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PROJECT REPORT

Geometry Optimization of Electrochemical Glucose Sensor using COMSOL Multiphysics.

Submitted by

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Abstract :

Diabetes is a global endemic growing at an alarming rate. Diabetic patients have to monitor their blood glucose levels at regular intervals. Therefore, it is high time for less harmful non-invasive blood glucose sensors. One of the ways to design such a device is by using electrochemical principles and amperometry to determine glucose concentration. A linear relationship is observed between average current density and glucose concentration. Numerical simulation and computer mathematical modelling play an essential role in science and engineering. It allows us to design and optimize devices such as sensors and biosensors by incorporating concepts of physics and reducing the experiments for optimization. In this study, we optimized the electrode geometry of an electrochemical glucose sensor using COMSOL Multiphysics, a finite element (FEM) software, by analysing various 2D and 3D models.

1. Introduction

Commercial glucose sensing meters use invasive methods in which the finger is pricked to draw a drop of blood, which is used to monitor blood glucose levels. The problem with the invasive approach is that regular pricking can cause skin infections, and the region of skin from which blood is drawn becomes hard over a period and even impotent to give blood. To overcome this issue, non-invasive glucose sensing techniques are required, which use saliva, sweat, tears or urine to detect blood glucose levels. Electrochemical method is one of the ways to detect blood glucose levels using non-invasive techniques. Electrochemical methods have several advantages. They offer higher selectivity, better sensitivity and reliability and are user-friendly and cost-effective. The miniaturization of electrochemical cells enhances the cost-effectiveness of the sensor by reducing the amount of reagents required. Numerical simulation allows us to design and optimize devices such as sensors and biosensors by incorporating concepts of physics and reducing the experiments for optimization. In the present study, various 2D and 3D models of an electrochemical glucose sensor were developed and analysed in COMSOL Multiphysics (ver. 5.2, COMSOL, Inc.), finite element (FEM) software, to study the effect of electrode geometry (size, shape of electrodes and spacing between the electrodes) in amperometric biosensing. Also, the enzymatic reaction rate of conversion of glucose to ferrocyanide was computed by numerical simulation.

2. Materials and methods

2.1. Reactions and governing equations

The enzymatic oxidation of glucose takes place in the bulk solution above the electrodes. Glucose reacts with ferricyanide in the presence of glucose oxidase (GOx) enzyme to form ferrocyanide in the solution between the electrodes[1]. The use of GOx enzyme makes the sensor specific to glucose sensing.

$$Glucose + GOx_{(ox)} \rightarrow Gluconic\ Acid + GOx_{(red)} \tag{1}$$

$$GOx_{(red)} + 2Fe(III) \rightarrow GOx_{(ox)} + 2Fe(II) + 2H^{+} \tag{2}$$

Reactions (1) and (2) can be combined to yield reaction (3)

$$Glucose + 2Fe(III) \rightarrow Gluconic\ Acid + 2Fe(II) + 2H^{+} \tag{3}$$

Ferrocyanide, then oxidizes at the anode to form ferricyanide and provides the working electrode current used to measure the glucose concentration.

$$2Fe(II) \rightarrow 2Fe(III) + 2e^{-} \tag{4}$$

The Michaelis-Menten model was used to determine the rate of reaction (3):

$$V = \frac{V_{max}[Glucose]}{(K_m + [Glucose])} \tag{5}$$

where V is the reaction rate, V_{max} is maximum reaction rate (1.5 x 10^{-5} M/s) and K_m is the Michaelis-Menten constant (0.5mM). The electrical response is directly proportional to the rate of diffusion of ferrocyanide from bulk solution to the working electrode and is given by Fick's I and II laws[2] :

$$J(x) = -D\frac{\partial C(x)}{\partial x} \tag{6}$$

$$\frac{\delta C}{\delta t} = -D\frac{\partial^2 C(x)}{\partial x^2} \tag{7}$$

where J(x) is the diffusion flux of a species in x direction, D is diffusion coefficient of the species in bulk solution and C is the concentration in x direction.

