Supplementary Materials

Low-cost resistive microfluidic salinity sensor for high-precision detection of drinking water salt levels

MohammadJavad FarshchiHeydari1, Nima Tabatabaei1, Pouya Rezai1

1Department of Mechanical Engineering, York University, Toronto, ON, Canada

1. HEAT TRANSFER IN OUR MODEL

Heat transfer in solids. To consider the possibility of resistive dissipation in form of heating in wires which perturbates the recorded signal, and to ensure that this physical phenomenon is not overlooked in the numerical model, equation (1) was employed to solve the steady-state heat transfer in a solid 1.

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \vec{u}_{\text{trans}} \cdot \nabla T \right) + \nabla \cdot \vec{q} = Q + Q_{\text{rad}} + Q_{\text{r}} \]  

where \( q \) is the conduction heat flux, \( \vec{u}_{\text{trans}} \) is the translational motion velocity, \( Q_\text{r} \) is the electromagnetic heating (resistive dissipation), \( Q_\text{e} \) is the heat source (or sink) and \( Q_{\text{rad}} \) is the thermoelastic dissipation that is responsible for the expansion of material upon heating. The conduction heat transfer of the wires in the microchannel is accounted for on the left side of the equation (1). On the right-hand side of equation, the first term considers the heat conduction in the wires, the second term computes the resistive losses in wires which employs the electric field profiles from the electric current module, and the third term is the electromagnetic heating. The last two terms are negligible and do not apply in the case of our salinity sensor.

Heat transfer in fluids. Similarly, the heat transfer in a fluid considers conduction, convection, viscous heating \( Q_\text{vd} \) which occurs as a result of friction upon microchannels walls, and the work that is resulted from pressure changes \( Q_p \) (similar to heating from adiabatic compression) which is negligible in our study. It is noteworthy to mention that the convection is only negligible in creeping flows since the flow velocity is small and conduction would be the main heat transfer method 2. Equation (2) was solved in a steady state condition to obtain heat transfer in the fluid traversing the microchannel where \( u \) is the velocity vector 1.

\[ \rho C_p \left( \frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T \right) + \nabla \cdot (\vec{q}) = Q + Q_{\text{rad}} + Q_{\text{r}} \]  

Heat transfer boundary conditions. For the heat transfer study, the characteristics of copper wires are considered according to the experimental study. The parameters and the values of the copper wires that were imposed in the simulation include thermal conductivity at \( k = 400 \, \text{W/mK} \), density at \( 8960 \, \text{kg/m}^3 \), and heat capacity at constant pressure equal to \( C_p = 385 \, \text{J/kgK} \). In the case of salt and water mixture, heat transfer properties of seawater at 25°C is reported to have a slight increase of 1.3% in heat capacity at constant pressure and 0% in thermal conductivity 3, which allows us to neglect any change in heat transfer properties of water in salt concentrations of 1-120 ppm. Therefore, the thermal conductivity of \( k = 0.6 \, \text{W/mK} \) and heat capacity at a constant pressure of \( C_p = 4186.5 \, \text{J/kgK} \) were assumed for the electrolyte.

2. SUPPLEMENTARY RESULTS

Numerical model domain independency study. The channel length (along the x-axis) in the numerical model was assumed to be smaller than the actual experimental sensor (20 mm) to reduce the numerical load. To ensure that this measure would not influence the results, the effect of channel length was studied in a series of simulations. We studied the effect of decreasing length from 20mm to 2mm and obtained the velocity magnitude and current density (in the x-axis) along an arbitrary vertical line (along the y-axis) in the middle of the two wires. As shown in Figure S1, smaller channel lengths would not perturb the numerical results, e.g., velocity magnitude and current density, and the changes were infinitesimal. Thereby, the microfluidic channel length was set to 3 mm in the numerical simulation.
Figure S1. Domain independency study of the primary sensor model. The (a) electric current density and (b) fluid velocity in the x-axis direction is plotted along an arbitrary vertical line (along y-axis) in the channel height direction, for four microchannel lengths of 20, 10, 5, 3, 2.5, and 2 mm in the legend.

**Experimental study of the primary sensor.** Resistances were recorded as the current was swept from 10 nA to 1 μA during 56 seconds and samples with 1-20 ppm NaCl were infused into the microchannel of the primary sensor at 1 mL/min. In Figure S2, the top plots of each figure panel depict the transient electrical resistances and the bottom plots demonstrate the standard deviation of signal throughout the 56 seconds. In the bottom subfigures, an algorithm was used to apply a green patch to the dataset as the standard deviation becomes smaller than the standard deviation of the 30-56 seconds, a plateau is reached.

