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Membrane Measurement, Device Simulations of Nanochannel, Nanopore and Nanofluidics Electronics Calculator

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ABSTRACT

In this article we measure the surface potential of the polycarbonate track etched membrane having multiple nanopores and graphene/copper membrane having multiple nanopores. We use potassium chloride electrolyte solution (KCl) with 0.6 mol in the high concentration inlet source reservoir. We use 0.6 mmol potassium chloride electrolyte solution in the low concentration outlet sink reservoir. We provide theory to match the surface potential of the membranes. We develop model to understand the potassium ion transference number inside the multiple nanopores for our membranes. We develop GUI simulation to understand the concentration of the potassium chloride electrolyte solution inside single nanochannel, single nanopore for different surface potential of the membranes. We use Gouy-Chapman equation to calculate the concentration and Smoluchowski model is used to calculate the velocity of the potassium chloride electrolyte solution. Here we present a detailed comparative analysis of the structural, transport mechanisms of nanochannels, nanopores to explain the several orders of magnitude difference in the current inside the nanochannel and the nanopore. The volume of the single nanochannel is larger than the volume of the single nanopore resulting in larger charge of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the single nanochannel compared to the single nanopore resulting in the significant difference in the current. We develop GUI based simulation of nanofluidics electronics calculator. Each button of the calculator is related to their own current of the potassium chloride electrolyte solution inside the nanochannel and nanopore, respectively.

Keywords: membrane, nanochannel, nanopore, current, nanofluidics electronics calculator.

INTRODUCTION

Nanofluidics is the study of fluids to manipulate, control and understand in nanometer sized structures. The understanding of transport mechanism from current in channels and pores of sizes few nanometers. The channel height and pore diameter varies from 1-100 nm [1–4]. The study of nanofluidics depends on the membrane materials that includes in the recent years

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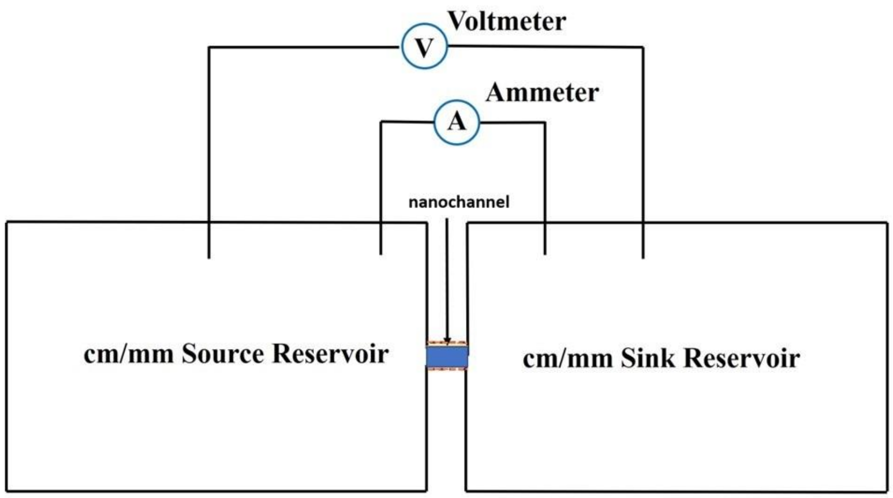
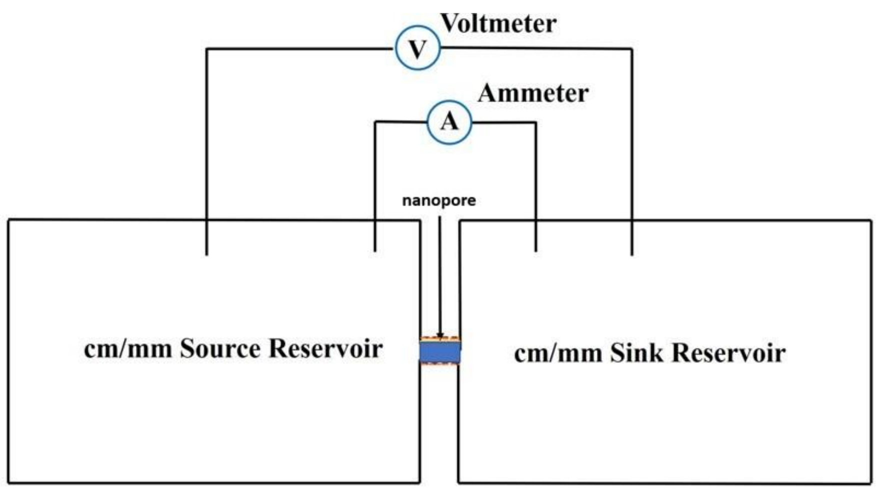
silicon nitride [1], polyimide (PI) [2], silicon nitride sputtered with silicon dioxide [3], carbon nanotubes [4], graphene [5], polycarbonate track etched membrane [6], molybdenum disulfide [7], graphene/copper [8], silicon nitride layered with palladium [9] and boron nitride nanotubes [10]. In this regard there are studies on single nanopore [7], single nanochannel [11], single nanoconduit [12], single nanocapillary [13], multiple nanopores [9,14,15], multiple nanochannels [11], multiple nanoconduits [12] and multiple nanocapillaries [13,16]. Fig. 1a shows the schematic representation of single nanochannel having negative surface charge integrated to cm/mm source-sink reservoirs. Fig. 1b shows the schematic representation of single nanopore membrane having negative surface charge integrated to cm/mm source-sink reservoirs.



(a)



(b)

Figure 1. Schematic representation of negatively charged (a) nanochannel and (b) nanopore integrated to cm/mm source-sink reservoirs. The voltmeter and ammeter are connected to the device.

Here potassium chloride electrolyte solution (KCl) [5], lithium chloride electrolyte solution (LiCl), sodium chloride electrolyte solution (NaCl), calcium chloride electrolyte solution ($CaCl_2$), magnesium chloride electrolyte solution ($MgCl_2$) [17], sodium phosphate electrolyte solution made from the sodium phosphate monobasic monohydrate NaH_2PO_4 and sodium phosphate dibasic heptahydrate Na_2HPO_4 [6]. Also, potassium chloride electrolyte solution is typically studied to understand the transport mechanism inside nanochannels and nanopores [7, 10, 18–22]. The transport in the nanochannels and the nanopores have shown fewer thermal effects [23,24]. The surface potential of the membrane having single nanochannel, single nanopore, multiple nanochannels, multiple nanopores are mathematically related to the surface capacitance, surface charge and surface charge density of the membrane. The surface charge density is used as a parameter in the simulations to obtain the current inside the single nanochannel and single nanopore [20, 25, 26].

In recent experiments the structure of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the single nanopore, single nanochannel, multiple nanopores and multiple nanochannels are studied [22]. The structure of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannels and nanopores are predicted using cation transference number [22]. The cation transference number is the ratio of cation charge inside the nanochannels to the total cation and anion charge inside the nanochannels. For instance, when we consider potassium chloride electrolyte solution the cation is potassium ion and anion is chlorine ion. The potassium ion transference number is the ratio of potassium ion charge inside the nanochannels to the total potassium and chlorine ions charge inside the nanochannels. The cation transference number is also calculated using the ratio of cation concentration inside the nanochannels to the total cation and anion concentration inside the nanochannels. The third method to calculate the cation transference number is using the ratio of cation current inside the nanochannels to the total cation and anion current inside the nanochannels. The simulations are carried out to understand the structure of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannels and nanopores [20, 25, 26].

Recent experiments by Emmerich et. al. [9] studied the ionic current inside the nanopores integrated to asymmetric reservoirs. The device unit namely the nanopores integrated to asymmetric reservoirs are connected in parallel to build a nanofluidic logic circuit for the first time. Surface potential measurements on the membrane material having multiple nanochannels are found to be important to fabricate nanofluidic memristors. The nanofluidic memristor results in different current when the surface potential of the membrane material to make the nanochannel is varied. The surface potential can be varied by changing the membrane material themselves [27]. The multiple conical nanopores of polyimide membrane material is used to fabricate nanofluidic memristors [28]. The memristive behavior is observed by series and parallel arrangement of the membrane materials. The surface potential of the membrane played a pivotal role in the nanofluidic memristors current measurement [9,23,27–34].

In this study we design, develop a complete experiment setup to measure the surface potential of two samples polycarbonate track etched membrane having multiple nanopores and graphene/copper membrane having multiple nanopores. We develop theoretical model to match the experiments for the surface potential of our samples. We develop model to understand the cation transference number for multiple nanopores in our samples. We calculate the surface capacitance, surface charge and surface charge density for the graphene/copper membrane having multiple nanopores. We calculate the surface capacitance, surface charge and surface charge density for the single nanopore in our graphene/copper membrane having multiple nanopores.

Here we perform simulations to understand the structure and transport mechanism of the potassium ions, chlorine ions, potassium chloride electrolyte solution inside single nanochannel and single nanopore. Here we calculate the current inside single nanochannel and single nanopore. We elucidate the difference in the obtained current between the single nanochannel and single nanopore. We extend our study for different surface potential of the membrane having single nanochannel and single nanopore, respectively. In this paper we develop GUI for the nanofluidics electronics calculator where each button in the calculator is related to their own current obtained from single nanochannel made on the membrane integrated between the source-sink reservoirs system. Further we develop GUI for the nanofluidics electronics calculator where each button in the calculator is related to their own current obtained from single nanopore made on the membrane integrated between the source-sink reservoirs system. Nanofluidics can find applications for energy-efficient nanofluidic memristors [9,27,28], energy storage [35], power generators [36–38], water desalination [15], nanofluidics circuits [39], DNA translocation [40,41] and the electro kinetic pumps [25, 26, 42–47].

