2)

After rearranging Eq. (2), the resulting equation is:

\[
\frac{Q_H}{Q_L} = \frac{\rho c_p \Delta T}{q} \left( \frac{Q_H}{Q_L} \right).
\]  \quad (3)

In Eq. (3), the \( \left( \frac{Q_H}{Q_L} \right) \) ratio is the scaling factor (unit less) and \( \left( \frac{q}{\rho c_p} \right) \) is the specific heat energy (W/kg/s) of the cooling liquid.
Combining the two terms will result in the scaled specific heat energy, \( q_s \) (Eq. (4)) for the designated cooling liquid.

\[
q_s = c_p \Delta T \left(\frac{Q_H}{Q_L}\right)
\]

The values of \( q_s \) for all cooling liquids were evaluated and plotted versus the EOF voltages. The scaled specific heat energy values for the different cooling liquids are shown in Fig. 9 for the three heating powers. The value of \( q_s \) for the DI water was the lowest among the four cooling liquids whereas the Al\(_2\)O\(_3\) nano-particle solution had the highest value of \( q_s \). At lower powers (0.5 W and 0.75 W; Figs. 9A and 9B), the values of \( q_s \) for DI water, DS water, and borax buffer were nearly similar at the same voltage. On the other hand, the Al\(_2\)O\(_3\) nano-particle solution showed higher...
values of $q_s$ for all heater powers and voltages. For the case of 1 W heater power (Fig. 9C), the value of $q_s$ for the Al$_2$O$_3$ nano-particle solution was slightly higher than those of DS water.

To assess the enhancement of heat transfer by the Al$_2$O$_3$ nano-particle solution, its $q_s$ was compared to that of DI water (lowest value of $q_s$). The percentage increase in $q_s$, when the Al$_2$O$_3$ nano-particle solution was used compared to DI water is presented in Table 1. A maximum slightly higher than those of DS water.

When $q_s$ for the Al$_2$O$_3$ nano-particle solution was compared to that of DI water (lowest value of $q_s$), the $q_s$ for the Al$_2$O$_3$ nano-particle solution was implemented. On a similar note, when $q_s$ for the Al$_2$O$_3$ nano-particle solution was compared to that of distilled water, there was an increase in the range of 1% to 46.9% in favor of the Al$_2$O$_3$ nano-particle solution. Comparing $q_s$ for the Al$_2$O$_3$ nano-particle solution relative to borax buffer, there was an increase in $q_s$ in the case of Al$_2$O$_3$ nano-particle solution ranging from 29.9% to 58.9%.

### 4. Discussion

The various cooling liquids used in this study performed differently when used in the micro-scale heat exchanger. The overall temperature change between the inlet and the outlet in relation to the flow rates varied for different power levels. The variation in the scaled specific heat energy for DI water, DS water, and borax buffer was similar. For the Al$_2$O$_3$ nano-particle solution, the scaled specific heat energy was significantly higher. The variation in flow rates at a fixed voltage for the different cooling liquids can be related to the variability among the values of zeta-potential between the surfaces of the micro-scale heat exchanger channels and the cooling liquid.

#### 4.1. Variations of the specific heat energy for the different cooling liquids

In general, the scaled specific heat energy of the cooling liquids was different when compared at the same heater power and voltage. These differences were more significant for the case of the Al$_2$O$_3$ nano-particle solution as shown in Fig. 9A and 9B. The increase in the scaled specific heat energy for the Al$_2$O$_3$ nano-particle solution compared to the other cooling liquids, that were mostly water based, can be correlated to the increase in the thermal conductivity of the solution when nanoparticles were introduced [15]. The increase in the thermal conductivity of the cooling liquid leads to an increase in the heat transfer rate from the surface of contact. Also, a recent research on pressure-driven flow by Jung et al. [5] reported a maximum increase of 32% in the heat transfer coefficient when the Al$_2$O$_3$ nano-particle solution was used as compared to pure water. Moreover, in their pressure-driven flow study, 180 nm size nano-particles were used compared to the current EOF study that tested nano-particles having a size of 50 nm. Several other studies [16–19] showed that solutions with smaller size nano-particles have higher thermal conductivity compared to solutions made of larger size nano-particles at the same volume fraction.

The increase in the thermal conductivity as well as the heat transfer coefficient that was evident for the Al$_2$O$_3$ nano-particle solutions will lead to an increase in the amount of heat transfer. The increase in the heat transfer from the microchip surfaces to the cooling liquid will allow increased capability for cooling microchip devices having higher heat generation.

#### 4.2. Variations of the flow rates of the different cooling liquids

The differences between the electro-osmotic flow rates of the different cooling liquids at the same voltage can be linked to the differences in the values of zeta-potential [12]. The zeta-potential is the difference in voltage potential between the Electric Double Layer (EDL) at the micro-channel surface and the bulk of the cooling liquid inside the micro-channel. Various surface-liquid combinations lead to different values of zeta-potential. Electro-osmotic velocity, and consequently, the flow rate of the cooling liquid are proportional to the value of zeta-potential. Detailed discussion of the effects of zeta-potential on the flow rates of different liquid-surface combinations can be found in our recent publication [14].

#### 4.3. Linearity of the flow rate–voltage and temperature–voltage correlations

The relationship between the flow rate and the voltage was linear with an $R^2$ value approximately equal to 1. The linearity can be observed in Figs. 5–8 for all cooling liquids using a voltage ranging from 100 to 400 V. This linearity of experimental data agrees with the theory of electro-osmotic flow based on Helmholtz–Smoluchowski equation [12]. The equation states that the EOF velocity is proportional to the applied electric field for a solution with constant properties. Since the micro-channels' length is constant in this study, the EOF velocity is directly proportional to the EOF voltage.