Cottrell Equation

2.2. Geometry and assumptions.

Four 3D models and one 2D model were considered to investigate the various factors of electrode geometry in the electrochemical amperometric glucose sensing. Factors include electrode shape and spacing between the electrodes, meshing .The four 3D models had working electrode and counter electrodes made of same materials with same analyte solution and hemispherical solution droplet above the electrode surface as depicted in fig.2(b) and similar reaction conditions but different electrode geometries as depicted in fig. 1.

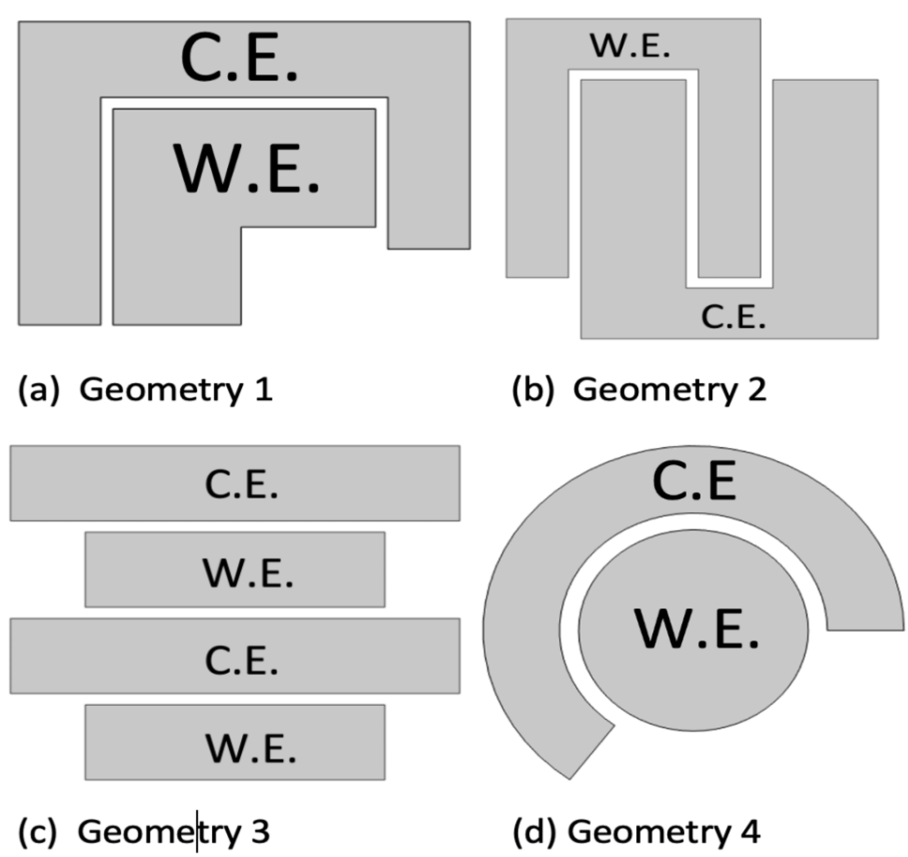


Fig. 1. Different Electrode Geometries

The 2D model was derived from 3D model containing electrode geometry 1 (fig. 3(b)) by taking a vertical cross-section passing through both the electrodes and its bottom surface containing both the electrodes along a line as depicted in fig. 2. A grid independence test was performed on the 2D model to get the optimum mesh size of various available mesh sizes in COMSOL Multiphysics (Extremely fine, extra fine, finer, fine, normal, coarse, coarser, extra coarse and extremely coarse) suitable for amperometric electrochemical glucose sensor model. The domain was meshed with free triangular mesh.