The rest of the paper is outlined as follows. Section 2 discusses the materials and methods. The theory is written in section 3. Comparative analysis of the structural, transport mechanisms for different surface potential of the membrane having single nanochannel and single nanopore are discussed in section 4. The results and detailed discussion are given in Section 5. In Section 6 we discuss nanofluidics electronics calculator. Finally, conclusions are presented in Section 7.

MATERIALS AND METHODS

Polycarbonate Track Etched Membrane Having Multiple Nanopores

Experimental Design:

We consider polycarbonate track etched membrane having multiple nanopores. The polycarbonate track etched membrane material having multiple nanopores is purchased from Whatman USA. The membrane material is of circular dimension of diameter 25 mm. The single pore diameter is 15 nm. The membrane parameters of sample 1 polycarbonate track etched membrane having multiple nanopores are given in Table 1. The polycarbonate track etched membrane having multiple nanopores are integrated between the inlet source and outlet sink reservoir. We consider potassium chloride electrolyte solution. The potassium chloride electrolyte solution of 0.6 mol is used in the inlet source reservoir. The outlet receiver reservoir has 0.6 mmol potassium chloride electrolyte solution. The concentration gradient is the ratio of high concentration of the potassium chloride electrolyte solution to the low concentration of the potassium chloride electrolyte solution. The concentration gradient is 1000. The experiment schematic set up is shown in Fig. 1b. The experiments are conducted at room temperature. The experiment set up is similar to previous studies [38]. The experiment measuring device is a digital multimeter unit DMM 6500 procured from Tektronix. The DMM has a current range from 10 pA to 10 A and a voltage range from 100 nV to 1010 V. The DMM unit measures the surface potential of the polycarbonate track etched membrane having multiple nanopores integrated between the two reservoirs.

Table 1: Membrane parameters of sample 1 polycarbonate track etched membrane material having multiple nanopores.

Polycarbonate track etched membrane parameters	numerical values
circular diameter	25 mm
diameter of nanopore	15 nm
number of nanopores	Multiple
fabrication method	purchased from Whatman USA
high KCl concentration source reservoir	0.6 mol
low KCl concentration sink reservoir	0.6 mmol
activity of KCl in high concentration source reservoir	0.6 mol
activity of KCl in low concentration sink reservoir	0.6 mmol
thermal voltage	0.026 V
surface potential	0.074 V
surface potential (theoretical)	0.074 V
Potassium ion transference number (theoretical)	0.58
membrane relative permittivity	2.9

Surface Potential:

The surface potential is measured for the potassium chloride electrolyte solution with concentration gradient 1000 in the device system. $\zeta_{membrane}$ is the surface potential of the membrane. The measurement value of the surface potential of the polycarbonate track etched membrane having multiple nanopores is 0.074 V. The experiment results are repeatable, reliable and reproducible. The experiment results agree to the previous studies [38]. We model the surface potential of the polycarbonate track etched membrane material having multiple nanopores. The model considers Nernst limit given in Eq. 1 [25].

$$\zeta_{membrane}^{theory} = \frac{RT}{zF} \log \frac{\alpha_H}{\alpha_L} \tag{1}$$

where R is the gas constant, T is the temperature and F is the Faraday constant. The numerical constants and parameter values used in the study are given in Table 2. In this study we consider symmetric monovalent potassium chloride electrolyte solution. We consider $z^{K^+} = 1$ is the valence of potassium ions. The valence of chlorine ions is $z^{Cl^-} = -1$. We consider $z^{K^+} = -z^{Cl^-} = z = 1$, where z is the valence. α_H is the activity of the KCl in the high concentration reservoir and α_L is the activity of the KCl in the low concentration reservoir? We consider the activity of the KCl solution to be same as the concentration [38]. The activity gradient is the ratio of activity of the KCl in the high concentration reservoir and the activity of the KCl in the low concentration reservoir. The activity gradient is denoted as $\nabla\alpha$.

$$\nabla\alpha = \frac{\alpha_H}{\alpha_L} \tag{2}$$

Table 2: Numerical constants and parameter values used in the study.

key parameters	numerical values
relative permittivity of water	80
permittivity of free space	8.854×10^{-12} F/m
viscosity of the water	1.003×10^{-3} Pa.s
Faraday constant	96485.3 C/mol
gas constant	8.314 J/ (mol K)
Avogadro number	6.023×10^{23} mol^{-1}
Boltzmann constant	1.38×10^{-23} J/K
electronic charge	1.602×10^{-19}C
Temperature	300 K

The activity gradient of the KCl is 1000. The theoretical surface potential of the polycarbonate track etched membrane material having multiple nanopores is 0.074 V that matches our experiments.

Potassium Ion Transference Number:

The potassium ion transference number is theoretically obtained by relating the thermal voltage and the activity gradient of the KCl in the inlet source and outlet sink reservoirs [38, 48, 49].

$$t^{+}_{membrane} = \frac{1}{2}\left[1 + \frac{F}{RT}\frac{V_T}{\ln\left(\frac{\alpha_H}{\alpha_L}\right)}\right] \tag{3}$$

where $t^{+}_{membrane}$ is the potassium ion transference number inside the multiple nanopores of polycarbonate track etched membrane and V_T is the thermal voltage. The thermal voltage is obtained from the temperature relation given below.

$$V_T = \frac{RT}{F} \tag{4}$$

The thermal voltage V_T is 0.026 V. The theoretical potassium ion transference number inside the multiple nanopores of polycarbonate track etched membrane is 0.58. The results are in agreement with the previous studies [38].

Graphene/Copper Membrane Having Multiple Nanopores Fabrication Details:

The commercially available graphene/copper membrane was procured from Graphenea, USA. The one layer of graphene is coated on a copper material. The membrane parameters of sample 2 graphene/copper having multiple nanopores are given in Table 3. The focused ion beam was used to fabricate nanopores. We fabricate nanopore of diameter 300 nm on graphene/copper membrane material. We fabricate multiple nanopores refer our earlier works [38]. The focused ion beam is also used to fabricate multiple micropores on the graphene/copper membrane material [38]. Further the Femtosecond laser (fs) micromachining (SATSUMA HP2, Amplitude System, France) can also be used to fabricate single millipore, multiple millipores, single micropore and multiple micropores on the graphene/copper membrane material [8, 37]. The fs micromachining technique has many advantages that includes the fabrication is one-step, rapid etching, and non-masking in the method [50] compared to other conventional pore fabrication techniques like photochemical [51] and reactive ion etching [52].

Table 3: Membrane parameters list 1 of sample 2 graphene/copper membrane material having multiple nanopores.

Graphene/copper membrane parameters	numerical values
Length	10 mm
Height	10 mm
Width	18 μm
diameter of single nanopore	300 nm
outer diameter for the single nanopore (assumed)	300.008 nm
number of pores	multiple
fabrication method 1	focused ion beam to create 300 nm diameter nanopore
fabrication method 2	focused ion beam to create multiple nanopores with spacings
surface area	10^{-4} m^2
high KCl concentration source reservoir	0.6 mol
low KCl concentration sink reservoir	0.6 mmol
activity of KCl in high concentration source reservoir	0.6 mol
activity of KCl in low concentration	0.06 mmol
thermal voltage	0.026 V
surface potential	0.1 V
surface potential (theoretical)	0.1 V
Potassium ion transference number (theoretical)	0.56
surface capacitance (theoretical)	3.8×10^{-13}F
surface charge (theoretical)	3.8×10^{-14} C
surface charge density (theoretical)	3.8×10^{-10} C/m^2

The graphene/copper membrane having multiple nanopores are integrated between the inlet source and outlet sink reservoir. The concentration gradient of the potassium chloride electrolyte solution between the inlet source and outlet sink reservoirs system is 1000. The same experiment set up discussed above is used here.

Surface Potential:

The surface potential is measured for the potassium chloride electrolyte solution with concentration gradient 1000 in the device system. The surface potential measurement of the graphene/copper membrane having multiple nanopores is 0.1 V. The experiment results are repeatable, reliable and reproducible. The experiment results are similar to our previous studies [38]. We model the surface potential of the graphene/copper membrane having multiple nanopores.

$$\zeta_{membrane}^{theory} = \frac{RT}{zF}\log\frac{\alpha_H}{\alpha_L} \tag{5}$$

activity of the potassium chloride electrolyte solution in the inlet source and outlet sink reservoirs. The inlet source reservoir has high concentration. The activity α_H in the inlet source reservoir is related to high concentration of the potassium chloride electrolyte solution and its activity coefficient.

$$\alpha_H = m_H \times \gamma_H \tag{6}$$

Where m_H is the molal concentration for higher concentration of potassium chloride electrolyte solution and γ_H is the activity coefficient for higher concentration of potassium chloride electrolyte solution. We assume $\gamma_H = 1$ because the surface potential measurement of the graphene/copper membrane having multiple nanopores is obtained from the low concentration outlet sink reservoir.