The increase in temperature between the inlet–outlet reservoirs was linearly proportional to the increase in the EOF voltage. Considering a constant surface heat flux condition, both bulk cooling liquid and micro-channel wall temperatures linearly increase in the axial direction [20]. In the experimental setup, an electrical heater (constant heat flux) was implemented leading to a linear increase in the cooling liquid temperature in the axial direction, from the inlet to the outlet reservoirs.

#### 4.4. Variations of flow rate for a specific cooling liquid at the same voltage

Each cooling liquid was tested at three different power levels of 0.5 W, 0.75 W, and 1.0 W. The flow rates of a specific cooling liquid were tested at these power levels using the same voltage. The variations can be observed in Figs. 5–8. The variations in the flow rates for DI water, DS water, and borax buffer were statistically insignificant with a p-value higher than 0.05 for the majority of the flow–voltage combinations. For the case of the Al$_2$O$_3$ nano-particle solution, the variations in the flow rates at the same voltage were, for the most part, statistically significant with a p-value less than 0.05.

The variations of the flow rate for a specific cooling liquid at the same voltage for different heater power levels can be correlated to the change in viscosity of the cooling liquid. With the increase in the heater power the cooling liquid temperature increased leading to a reduction in the viscosity of the cooling liquid. In addition, for the case of the

### Table 1

Comparison of scaled specific heat energy for DI water and the Al$_2$O$_3$ nano-particle solution, showing the percentage increase in the scaled specific heat energy when the Al$_2$O$_3$ nano-particle solution was used.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>DI water – scaled specific heat energy (W/kg/s)</th>
<th>Al$_2$O$_3$ – scaled specific heat energy (W/kg/s)</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 W heater power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>2.0E + 03</td>
<td>6.4E + 03</td>
<td>68.7</td>
</tr>
<tr>
<td>200</td>
<td>2.6E + 03</td>
<td>9.2E + 03</td>
<td>171.4</td>
</tr>
<tr>
<td>300</td>
<td>3.0E + 03</td>
<td>1.0E + 04</td>
<td>71.3</td>
</tr>
<tr>
<td>400</td>
<td>3.6E + 03</td>
<td>1.1E + 04</td>
<td>66.5</td>
</tr>
<tr>
<td>0.75 W heater power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>3.7E + 03</td>
<td>9.6E + 03</td>
<td>61.3</td>
</tr>
<tr>
<td>200</td>
<td>5.2E + 03</td>
<td>1.2E + 04</td>
<td>57.5</td>
</tr>
<tr>
<td>300</td>
<td>5.4E + 03</td>
<td>1.3E + 04</td>
<td>58.2</td>
</tr>
<tr>
<td>400</td>
<td>5.7E + 03</td>
<td>1.5E + 04</td>
<td>63.0</td>
</tr>
<tr>
<td>1.0 W heater power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>3.6E + 03</td>
<td>9.9E + 03</td>
<td>63.4</td>
</tr>
<tr>
<td>200</td>
<td>4.6E + 03</td>
<td>1.2E + 04</td>
<td>68.5</td>
</tr>
<tr>
<td>300</td>
<td>6.6E + 03</td>
<td>1.4E + 04</td>
<td>53.6</td>
</tr>
<tr>
<td>400</td>
<td>8.7E + 03</td>
<td>1.7E + 04</td>
<td>48.2</td>
</tr>
</tbody>
</table>
Al$_2$O$_3$ nano-particle solution, there was some deposition of nano-particles on the walls of the micro-channels inside the heat exchanger. These deposits can influence the value of zeta-potential leading to a decrease in the flow rate. For the Al$_2$O$_3$ nanoparticle solution, the same test section was used for all heater powers and the testing at 1.0 W was performed first followed by the 0.75 W and 0.5 W, respectively. This led to somewhat higher flow rates at the 1.0 W case and 0.75 W case when compared to the 0.5 W case.

5. Conclusion

A micro-scale heat exchanger was experimentally tested using EOF as a means to drive the cooling liquid. The device was fabricated using a combination of PDMS and silicon, where the micro-channels of the micro-scale heat exchanger were cast in PDMS and the silicon surface sealed them. Four water-based fluids were used as cooling liquids in the micro-scale heat exchanger including the Al$_2$O$_3$ nanoparticle solution. The device was tested at different heating powers using EOF voltages ranging from 100 V to 400 V. Increases in the flow rates of the cooling liquids were linearly proportional to the increases in the EOF voltage. The Al$_2$O$_3$ nanoparticle solution had the highest heat removal capacity at equivalent heating power and flow rate. There was a ~69% increase in the scaled specific heat energy when the Al$_2$O$_3$ nanoparticle solution was used compared to DI water that had the least scaled specific heat energy. Although the Al$_2$O$_3$ nanoparticle solution had the lowest flow rates compared to other cooling liquids, the relative increase in its heat removal capacity at equivalent heating power and flow rate was much larger than for other cooling liquids. For the Al$_2$O$_3$ nanoparticle solution, the same test section was used for all heater powers and the testing at 1.0 W was performed first followed by the 0.75 W and 0.5 W, respectively. This led to somewhat higher flow rates at the 1.0 W case and 0.75 W case when compared to the 0.5 W case.

References