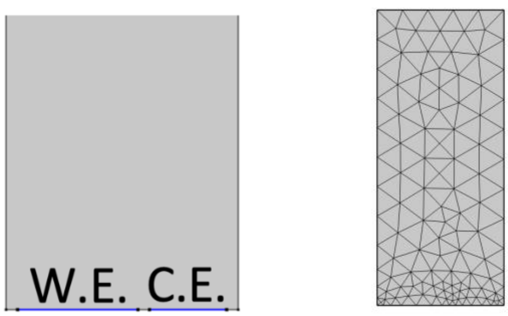
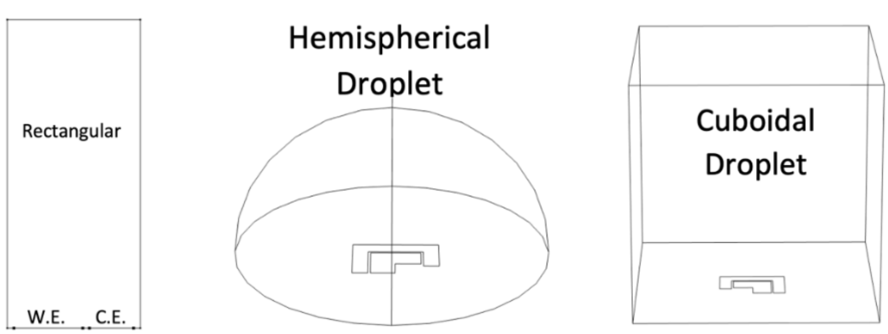


Fig 2. (a) 2D Model *(b) Free Triangular Mesh*

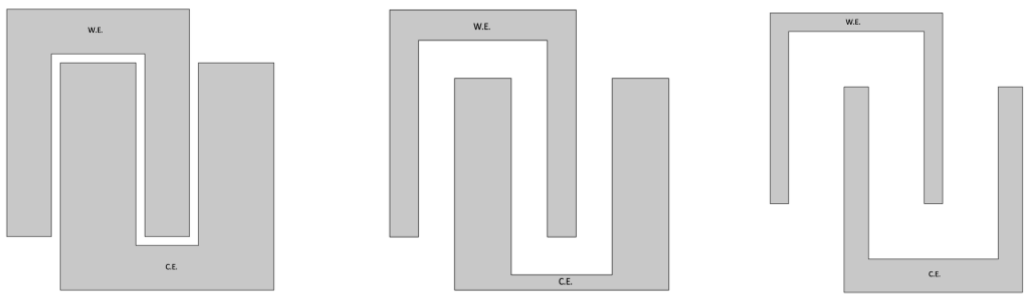
Then we compared a 2D model (rectangular) with 2 different 3D models (hemispherical and cuboidal) with electrode geometry 1 as shown in fig. 4 to check if the derived 2D model can give results in sync with its parent 3D model without a major offset. 2D models as compared to 3D models offer higher computational speed because of lower memory requirements and therefore have considerably low computation time.



(a) Rectangular (b) Hemispherical (c) Cuboidal

Fig. 3. Comparison between 2D and 3D models.

Then the role of spacing between the working and counter electrodes was investigated by taking 3 different values of spacing for each of all the 4 electrode geometries. For instance, 3 different spacing have been depicted for the electrode geometry 2 in fig. 4.



(a) 0.15 mm (b) 0.75 mm (c) 1.5 mm

Fig. 4. Electrode Geometry

2.3. Initialization and boundary conditions

The diffusion coefficients of glucose, ferricyanide and ferrocyanide were taken to be $\mathbf{10^{-9}\ m^2/s}$, $\mathbf{10^{-9} m^2/s}$ and $\mathbf{10^{-9}\ m^2/s}$ respectively. The external concentration of glucose, ferricyanide and ferrocyanide were taken to be 5uM, 50mM and 1uM respectively. It was assumed that there is no leakage of analytical solution through the impermeable bottom flat surface containing both the working and counter electrodes and the inert surface. Electrical conduction was only possible through the 2 electrodes. Initial concentration values of glucose, ferrocyanide and ferricyanide in the bulk solution at t = 0 were assumed to be equal to external concentrations. External electric potential $\boldsymbol{\phi_{s,ext}}$ applied to the working and counter electrodes were 0.4V and 0.1V, respectively. The concentrations of glucose, ferricyanide and ferrocyanide at the bulk boundary i.e., at the top hemispherical dome at t = 0, were assumed to be equal to the bulk concentrations with concentration of glucose equal to that in the analytical mixture and concentrations of ferricyanide and ferrocyanide in the ratio 50000: 1 [3].