The outlet sink reservoir has low concentration. The activity α_L in the outlet sink reservoir is related to low concentration of the potassium chloride electrolyte solution and its activity coefficient.

$$\alpha_L = m_L \times \gamma_L \tag{7}$$

where m_L is the molal concentration for low concentration of potassium chloride electrolyte solution and γ_L is the activity coefficient for low concentration of potassium chloride electrolyte solution. We assume $\gamma_L = 0.1$ for the surface potential of the graphene/copper membrane having multiple nanopores to match our experiments. The low value of the activity coefficient implies the activity of the potassium chloride electrolyte solution in the low concentration reservoir is small. The activity gradient is given in Eq. (8).

$$\nabla\alpha = \frac{\alpha_H}{\alpha_L} \tag{8}$$

The activity gradient of the potassium chloride electrolyte solution is 10000. The theoretical surface potential of the graphene/copper membrane having multiple nanopores is 0.1 V that matches our experiments.

Potassium Ion Transference Number:

The potassium ion transference number is theoretically obtained by relating the thermal voltage and the activity gradient of KCl in the inlet source and outlet sink reservoirs.

$$t^{+}_{membrane} = \frac{1}{2}\left[1 + \frac{F}{RT}\frac{V_T}{\ln\left(\frac{\alpha_H}{\alpha_L}\right)}\right] \quad (9)$$

Where $t^{+}_{membrane}$ is the potassium ion transference number inside the multiple nanopores made up of graphene/copper membrane material and V_T is the thermal voltage. The thermal voltage is obtained from the temperature relation given below.

$$V_T = \frac{RT}{F} \quad (10)$$

The thermal voltage VT is 0.026 V. The theoretical potassium ion transference number inside the multiple nanopores made up of graphene/copper membrane material is 0.56. The results are in agreement with the previous studies [37].

Surface Charge of the Graphene/Copper Membrane Material Having Multiple Nanopores:

The surface charge of the graphene/copper membrane having multiple nanopores is calculated from the surface capacitance and surface potential [25].

$$q_{membrane} = C_{membrane}\zeta_{membrane} \quad (11)$$

where $q_{membrane}$ is the surface charge of the graphene/copper membrane material having multiple nanopores. $C_{membrane}$ is the surface capacitance. The surface capacitance of the graphene/copper membrane material having multiple nanopores is calculated from the relative permittivity of the graphene/copper membrane having multiple nanopores, surface area and height of the graphene/copper membrane.

$$C_{membrane} = \frac{\epsilon_0\epsilon_{membrane}A_{membrane}}{h_{membrane}} \quad (12)$$

where $\epsilon_{membrane}$ is the relative permittivity of the graphene/copper membrane material having multiple nanopores. We assume the relative permittivity of the graphene/copper membrane material having multiple nanopores is 4.3. $A_{membrane}$ is the surface area and $h_{membrane}$ is the height of the graphene/copper membrane material having multiple nanopores. The surface area is obtained from the length and height of the graphene/copper membrane material having multiple nanopores. The length is 10 mm and the height is 10 mm. The membrane parameters of graphene/copper membrane having multiple nanopores are given in Table 3. The surface area of the graphene/copper membrane material having multiple nanopores is 10^{-4} m^2. The surface capacitance of the graphene/copper membrane material having multiple nanopores is 3.8×10^{-13} F. The surface charge of the graphene/copper membrane material having multiple nanopores is 3.8×10^{-14} C. The surface charge density of the graphene/copper membrane material having multiple nanopores is calculated from the surface charge and the surface area of the graphene/copper membrane material having multiple nanopores.

$$\sigma_{membrane} = \frac{q_{membrane}}{A_{membrane}}$$

where $\sigma_{membrane}$ is the surface charge density of the graphene/copper membrane material having multiple nanopores. The surface charge density of the graphene/copper membrane material having multiple nanopores is 3.8×10^{-10} C/m^2.

Surface charge on the single nanopore in the graphene/copper membrane material having multiple nanopores. The surface charge on the single nanopore in the graphene/copper membrane material having multiple nanopores is calculated from the surface capacitance on the single nanopore in the graphene/copper membrane material having multiple nanopores and surface potential of the single nanopore in the graphene/copper membrane material having multiple nanopores.

$$q_{nanopore} = C_{nanopore}\zeta_{membrane} \tag{13}$$

where $q_{nanopore}$ is the surface charge on the single nanopore in the graphene/copper membrane material having multiple nanopores. $C_{nanopore}$ is the surface capacitance on the single nanopore in the graphene/copper membrane material having multiple nanopores. Surface capacitance on the single nanopore in the graphene/copper membrane material having multiple nanopores. The surface capacitance on the single nanopore in the graphene/copper membrane material having multiple nanopores is calculated from the relative permittivity of the graphene/copper membrane material having multiple nanopores and the geometry of the single nanopore. We consider small solid region in the graphene/copper membrane as the outer diameter for the single nanopore that is bigger than the diameter of the single nanopore.

$$C_{nanopore} = \frac{2\pi\epsilon_0\epsilon_{membrane}L_{nanopore}}{\ln\left(\frac{b_{nanopore}}{d_{nanopore}}\right)} \tag{14}$$

where $b_{nanopore}$ is the outer diameter for the single nanopore. $d_{nanopore}$ is the diameter of the single nanopore. We assume the outer diameter for the single nanopore is 300.008 nm. The diameter of the single nanopore is 300 nm. $L_{nanopore}$ is the length of the single nanopore. The length of the single nanopore is 18 μm The surface capacitance on the single nanopore in the graphene/copper membrane material having multiple nanopores is 1.6×10^{-10} F. The surface charge on the single nanopore in the graphene/copper membrane material having multiple nanopores is 1.6×10^{-11} C.

Surface Charge Density on the Single Nanopore in the Graphene/Copper Membrane Material Having Multiple Nanopores:

The surface charge density on the single nanopore in the graphene/copper membrane material having multiple nanopores is calculated from the surface charge and surface area on the single nanopore in the graphene/copper membrane material having multiple nanopores.

$$\sigma_{nanopore} = \frac{q_{nanopore}}{A_{nanopore}}$$

where $\sigma_{nanopore}$ is the surface charge density on the single nanopore in the graphene/copper membrane material having multiple nanopores. $A_{nanopore}$ is the surface area on the single nanopore in the graphene/copper membrane material having multiple nanopores. The surface area is calculated from the length and the diameter of the single nanopore. The surface area on the single nanopore is 1.7×10^{-11} m^2. The surface charge density on the single nanopore in the graphene/copper membrane material having multiple nanopores is 1 C/m^2. The results are similar to our previous numerical simulations [8]. The membrane parameters of graphene/copper membrane material having multiple nanopores are given in Table 4.

Table 4. Membrane parameters list 2 of sample 2 graphene/copper membrane material having multiple nanopores.

Graphene/copper membrane parameters	numerical values
surface area on the single nanopore	1.7×10^{-11} m^2
surface capacitance on the single nanopore (theoretical)	1.6×10^{-10} F
surface charge on the single nanopore (theoretical)	1.6×10^{-11} C
surface charge density on the single nanopore (theoretical)	1 C/m^2
membrane relative permittivity (assumed)	4.3

THEORY

Here we study the structural and transport mechanisms of nanochannels and nanopores. In our study the membrane contains single nanochannel and single nanopore, respectively. The nanochannel/nanopore is integrated to source inlet and sink outlet reservoirs. The length of the nanochannel is 5 μm, width is 1 m and the height is 30 nm. The volume of the nanochannel is 1.5×10^{-13} m^3. We consider the membrane parameters having single nanochannel and single nanopore in our simulations. The membrane parameters having single nanochannel, single nanopore, respectively integrated to source inlet, sink outlet reservoirs are given in Table 5 and Table 6.

Table 5. Membrane parameters list 1 for surface potential $\zeta_{membrane} = 0.052\ V$ having single nanochannel and single nanopore. d is the diameter of the nanopore.

parameters	length	width	height	volume	concentration	moles
inlet	1 cm	1 m	1 mm	10^{-5} m^3	-	-
outlet	1 cm	1 m	1 mm	10^{-5} m^3	-	-
membrane to make nanochannel	5 μm	1 m	10 μm	10^{-10} m^3	5×10^{-7} mM	5×10^{-17} mol
membrane to make nanopore	5 μm	1 m	1 μm	5×10^{-12} m^3	0.1 mM	5×10^{-13} mol

nanochannel	5 µm	1 m	30 nm	1.5×10^{-13} m^3	-	-
nanopore	5 µm	-	d = 30 nm	3.6×10^{-21} m^3	-	-

Table 6. Membrane parameters list 2 for surface potential $\zeta_{membrane} = 0.052\ V$ having single nanochannel and single nanopore. $n_{elements}$ are the number of elements.

parameters	atomic mass	mass	$n_{elements}$	valence	$\epsilon(\zeta_{membrane}, charge)$
membrane to make nanochannel	140.28 g/mol	$7 \times 10^{-18} kg$	3×10^7	7	2.6 (0.052 V, $3.4 \times 10^{-11} C$)
membrane to make nanopore	140.28 g/mol	7×10^{-14} kg	3×10^{11}	7	2.6 (0.052 V, $3.4 \times 10^{-7} C$)

Membrane Parameters Having Single Nanochannel

The length of the membrane having single nanochannel is 5 µm, width is 1 m and height is 10 µm. The volume of the membrane having single nanochannel is 10^{-10} m^3. Here we consider the concentration of the membrane material having single nanochannel is $(c_{membrane}^{nanochannel})$ 5×10^{-7} mM. The number of membrane elements are calculated.