Figure S2. Resistances were recorded as the current was swept from 10 nA to 1 μA during 56 seconds and samples with (a) 1, (b) 2, (c) 3, (d) 5, (e) 7.5, (f) 10, (g) 15, and (h) 20 ppm NaCl were infused into the microchannel of the primary sensor at 1 mL/min. The top plots of each figure panel depict the transient electrical resistances and the bottom plots demonstrate the standard deviation of signal throughout the 56 seconds. In the bottom subfigures, an algorithm was used to apply a green patch to the dataset as the standard deviation becomes smaller than the standard deviation of the 30-56 seconds, a plateau is reached. Each panel consists of twenty eight recorded measurements from four replicates and seven measurements. Colors denote experimental repetitions.

**Numerical model mesh independency.** Mesh independency was investigated by simulating the geometry of the primary sensor using six triangular meshing conditions with mesh elements ranging from 2,000 to more than half a million with element sizes ranging from 0.026 to 14 μm to ensure high accuracy around the wires. As depicted in Figure S3, the current density and velocity magnitude are plotted between the two wires and along the x-axis and y-axis to evaluate the results based on different mesh configurations, respectively. The first configuration with 2,306 mesh elements resulted in a significant deviation from the rest of the arrangements in the current density and thereby disregarded as it would produce unreliable results if employed. The remaining five configurations were similar at the first glance. The insets in Figure S3a and Figure S3b show magnified views of the five arrangements in a plot section. It was established that increasing the number of mesh elements to more than 191,026 would
result in a deviation of only 0.07%. Therefore, to maintain accuracy and minimize the computational load, this mesh configuration (191,026 elements) was selected to be used in our study. There is a valley between the two peaks in the velocity magnitude since the velocity magnitude was studied on a vertical line between the two wires. The presence of the wire in the channel just before the studied line is the reason the velocity profile was disturbed, and valley was observed.

Figure S3. Mesh independency study of the primary sensor model. (a) Electric current density between the wires in the x-axis direction and (b) fluid x-velocity along the y-axis in six different mesh configurations ranging from 2,000 to half a million elements were plotted.

**Numerical parametric study of the wire diameter.** Using the numerical model in the parametric study, the importance of geometry parameters was studied, and the wire diameter was found to be of negligible importance in the range of 90-130μm. To further investigate this, the wire diameter was altered in the range of 1-130 μm and the current density discharge from each of these wires were plotted in Figure S4. The current density was studied along a vertical line drawn tangential to all the wires along the y-axis (4) As identical currents were discharged from wires with different sizes and surface areas, peaks with higher intensities were observed for the wires with smaller diameters. The current density showed less than 10% variations among 90, 110, and 130 μm that supports the hypothesis.

Figure S4. Numerical study of the effect of wire diameter on the current density discharge in the primary sensor. (a) A tangential cut-line is drawn next to the wire along the y-axis and (b) the current density along this cut-line in the y-axis direction is plotted.

**Experimental study of the optimized sensor.** Resistance is recorded as the current is swept from 10nA to 1μA during 56 seconds as samples with 1-120 ppm NaCl are infused into the optimized sensor at 0.2 ml/min. In Figure S5, the top plots of each figure panel depict the transient electrical resistances and the bottom plots demonstrate the standard deviation of signal throughout the 56 seconds. In the bottom subfigures, an algorithm was used to apply a green patch to the dataset as the standard deviation becomes smaller than the standard deviation of the 30-56 seconds, a green patch would be shown from that moment to the right side of the plot, indicating a plateau is reached.
Figure S5. Resistance is recorded as the current is swept from 10nA to 1μA during 56 seconds as samples with (a) 1, (b) 2, (c) 3, (d) 5, (e) 7.5, (f) 10, (g) 15, (h) 20, (i) 30, (j) 40, (k) 50, (l) 60, (m) 80, (n) 100, and (o) 120 ppm NaCl are infused into the optimized sensor at 0.2 ml/min. The top plots of each figure panel depict the transient electrical resistances and the bottom plots demonstrate the standard deviation of signal throughout the 56 seconds. In the bottom subfigures, an algorithm was used to apply a green patch to the dataset as the standard deviation becomes smaller than the standard deviation of the 30-56 seconds, a green patch would be shown from that moment to the right side of the plot, indicating a plateau is reached. Each panel consists of fifteen recorded measurements from three replicates and five measurements. Colors denote experimental repetitions.

References

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