3. Results and discussion

3.1. Optimal Mesh

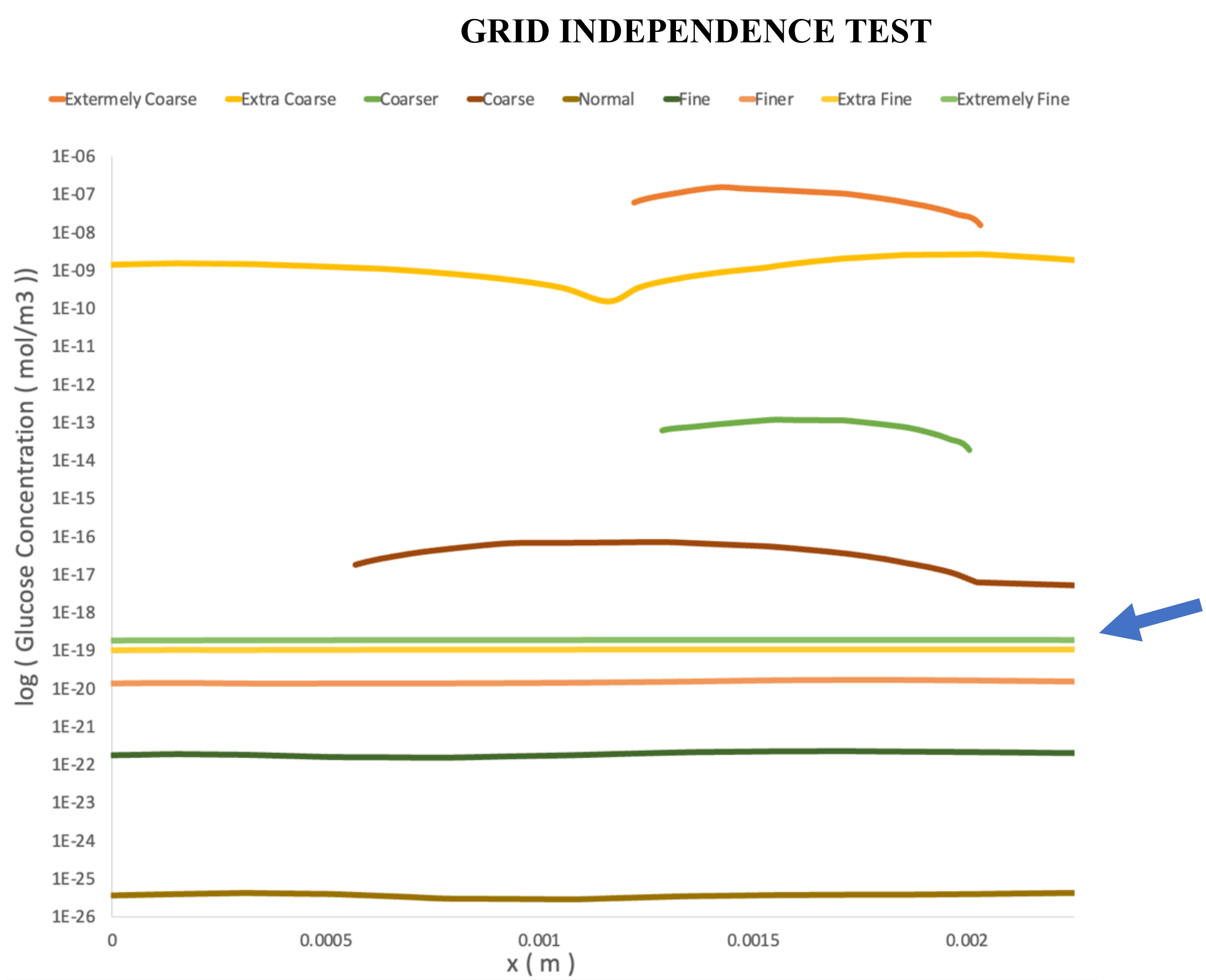


Fig. 5. Log(glucose concentration) vs x graph

As evident from the graph, extra fine and extremely fine free triangular meshing types showed convergence. Hence, extremely fine mesh size was used throughout the numerical simulation.

3.2. 2D Simulation vs 3D Simulation

The graph in fig. 5 was plotted for 3 models – rectangular, hemispherical and cuboidal to chech for the offset in results of 2D derived model from its parent 3D model.