Number of Elements of the Membrane Having Single Nanochannel:

$$N_{membrane}^{nanochannel} = mole_{membrane}^{nanochannel} N_{Avogadro} \tag{15}$$

where $N_{membrane}^{nanochannel}$ are the number of elements of the membrane having single nanochannel, $mole_{membrane}^{nanochannel}$ is the mole of the membrane having single nanochannel and $N_{Avogadro}$ is the Avogadro constant. The numerical constants and parameter values used in the study are given in Table 2.

Mole of the Membrane Material Having Single Nanochannel:

The mole of the membrane having single nanochannel is calculated from the concentration and the volume of the membrane having single nanochannel.

$$mole_{membrane}^{nanochannel} = c_{membrane}^{nanochannel} V_{membrane}^{nanochannel} \tag{16}$$

where $V_{membrane}^{nanochannel}$ is the volume of the membrane having single nanochannel. The mole of the membrane having single nanochannel is 5×10^{-17} mol. The number of the membrane elements having single nanochannel is 3×10^7 elements. Fig. 2 shows the schematic representation of the structure of the membrane. The number of membrane elements are represented in the Fig. 2. The membrane has single nanochannel.

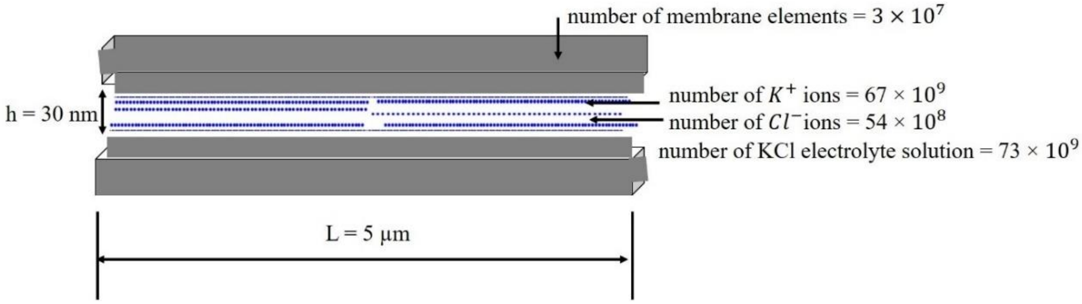


Figure 2. Schematic representation of membrane having single nanochannel. The membrane material is represented in gray color. Schematic representation of the structure of KCl inside the nanochannel.

Mass of the Membrane Material Having Single Nanochannel:

The mass of the membrane having single nanochannel is calculated from the mole and atomic mass of the membrane having single nanochannel.

$$m_{membrane}^{nanochannel} = mole_{membrane}^{nanochannel} \times atomic\ mass\ of\ the\ membrane \quad (17)$$

where $m_{membrane}^{nanochannel}$ is the mass of the membrane having single nanochannel and we consider atomic mass of the membrane is 140.28 g/mol. The mass of the membrane having single nanochannel is 7×10^{-18} kg.

Charge of the Membrane Having Single Nanochannel:

The charge of the membrane having single nanochannel is calculated from the concentration, valence and the volume of the membrane having single nanochannel. We use Faraday-concentration model [25].

$$q_{membrane}^{nanochannel} = c_{membrane}^{nanochannel} z_{membrane} F V_{membrane}^{nanochannel} \quad (18)$$

where $q_{membrane}^{nanochannel}$ is the charge of the membrane having single nanochannel, $z_{membrane}$ is the valence of the membrane having single nanochannel. F is the Faraday constant. The charge of the membrane having single nanochannel is 3.4×10^{-11} C.

Parameters of the Potassium Chloride Electrolyte Solution at the Inlet/Outlet Reservoirs Concentration of KCl:

Here we consider the length of the inlet source and outlet sink reservoirs are 1 cm, width is 1 m and the height is 1 mm. The volume of the inlet/outlet reservoirs are $V_{inlet} = 10^{-5}$ m³. We consider the inlet concentration of the potassium ions are 0.1 mM, chlorine ions are 0.1 mM and the concentration of potassium chloride electrolyte solution is 0.2 mM.

Charge of the Potassium Ions in the Inlet Reservoir:

The charge of the potassium ions in the inlet reservoir are calculated from the concentration of the potassium ions, valence of the potassium ions and the volume of the inlet reservoir.

$$q_{inlet}^{K^+} = c_{inlet}^{K^+} V_{inlet} zF \tag{19}$$

where $q_{inlet}^{K^+}$ is the charge of the potassium ions, $c_{inlet}^{K^+}$ is the concentration of the potassium ions. The charge of the potassium ions in the inlet reservoir are 0.097 C.

Space Charge Density of the Potassium Ions in the Inlet Reservoir:
The space charge density of the potassium ions in the inlet reservoir is calculated from the charge of the potassium ions and the volume of the inlet reservoir.

$$\rho_{q}{}_{inlet}^{K^+} = \frac{q_{inlet}^{K^+}}{V_{inlet}} \tag{20}$$

where $\rho_{q}{}_{inlet}^{K^+}$ is the space charge density of the potassium ions. The space charge density of the potassium ions inside the inlet reservoir is 9700 C/m^3.

Charge of the Chlorine Ions in the Inlet Reservoir:
The charge of the chlorine ions in the inlet reservoir is calculated from the concentration of the chlorine ions, valence of the chlorine ions and the volume of the inlet reservoir.

$$q_{inlet}^{Cl^-} = c_{inlet}^{Cl^-} V_{inlet} zF \tag{21}$$

where $q_{inlet}^{Cl^-}$ is the charge of the chlorine ions and $c_{inlet}^{Cl^-}$ is the concentration of the chlorine ions. The charge of the chlorine ions in the inlet reservoir are 0.097 C.

Space Charge Density of the Chlorine Ions in the Inlet Reservoir:
The space charge density of the chlorine ions is calculated from the charge of the chlorine ions and the volume of the inlet reservoir.

$$\rho_{q}{}_{inlet}^{Cl^-} = \frac{q_{inlet}^{Cl^-}}{V_{inlet}} \tag{22}$$

where $\rho_{q}{}_{inlet}^{Cl^-}$ is the space charge density of the chlorine ions. The space charge density of the chlorine ions in the inlet reservoir is 9700 C/m^3.

Charge of the KCl in the Inlet Reservoir:
We calculate the charge of the KCl

$$q_{inlet}^{KCl} = q_{inlet}^{K^+} + q_{inlet}^{Cl^-}$$

where q_{inlet}^{KCl} is the charge of the KCl. The charge is 0.194 C.

Space Charge Density of the KCl in the Inlet Reservoir:

The space charge density of the KCl is calculated from the charge and the volume of the inlet reservoir.

$$\rho_{q_{inlet}}^{KCl} = \frac{q_{inlet}^{KCl}}{V_{inlet}} \tag{23}$$

where $\rho_{q_{inlet}}^{KCl}$ is the space charge density of the KCl. The space charge density in the inlet reservoir is 19400 C/m^3.

Mass of The Potassium Ions in The Inlet Reservoir:
The mass of the potassium ions is calculated from the mole of the potassium ions and the atomic mass of the potassium. The atomic mass of potassium is 39.1 g/mol.

$$m_{inlet}^{K^+} = mole_{inlet}^{K^+} \times atomic\ mass\ of\ potassium \tag{24}$$

where $m_{inlet}^{K^+}$ is the mass of the potassium ions and $mole_{inlet}^{K^+}$ is the mole of the potassium ions.

Mole of the Potassium Ions in the Inlet Reservoir:
The mole of the potassium ions are from the concentration of the potassium ions and the volume.

$$mole_{inlet}^{K^+} = c_{inlet}^{K^+} V_{inlet} \tag{25}$$

The mole of the potassium ions in the inlet reservoir is 10^{-6} mol. The mass of the potassium ions is 3.9×10^{-8} kg.

Number of the Potassium Ions in the Inlet Reservoir:
The number of the potassium ions are from the mole of the potassium ions and Avogadro number.

$$N_{inlet}^{K^+} = mole_{inlet}^{K^+} N_{Avogadro} \tag{26}$$

where $N_{inlet}^{K^+}$ are the number of the potassium ions. The number of the potassium ions in the inlet reservoir are 6×10^{17} elements.

Mass of the Chlorine Ions in the Inlet Reservoir:
The mass of the chlorine ions is calculated from the mole of the chlorine ions and the atomic mass of the chlorine. The atomic mass of chlorine is 35.5 g/mol.

$$m_{inlet}^{Cl^-} = mole_{inlet}^{Cl^-} \times atomic\ mass\ of\ chlorine \tag{27}$$

where $m_{inlet}^{Cl^-}$ is the mass of the chlorine ions and $mole_{inlet}^{Cl^-}$ is the mole of the chlorine ions.

Mole of the Chlorine Ions in the Inlet Reservoir:
The mole of the chlorine ions is calculated from the concentration of the chlorine ions and the volume.

$$mole_{inlet}^{Cl^-} = c_{inlet}^{Cl^-} V_{inlet} \tag{28}$$

The mole of the chlorine ions is 10^{-6} mol. The mass of the chlorine ions is 3.6×10^{-8} kg.

Number of the Chlorine Ions in the Inlet Reservoir:
The number of the chlorine ions is calculated from the mole of the chlorine ions and Avogadro number.

$$N_{inlet}^{Cl^-} = mole_{inlet}^{Cl^-} N_{Avogadro} \tag{29}$$

where $N_{inlet}^{Cl^-}$ is the number of the chlorine ions. The number of the chlorine ions in the inlet reservoir are 6×10^{17} elements.

Mass of the KCl in the Inlet Reservoir:
The mass of the KCl in the inlet reservoir is calculated as,

$$m_{inlet}^{KCl} = m_{inlet}^{K^+} + m_{inlet}^{Cl^-} \tag{30}$$

where m_{inlet}^{KCl} is the mass of the KCl. The mass of the KCl in the inlet reservoir is 7.5×10^{-8} kg.

Mole of the KCl in the Inlet Reservoir:
The mole of the KCl is calculated from the concentration and the volume.

$$mole_{inlet}^{KCl} = c_{inlet}^{KCl} V_{inlet} \tag{31}$$

where $mole_{inlet}^{KCl}$ is the mole of the KCl. c_{inlet}^{KCl} is the concentration of the KCl in the inlet reservoir. The mole of the KCl in the inlet reservoir is 2×10^{-6} mol.

Number of the KCl in the Inlet Reservoir:
The number of the KCl is calculated from the mole and Avogadro number.

$$N_{inlet}^{KCl} = mole_{inlet}^{KCl} N_{Avogadro} \tag{32}$$

where N_{inlet}^{KCl} is the number of the KCl. The number of the KCl are 12×10^{17} elements. Here the parameters of the KCl in the outlet reservoir are same as the inlet reservoir.

Parameters of KCl Inside the Single Nanochannel
Gouy-Chapman Equation:

Here we consider the surface potential of the membrane having single nanochannel is 0.052 V. We use the Gouy-Chapman equation to understand the concentration of the potassium ions, chlorine ions and the concentration of the potassium chloride electrolyte inside the nanochannel [11]. Gouy-Chapman equation relates the interaction between the membrane having single nanochannel in contact with the potassium chloride electrolyte solution, potassium ions and the chlorine ions inside the single nanochannel as given in Eq. 33 and Eq. 34, respectively.

Concentration of the Potassium Ions Inside the Nanochannel

$$c_{nanochannel}^{K^+} = c_{inlet}^{K^+} \exp\left(\frac{\zeta_{membrane} ze}{k_B T}\right) \tag{33}$$

where $c_{nanochannel}^{K^+}$ is the concentration of the potassium ions inside the nanochannel. We assume $\zeta_{membrane} = 0.052$ V is the surface potential of the membrane having single nanochannel. z is the valence, e is the electronic charge, k_B is the Boltzmann constant and T is the temperature. The numerical constants and parameter values used in the study are given in Table 2. The concentration of the potassium ions inside the nanochannel is 0.75 mM. The parameters of the KCl for membrane having single nanochannel with surface potential of 0.052 V are given in Table 7.

Table 7. Parameters of the KCl list 1 for membrane with surface potential $\zeta_{membrane} = 0.052\ V$. The membrane has single nanochannel, single nanopore, respectively integrated to source and sink outlet reservoirs.

Numerical values	**inlet/outlet**	**nanochannel**	**nanopore**
atomic mass of potassium ions	39.1 g/mol	39.1 g/mol	39.1 g/mol
atomic mass of chlorine ions	35.5 g/mol	35.5 g/mol	35.5 g/mol
concentration of the potassium ions	0.1 mM	0.75 mM	0.75 mM
concentration of the chlorine ions	0.1 mM	0.06 mM	0.06 mM
concentration of KCl	0.2 mM	0.81 mM	0.81 mM
mole of the potassium ions	10^{-6} mol	1.2×10^{-13} mol	2.6×10^{-21} mol
mole of the chlorine ions	10^{-6} mol	9×10^{-15} mol	2.1×10^{-22} mol
mole of the KCl	2×10^{-6} mol	1.2×10^{-13} mol	2.8×10^{-21} mol

Concentration of the Chlorine Ions Inside the Nanochannel:

$$c_{nanochannel}^{Cl^-} = c_{inlet}^{Cl^-} \exp\left(\frac{\zeta_{membrane}(-z)e}{k_B T}\right) \tag{34}$$

where $c_{nanochannel}^{Cl^-}$ is the concentration of the chlorine ions inside the nanochannel. The concentration of the chlorine ions inside the nanochannel is 0.06 mM.

Concentration of KCl Inside the Nanochannel

$$c_{nanochannel}^{KCl} = c_{nanochannel}^{K^+} + c_{nanochannel}^{Cl^-}$$

where $c_{nanochannel}^{KCl}$ is the concentration of KCl inside the nanochannel. The concentration of the KCl inside the nanochannel is 0.81 mM.

Charge of the Potassium Ions Inside the Nanochannel:
The charge of the potassium ions inside the nanochannel is calculated from the concentration of the potassium ions inside the nanochannel, valence of the potassium ions and the volume of the nanochannel.

$$q_{nanochannel}^{K^+} = c_{nanochannel}^{K^+} zFV_{nanochannel} \tag{35}$$

where $q_{nanochannel}^{K^+}$ is the charge of the potassium ions inside the nanochannel. $V_{nanochannel}$ is the volume of the nanochannel. The charge of the potassium ions inside the nanochannel is 1.1×10^{-8} C.

Space Charge Density of the Potassium Ions Inside the Nanochannel:
The space charge density of the potassium ions inside the nanochannel is calculated from the charge of the potassium ions inside the nanochannel and the volume of the nanochannel.

$$\rho_{q_{nanochannel}}^{K^+} = \frac{q_{nanochannel}^{K^+}}{V_{nanochannel}} \tag{36}$$

where $\rho_{q_{nanochannel}}^{K^+}$ is the space charge density of the potassium ions inside the nanochannel. The space charge density of the potassium ions inside the nanochannel is 71334 C/m^3.

charge of the chlorine ions inside the nanochannel
The charge of the chlorine ions inside the nanochannel is calculated from the concentration of the chlorine ions inside the nanochannel and the volume of the nanochannel.

$$q_{nanochannel}^{Cl^-} = c_{nanochannel}^{Cl^-} zFV_{nanochannel} \tag{37}$$

where $q_{nanochannel}^{Cl^-}$ is the charge of the chlorine ions inside the nanochannel. The charge of the chlorine ions inside the nanochannel is 8.7×10^{-10} C.

Space Charge Density of the Chlorine Ions Inside the Nanochannel:
The space charge density of the chlorine ions inside the nanochannel is calculated from the charge of the chlorine ions inside the nanochannel and the volume of the nanochannel.

$$\rho_{q\,nanochannel}^{\;Cl^-} = \frac{q_{nanochannel}^{Cl^-}}{V_{nanochannel}} \tag{38}$$

where ${\rho_q}^{Cl^-}_{nanochannel}$ is the space charge density of the chlorine ions inside the nanochannel. The space charge density of the chlorine ions inside the nanochannel is 5787 C/m³.

Charge of KCl Inside the Nanochannel:

$$q^{KCl}_{nanochannel} = q^{K^+}_{nanochannel} + q^{Cl^-}_{nanochannel}$$

where $q^{KCl}_{nanochannel}$ nanochannel is the charge of KCl inside the nanochannel. The charge of the KCl inside the nanochannel is 1.2×10^{-8} C.

Space Charge Density of KCl Inside the Nanochannel:

The space charge density of the potassium chloride electrolyte inside the nanochannel is calculated from the charge of the potassium chloride electrolyte inside the nanochannel and the volume of the nanochannel.

$$ {\rho_q}^{KCl}_{nanochannel} = \frac{q^{KCl}_{nanochannel}}{V_{nanochannel}} \quad (39)$$

where ${\rho_q}^{KCl}_{nanochannel}$ nanochannel is the space charge density of the potassium chloride electrolyte inside the nanochannel. The space charge density of the potassium chloride electrolyte inside the nanochannel is 77121 C/m³. The parameters of the potassium chloride electrolyte solution for membrane having single nanochannel with surface potential ζmembrane = 0.052 V are given in Table 8.

Table 8. Parameters of the KCl list 2 for membrane with surface potential $\zeta_{membrane} = 0.052\ V$. The membrane has single nanochannel, single nanopore, respectively integrated to source inlet and sink outlet reservoirs.

Numerical values	inlet/outlet	nanochannel	nanopore
charge of the potassium ions	0.097 C	$1.1 \times 10^{-8} C$	2.5×10^{-16} C
charge of the chlorine ions	0.097 C	8.7×10^{-10}C	$2 \times 10^{-17} C$
charge of the KCl	0.194 C	1.2×10^{-8} C	$2.7 \times 10^{-16} C$
space charge density of the potassium ions	9700 C/m³	71334 C/m³	71388 C/m³
space charge density of the chlorine ions	9700 C/m³	5787 C/m³	5807 C/m³
space charge density of the KCl	19400 C/m³	77121 C/m³	77196 C/m³
mobility	-	3.7×10^{-8} (Am/N)	3.7×10^{-8} (Am/N)
velocity (Smoluchowski model)	-	7.3 mm/s	7.3 mm/s
velocity (assumed)	-	12.7 mm/s	12.7 mm/s
acceleration (assumed)	-	50 mm/s²	50 mm/s²

Smoluchowski Model to Calculate the Velocity of the Potassium Chloride Electrolyte

The velocity of the potassium chloride electrolyte solution inside the nanochannel is calculated from the Smoluchowski model [11].

$$u_{nanochannel} = -\mu_E E_{nanochannel} \quad (40)$$

where $u_{nanochannel}$ is the velocity of the potassium chloride electrolyte solution inside the nanochannel, μ_E is the mobility of the potassium chloride electrolyte solution inside the nanochannel.

$$E_{nanochannel} = -\frac{\Delta V}{L_{nanochannel}} \quad (41)$$

where $E_{nanochannel}$ is the electric field inside the nanochannel, V is the applied voltage between the reservoirs. $L_{nanochannel}$ is the length of the nanochannel. The length of the nanochannel is 5 µm. Here the applied voltage is 1 V. Also $\Delta V = 1$ V.