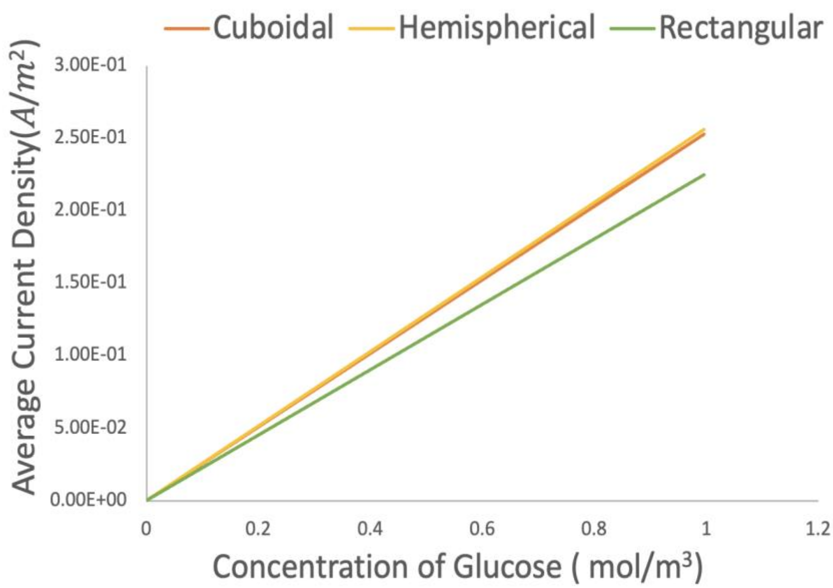


Fig. 6. Average current density(A/m^2) vs Concentration of glucose(mol/m^3)

The offset was signifiant and 2D models couldn't be used for faster computations and 3D models were used for numerical simlution. Using this graph, one more inference was drawn that geomotery of droplet whether cuboidal or hemispherical does not really affect the results, but as spherical droplet is more realistic, found in nature, hemispherical droplet was employed for simulation in all the four 3D models.

3.3. Spacing between the electrodes.

The four graphs in fig. 7 represent the sensitivity and selectivity w.r.t 3 different spacings between the working and counter electrodes for each of the 3D models with four different electrode geometries 1, 2, 3 and 4.