Mobility of the Potassium Chloride Electrolyte:
The mobility of the potassium chloride electrolyte solution inside the nanochannel is calculated from the relative permittivity of water, surface potential of the membrane having single nanochannel and viscosity of the water.

$$\mu_E = \frac{\epsilon_{water}\epsilon_0\zeta_{membrane}}{\mu} \quad (42)$$

where ϵ_{water} is the relative permittivity of the water, ϵ_0 is the permittivity of free space and μ is the viscosity of the water. The numerical constants and parameter values used in the study are given in Table 2.

The mobility of the potassium chloride electrolyte inside the nanochannel is 3.7×10^{-8} (Am/N). The velocity of the potassium chloride electrolyte solution inside the nanochannel is 7.3 mm/s. In order to calculate the velocity of the potassium chloride electrolyte solution at each grid location inside the nanochannel we consider 25 grid points. The electric field inside the nanochannel varies between 0.1 $E_{nanochannel}$ near the wall of the nanochannel and $E_{nanochannel}$ at the center of the nanochannel. The electric field is assumed to be symmetric so that the velocity is parabolic inside the nanochannel. The calculated velocity of the potassium chloride electrolyte solution inside nanochannel is in accordance with the literature [46, 47].

Current of the Potassium Ions Inside the Nanochannel:
The current of the potassium ions inside the nanochannel is calculated by Eq. 43,

$$I_{nanochannel}^{K^+} = \frac{u_{nanochannel}q_{nanochannel}^{K^+}}{L_{nanochannel}} + \frac{m_{nanochannel}^{K^+}a_{nanochannel}u_{nanochannel}}{Voltage} \quad (43)$$

where $I_{nanochannel}^{K^+}$ is the current of the potassium ions inside the nanochannel. $u_{nanochannel} =$ 12.7 mm/s is the assumed velocity of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel, $a_{nanochannel} = 50$ mm/s^2 is the assumed acceleration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel. $m_{nanochannel}^{K^+}$ is the mass of the potassium ions inside the nanochannel.

Mass of The Potassium Ions Inside the Nanochannel:
The mass of the potassium ions inside the nanochannel is calculated from the mole of the potassium ions inside the nanochannel and the atomic mass of the potassium.

$$m_{nanochannel}^{K^+} = mole_{nanochannel}^{K^+} \times atomic\ mass\ of\ potassium \tag{44}$$

where $mole_{nanochannel}^{K^+}$ is the mole of the potassium ions inside the nanochannel.

Mole of the Potassium Ions Inside the Nanochannel:
The mole of the potassium ions inside the nanochannel is calculated from the concentration of the potassium ions inside the nanochannel and the volume of the nanochannel.

$$mole_{nanochannel}^{K^+} = c_{nanochannel} V_{nanochannel} \tag{45}$$

The mole of the potassium ions inside the nanochannel is 1.1×10^{-13} mol. The mass of the potassium ions inside the nanochannel is 4.3×10^{-15} kg. The current of the potassium ions inside the nanochannel is calculated from Eq. 43. The current of the potassium ions inside the nanochannel is 27.7 µA. The current of the potassium ions inside the nanochannel match the literature [25]. The parameters of the potassium chloride electrolyte solution for membrane having single nanochannel with surface potential of 0.052 V are given in Table 9.

Table 9. Parameters of the KCl list 3 for membrane with surface potential $\zeta_{membrane} = 0.052\ V$. The membrane has single nanochannel, single nanopore, respectively integrated to source inlet and sink outlet reservoirs.

Numerical values	inlet/outlet	nanochannel	nanopore
number of potassium ions	6×10^{17}	67×10^{9}	1573
number of chlorine ions	6×10^{17}	54×10^{8}	128
number of KCl	12×10^{17}	73×10^{9}	1701
mass of potassium ions	3.9×10^{-8} kg	4.3×10^{-15} kg	10^{-22} kg
mass of chlorine ions	3.6×10^{-8} kg	3.2×10^{-16} kg	7.5×10^{-24} kg
mass of KCl	7.5×10^{-8} kg	4.7×10^{-15} kg	1.08×10^{-22} kg
applied voltage	1 V	-	-
current of the potassium ions	-	27.7 µA	0.63 pA
current of the chlorine ions	-	2.3 µA	0.05 pA
current of the KCl		30 µA	0.68 pA

Number of the Potassium Ions Inside the Nanochannel:
The number of the potassium ions inside the nanochannel is calculated from the mole of the potassium ions and Avogadro number.

$$N_{nanochannel}^{K^+} = mole_{nanochannel}^{K^+} N_{Avogadro} \tag{46}$$

where $N_{nanochannel}^{K^+}$ is the number of the potassium ions inside the nanochannel. The number of the potassium ions inside the nanochannel is 67×10^9 elements. Fig. 2 shows the schematic representation of the number of potassium ions inside the single nanochannel.

Current of the Chlorine Ions Inside the Nanochannel:

The current of the chlorine ions inside the nanochannel is,

$$I_{nanochannel}^{Cl^-} = \frac{u_{nanochannel} q_{nanochannel}^{Cl^-}}{L_{nanochannel}} + \frac{m_{nanochannel}^{Cl^-} a_{nanochannel} u_{nanochannel}}{Voltage} \tag{47}$$

where $I_{nanochannel}^{Cl^-}$ is the current of the chlorine ions inside the nanochannel. $m_{nanochannel}^{Cl^-}$ is the mass of the chlorine ions inside the nanochannel.

Mass of the Chlorine Ions Inside the Nanochannel:

The mass of the chlorine ions inside the nanochannel is calculated from the mole of the chlorine ions inside the nanochannel and the atomic mass of the chlorine.

$$m_{nanochannel}^{Cl^-} = mole_{nanochannel}^{Cl^-} \times atomic\ mass\ of\ chlorine \tag{48}$$

where $mole_{nanochannel}^{Cl^-}$ is the mole of the chlorine ions inside the nanochannel.

Mole of the Chlorine Ions Inside the Nanochannel:

The mole of the chlorine ions inside the nanochannel is calculated from the concentration of the chlorine ions inside the nanochannel and the volume of the nanochannel.

$$mole_{nanochannel}^{Cl^-} = c_{nanochannel}^{Cl^-} V_{nanochannel} \tag{49}$$

The mole of the chlorine ions inside the nanochannel is 9×10^{-15} mol. The mass of the chlorine ions inside the nanochannel is 3.2×10^{-16} kg. We obtain the current of the chlorine ions inside the nanochannel is 2.3 μA.

Number of the Chlorine Ions Inside the Nanochannel:

The number of the chlorine ions inside the nanochannel is calculated from the mole of the chlorine ions and Avogadro number.

$$N_{nanochannel}^{Cl^-} = mole_{nanochannel}^{Cl^-} N_{Avogadro} \tag{50}$$

where $N_{nanochannel}^{Cl^-}$ is the number of the chlorine ions inside the nanochannel. The number of the chlorine ions inside the nanochannel is 54×10^8 elements. Fig. 2 shows the schematic representation of the number of the chlorine ions inside the single nanochannel.

Current of the Potassium Chloride Electrolyte Solution Inside the Nanochannel:
The current of the potassium chloride electrolyte solution inside the nanochannel is,

$$I_{nanochannel}^{KCl} = I_{nanochannel}^{K^+} + I_{nanochannel}^{Cl^-} \tag{51}$$

where $I_{nanochannel}^{KCl}$ is the current of the potassium chloride electrolyte solution inside the nanochannel. The current of the potassium chloride electrolyte solution inside the nanochannel is 30 μA.

Mass of the Potassium Chloride Electrolyte Solution Inside the Nanochannel:
The mass of the potassium chloride electrolyte solution inside the nanochannel is calculated as the sum of the mass of the potassium ions and mass of the chlorine ions inside the nanochannel. The mass of KCl ($m_{nanochannel}^{KCl}$) inside the nanochannel is 4.7×10^{-15} kg.

Mole of KCl Inside the Nanochannel:
The mole of the KCl inside the nanochannel is,

$$mole_{nanochannel}^{KCl} = mole_{nanochannel}^{K^+} + mole_{nanochannel}^{Cl^-}$$

where $mole_{nanochannel}^{KCl}$ is the mole of the KCl inside the nanochannel. The mole of KCl solution inside the nanochannel is 1.2×10^{-13} mol.

Number of KCl Inside the Nanochannel:
The number of the KCl inside the nanochannel is,

$$N_{nanochannel}^{KCl} = N_{nanochannel}^{K^+} + N_{nanochannel}^{Cl^-}$$

where $N_{nanochannel}^{KCl}$ is the number of KCl inside the nanochannel. The number KCl inside the nanochannel is 73×10^{9} elements. Fig. 2 shows the schematic representation of the number of KCl inside the single nanochannel. Here we assume the relative permittivity of the membrane having single nanochannel is 2.6. $\epsilon_{nanochannel}^{membrane}$ is the relative permittivity of the membrane having single nanochannel.

Membrane Parameters Having Single Nanopore
The length of the membrane having single nanopore is 5μm, width is 1 m and height is 1μm. The volume of the membrane having single nanopore $V_{nanopore}^{membrane}$ is 5×10^{-12} m^3. Here we consider the concentration of the membrane having single nanopore $c_{nanopore}^{membrane}$ is 0.1 mM. Further the length of the nanopore is 5 μm and the diameter of the nanopore is 30 nm. The volume of the nanopore is $V_{nanopore}$ is 3.6×10^{-21} m^3. The inlet concentration of the potassium ions is 0.1 mM, chlorine ions is 0.1 mM and concentration of potassium chloride electrolyte solution is 0.2 mM. The membrane parameters having single nanopore integrated to source inlet, sink outlet reservoirs are given in Table 5 and Table 6, respectively. The number of membrane elements are calculated.

Number of Elements of the Membrane Having Single Nanopore:

$$N_{membrane}^{nanopore} = mole_{membrane}^{nanopore} N_{Avogadro} \tag{52}$$

where $N_{membrane}^{nanopore}$ are the number of elements of the membrane having single nanopore. $mole_{membrane}^{nanopore}$ is the mole of the membrane having single nanopore.

Mole of the Membrane Material Having Single Nanopore:
The mole of the membrane material having single nanopore is calculated from the concentration and the volume of the membrane having single nanopore.

$$mole_{membrane}^{nanopore} = c_{membrane}^{nanopore} V_{membrane}^{nanopore} \tag{53}$$

The mole of the membrane material having single nanopore is 5×10^{-13} mol. The number of the membrane elements having single nanopore are 3×10^{11} elements. Fig. 3 shows the schematic representation of the structure of the membrane having single nanopore. The number of membrane elements are represented in the Fig. 3.

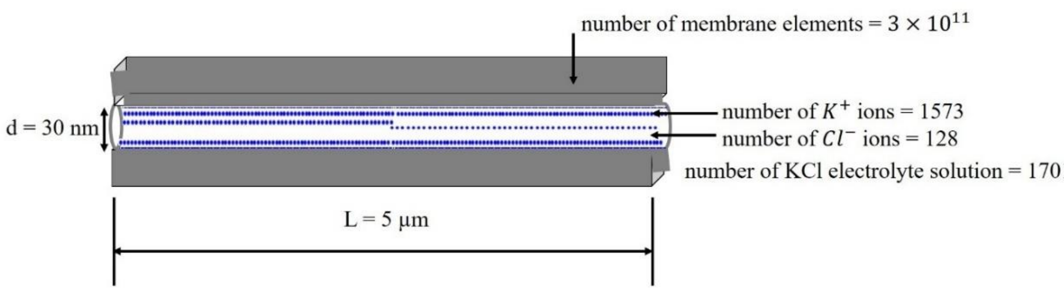


Figure 3. Schematic representation of membrane having single nanopore. The membrane material is represented in gray color. Schematic representation of the structure of the KCl inside the nanopore.

Mass of the Membrane Having Single Nanopore:
The mass of the membrane having single nanopore is calculated from the mole and the atomic mass of the membrane having single nanopore.

$$m_{membrane}^{nanopore} = mole_{membrane}^{nanopore} \times atomic\ mass\ of\ the\ membrane\ material \tag{54}$$

where $m_{membrane}^{nanopore}$ is the mass of the membrane having single nanopore. Here we consider the atomic mass of the membrane having single nanopore is 140.28 g/mol. The mass of the membrane having single nanopore is 7×10^{-14} kg.

Charge of the Membrane Having Single Nanopore:
The charge of the membrane having single nanopore is calculated from the concentration of the membrane having single nanopore, valence of the membrane material and the volume of the membrane having single nanopore.

$$q_{membrane}^{nanopore} = c_{membrane}^{nanopore} z_{membrane} F V_{membrane}^{nanopore} \tag{55}$$

where $q_{membrane}^{nanopore}$ is the charge of the membrane having single nanopore, $z_{membrane}$ is the valence of the membrane having single nanopore. The charge of the membrane having single nanopore is 3.4×10^{-7} C.

Parameters of the Potassium Chloride Electrolyte Solution Inside the Single Nanopore
Gouy-Chapman Equation for Nanopore
The Gouy-Chapman equation gives the relation between the surface potential of the membrane having single nanopore with the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanopore.

concentration of the potassium ions inside the nanopore

$$c_{nanopore}^{K^+} = c_{inlet}^{K^+} \exp\left(\frac{\zeta_{membrane} z e}{k_B T}\right) \tag{56}$$

where $c_{nanopore}^{K^+}$ is the concentration of the potassium ions inside the nanopore. We assume surface potential is 0.052 V. The concentration of the potassium ions inside the nanopore is 0.75 mM.

Concentration of the Chlorine Ions Inside the Nanopore:

$$c_{nanopore}^{Cl^-} = c_{inlet}^{Cl^-} \exp\left(\frac{\zeta_{membrane}(-z)e}{k_B T}\right) \tag{57}$$

where $c_{nanopore}^{Cl^-}$ is the concentration of the chlorine ions inside the nanopore. The concentration of the chlorine ions inside the nanopore is 0.06 mM.

Concentration of the Potassium Chloride Electrolyte Solution Inside the Nanopore:

$$c_{nanopore}^{KCl} = c_{nanopore}^{K^+} + c_{nanopore}^{Cl^-}$$

where $c_{nanopore}^{KCl}$ is the concentration of the potassium chloride electrolyte solution inside the nanopore. The concentration of the potassium chloride electrolyte solution inside the nanopore is 0.81 mM.

Charge of the Potassium Ions Inside the Nanopore:
The charge of the potassium ions inside the nanopore is calculated from the concentration of the potassium ions inside the nanopore, valence of the potassium ions and the volume of the nanopore.

$$q_{nanopore}^{K^+} = c_{nanopore}^{K^+} z F V_{nanopore} \tag{58}$$

where $q_{nanopore}^{K^+}$ is the charge of the potassium ions inside the nanopore. The charge of the potassium ions inside the nanopore is 2.5×10^{-16} C.

Space Charge Density of the Potassium Ions Inside the Nanopore:
The space charge density of the potassium ions inside the nanopore is calculated from the charge of the potassium ions inside the nanopore and the volume of the nanopore.

$$\rho_{q_{nanopore}}^{K^+} = \frac{q_{nanopore}^{K^+}}{V_{nanopore}} \tag{59}$$

where $\rho_{q_{nanopore}}^{K^+}$ is the space charge density of the potassium ions inside the nanopore. The space charge density of the potassium ions inside the nanopore is 71388 C/m^3.

Charge of the Chlorine Ions Inside the Nanopore:
The charge of the chlorine ions inside the nanopore is calculated from the concentration of the chlorine ions inside the nanopore and the volume of the nanopore.

$$q_{nanopore}^{Cl^-} = c_{nanopore}^{Cl^-} zFV_{nanopore} \tag{60}$$

where $q_{nanopore}^{Cl^-}$ is the charge of the chlorine ions inside the nanopore. The charge of the chlorine ions inside the nanopore is 2.05×10^{-17} C.

Space Charge Density of The Chlorine Ions Inside the Nanopore:
The space charge density of the chlorine ions inside the nanopore is calculated from the charge of the chlorine ions inside the nanopore and the volume of the nanopore.

$$\rho_{q_{nanopore}}^{Cl^-} = \frac{q_{nanopore}^{Cl^-}}{V_{nanopore}} \tag{61}$$

where $\rho_{q_{nanopore}}^{Cl^-}$ is the space charge density of the chlorine ions inside the nanopore. The space charge density of the chlorine ions inside the nanopore is 5807 C/m^3.

Charge of KCl Inside the Nanopore:

$$q_{nanopore}^{KCl} = q_{nanopore}^{K^+} + q_{nanopore}^{Cl^-}$$

where $q_{nanopore}^{KCl}$ is the charge of KCl inside the nanopore. The charge of KCl inside the nanopore is 2.7×10^{-16} C.

Space Charge Density of KCl Inside the Nanopore:
The space charge density of KCl inside the nanopore is calculated from the charge of KCl and the volume of the nanopore.

$$\rho_{q}{}^{KCl}_{nanopore} = \frac{q^{KCl}_{nanopore}}{V_{nanopore}} \quad (62)$$

where $\rho_{q}{}^{KCl}_{nanopore}$ is the space charge density of KCl inside the nanopore. The space charge density of KCl inside the nanopore is 77196 C/m^3.

Smoluchowski Model to Calculate the Velocity of the Potassium Chloride Electrolyte

The velocity of the potassium chloride electrolyte solution inside the nanopore is calculated from the Smoluchowski model [11].

$$u_{nanopore} = -\mu_E E_{nanopore} \quad (63)$$

where $u_{nanopore}$ is the velocity of the potassium chloride electrolyte solution inside the nanopore, μ_E is the mobility of the potassium chloride electrolyte solution inside the nanopore.

$$E_{nanopore} = -\frac{\Delta V}{L_{nanopore}} \quad (64)$$

where $E_{nanopore}$ is the electric field inside the nanopore and V is the applied voltage. $L_{nanopore}$ is the length of the nanopore. The length of the nanopore is 5μm. We consider applied voltage = 1 V. We consider $\Delta V = 1$ V.