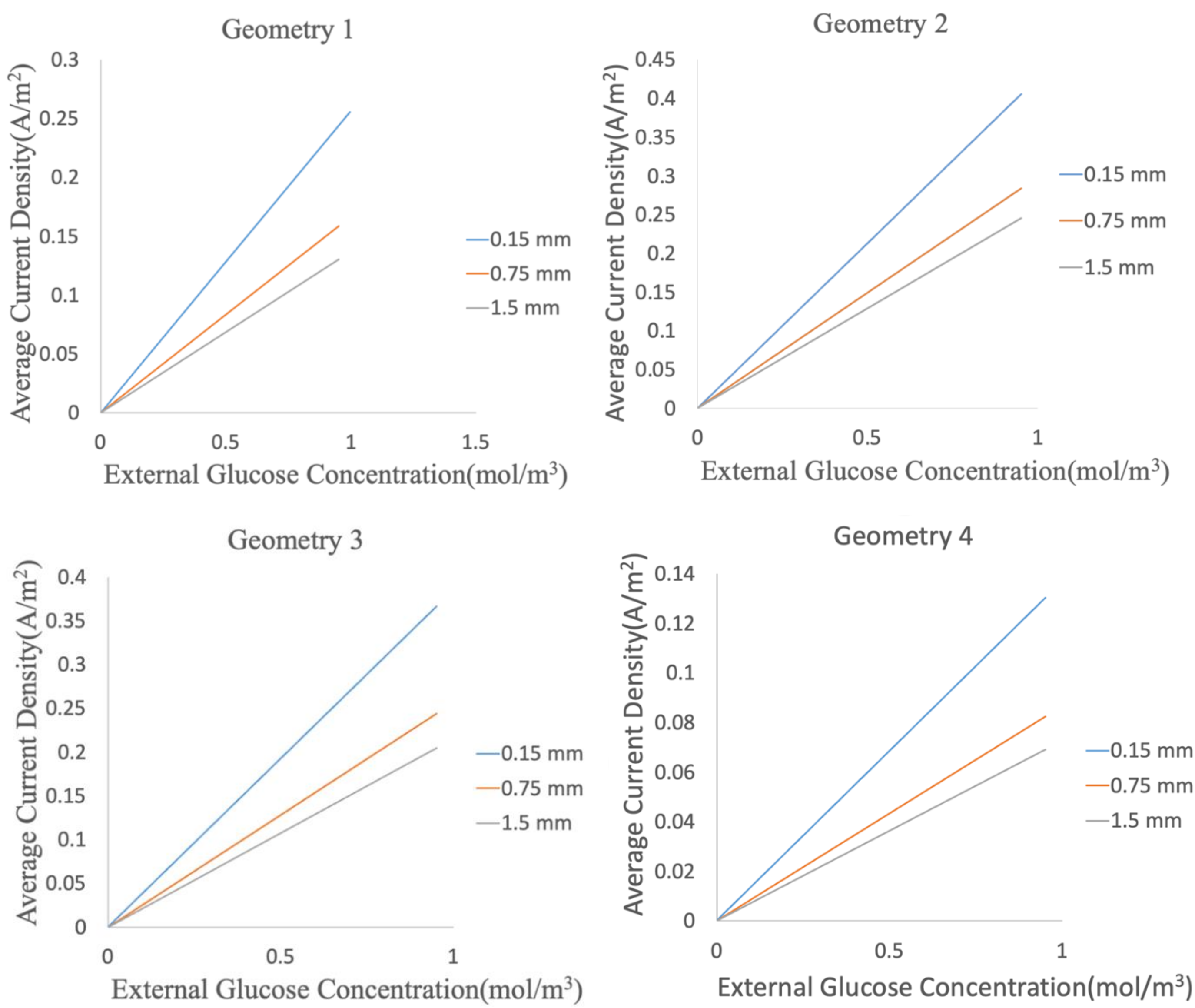


Fig 7. Spacing between the working and counter electrodes for 4 different geometries

3.4. Most optimal electrode geometry

The graph in Fig. 8 compares all 4 electrode geometries with their most optimal spacing utilized.

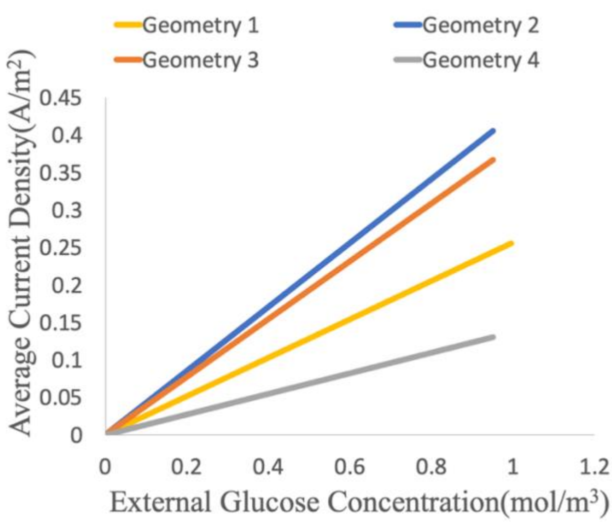


Fig 8. Graph

The most optimal electrode geometry with best possible electrochemical response was geometry 2 as evident from fig.8.

Conclusion

Specific glucose oxidation reaction and reaction conditions were used to optimize electrode geometries for an electrochemical amperometric glucose sensor. Two different aspects of electrode geometry, spacing between the working and counter electrodes and different shapes of the electrodes were investigated. Average current density vs concentration of glucose graphs for three different values of spacing between the electrodes showed inverse relation between the electrochemical response and increasing values of spacing. The lower limit of spacing taken to be 0.15 mm could not have been decreased further due to the constraints of screen printing and some phenomenon of physics. On the other hand, for different electrode shapes, best electrochemical response was observed for geometries with maximum perimeter of working and counter electrodes in the vicinity of each other, as evident from physics, area for conduction will increase and therefore, electrical response will be better. Hence geometry 2 with maximum perimeter vicinity showed the best electrical response.

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