Mobility of the Potassium Chloride Electrolyte:

$$\mu_E = \frac{\epsilon_{water}\epsilon_0\zeta_{membrane}}{\mu} \quad (65)$$

We consider the surface potential of the membrane having single nanopore is 0.052 V. The mobility of the potassium chloride electrolyte inside the nanopore is 3.7×10^{-8} (Am/N). The velocity of KCl inside the nanopore is 7.3 mm/s.

Current of the Potassium Ions Inside the Nanopore:

$$I^{K^+}_{nanopore} = \frac{u_{nanopore}q^{K^+}_{nanopore}}{L_{nanopore}} + \frac{m^{K^+}_{nanopore}a_{nanopore}u_{nanopore}}{Voltage} \quad (66)$$

where $I^{K^+}_{nanopore}$ is the current of the potassium ions inside the nanopore.

$u_{nanopore} = 12.7$ mm/s is the assumed velocity of the potassium ions, chlorine ions and KCl inside the nanopore. $a_{nanopore}$ = 50 mm/s^2 is the assumed acceleration of the potassium ions, chlorine ions and KCl inside the nanopore. $m^{K^+}_{nanopore}$ is the mass of the potassium ions inside the nanopore.

Mass of the Potassium Ions Inside the Nanopore:

$$m_{nanopore}^{K^+} = mole_{nanopore}^{K^+} \times atomic\ mass\ of\ potassium \tag{67}$$

where $mole_{nanopore}^{K^+}$ is the mole of the potassium ions inside the nanopore.

Mole of the Potassium Ions Inside the Nanopore:
The moles of the potassium ions inside the nanopore is calculated from the concentration of the potassium ions inside the nanopore and the volume of the nanopore.

$$mole_{nanopore}^{K^+} = c_{nanopore} V_{nanopore} \tag{68}$$

The mole of the potassium ions inside the nanopore is 2.6×10^{-21} mol. The mass of the potassium ions inside the nanopore is 10^{-22} kg. We obtain the ionic current of the potassium ions inside the nanopore is 0.63 pA.

Number of the Potassium Ions Inside the Nanopore:
The number of the potassium ions inside the nanopore is calculated from the mole of the potassium ions and Avogadro number.

$$N_{nanopore}^{K^+} = mole_{nanopore}^{K^+} N_{Avogadro} \tag{69}$$

where $N_{nanopore}^{K^+}$ is the number of the potassium ions inside the nanopore. The number of the potassium ions inside the nanopore are 1573 elements.

Fig. 3 shows the schematic representation of the number of potassium ions inside the nanopore.

Current of the Chlorine Ions Inside the Nanopore

$$I_{nanopore}^{Cl^-} = \frac{u_{nanopore} q_{nanopore}^{Cl^-}}{L_{nanopore}} + \frac{m_{nanopore}^{Cl^-} a_{nanopore} u_{nanopore}}{Voltage} \tag{70}$$

where $I_{nanopore}^{Cl^-}$ is the current of the chlorine ions inside the nanopore. $m_{nanopore}^{Cl^-}$ is the mass of the chlorine ions inside the nanopore.

Mass of the Chlorine Ions Inside the Nanopore:

$$m_{nanopore}^{Cl^-} = mole_{nanopore}^{Cl^-} \times atomic\ mass\ of\ chlorine \tag{71}$$

where $mole_{nanopore}^{Cl^-}$ is the mole of the chlorine ions inside the nanopore.

Mole of the Chlorine Ions Inside the Nanopore:

The mole of the chlorine ions inside the nanopore is calculated from the concentration of the chlorine ions inside the nanopore and the volume of the nanopore.

$$mole_{nanopore}^{Cl^-} = c_{nanopore}^{Cl^-} V_{nanopore} \tag{72}$$

The mole of the chlorine ions inside the nanopore is 2.1×10^{-22} mol. The mass of the chlorine ions inside the nanopore is 7.5×10^{-24} kg. The current of the chlorine ions inside the nanopore is 0.05 pA.

Number of the Chlorine Ions Inside the Nanopore:

The number of the chlorine ions inside the nanopore is calculated from the mole of the chlorine ions and Avogadro number.

$$N_{nanopore}^{Cl^-} = mole_{nanopore}^{Cl^-} N_{Avogadro} \tag{73}$$

where $N_{nanopore}^{Cl^-}$ is the number of the chlorine ions inside the nanopore. The number of the chlorine ions inside the nanopore is 128 elements. Fig. 3 shows the schematic representation of the number of the chlorine ions inside the single nanopore.

Current of KCl Inside the Nanopore:

$$I_{nanopore}^{KCl} = I_{nanopore}^{K^+} + I_{nanopore}^{Cl^-} \tag{74}$$

where $I_{nanopore}^{KCl}$ is the current of KCl inside the nanopore. The current of KCl inside the nanopore is 0.68 pA.

Mass of the Potassium Chloride Electrolyte Solution Inside the Nanopore:

The mass of the potassium chloride electrolyte solution ($m_{nanopore}^{KCl}$) inside the nanopore is calculated from the sum of the mass of the potassium ions and mass of the chlorine ions inside the nanopore. The mass of the potassium chloride electrolyte solution inside the nanopore is 1.08×10^{-22} kg.

Mole of KCl Inside the Nanopore:

The mole of KCl inside the nanopore is given.

$$mole_{nanopore}^{KCl} = mole_{nanopore}^{K^+} + mole_{nanopore}^{Cl^-}$$

where $mole_{nanopore}^{KCl}$ is the mole of KCl inside the nanopore. The mole of KCl inside the nanopore is 2.8×10^{-21} mol.

Number of the Potassium Chloride Electrolyte Solution Inside the Nanopore:

$$N_{nanopore}^{KCl} = N_{nanopore}^{K^+} + N_{nanopore}^{Cl^-}$$

where $N_{nanopore}^{KCl}$ is the number of the potassium chloride electrolyte solution inside the nanopore. The number of the potassium chloride electrolyte solution inside the nanopore is 1701 elements. Fig. 3 shows the schematic representation of the number of the potassium chloride electrolyte solution inside the single nanopore. We assume the relative permittivity of the nanopore membrane is 2.6.

COMPARATIVE ANALYSIS OF THE STRUCTURAL, TRANSPORT MECHANISMS OF NANOCHANNELS AND NANOPORES

Nanochannels

Here we study for different surface potential of the membrane having single nanochannel and single nanopore, respectively. The length of the nanochannel is 5 μm, width is 1 m and the height is 30 nm. The volume of the nanochannel $V_{nanochannel}$ is 1.5×10^{-13} m³. The membrane parameters having single nanochannel, single nanopore with different surface potential are given in the Table 10 and Table 11, respectively.

Table 10. Membrane parameters list 1 for surface potential $\zeta_{membrane} = 0.074\ V$, $\zeta_{membrane} = 0.1\ V$, respectively having single nanochannel and single nanopore. d is the diameter of the nanopore.

parameters	length	width	height	volume	concentration	moles
inlet	1 cm	1 m	1 mm	10^{-5} m³	-	-
outlet	1 cm	1 m	1 mm	10^{-5} m³	-	-
membrane to make nanochannel	5 μm	1 m	10 μm	10^{-10} m³	5×10^{-7} mM	5×10^{-17} mol
membrane to make nanopore	5 μm	1 m	1 μm	5×10^{-12} m³	0.1 mM	5×10^{-13} mol
nanochannel	5 μm	1 m	30 nm	1.5×10^{-13} m³	-	-
nanopore	5 μm	-	d = 30 nm	3.6×10^{-21} m³	-	-

Table 11. Membrane parameters list 2 for surface potential $\zeta_{membrane} = 0.074\ V$, $\zeta_{membrane} = 0.1\ V$, respectively having single nanochannel and single nanopore. $n_{elements}$ are the number of elements.

parameters	atomic mass	mass	$n_{elements}$	valence	$\epsilon(\zeta_{membrane}, charge)$
membrane to make nanochannel	140.28 g/mol	$7 \times 10^{-18} kg$	3×10^{7}	7	2.9 (0.074 V, $3.4 \times 10^{-11} C$)
membrane to make nanochannel	140.28 g/mol	$7 \times 10^{-18} kg$	3×10^{7}	7	4.3 (0.1 V, $3.4 \times 10^{-11} C$)
membrane to make nanopore	140.28 g/mol	$7 \times 10^{-14} kg$	3×10^{11}	7	2.9 (0.074 V, $3.4 \times 10^{-7} C$)
membrane to make nanopore	140.28 g/mol	$7 \times 10^{-14} kg$	3×10^{11}	7	4.3 (0.1 V, $3.4 \times 10^{-7} C$)

Gouy-Chapman Equation for Nanochannel

We consider the surface potential of the membrane having single nanochannel is 0.074 V. The inlet concentration of the potassium ions is 0.1 mM, chlorine ions is 0.1 mM and total concentration of potassium chloride electrolyte solution is 0.2 mM. The Gouy-Chapman equation gives the relation between the surface potential of the membrane having single nanochannel with the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel.

Concentration of the Potassium Ions Inside the Nanochannel:

$$c_{nanochannel}^{K^+} = c_{inlet}^{K^+} \exp\left(\frac{\zeta_{membrane} ze}{k_B T}\right) \tag{75}$$

where surface potential is 0.074 V. The concentration of the potassium ions inside the nanochannel is 1.75 mM. The parameters of the potassium chloride electrolyte solution for surface potential of the membrane having single nanochannel 0.074 V are given in Table 12.

Table 12. Parameters of the KCl list 1 for membrane with surface potential $\zeta_{membrane} = 0.074\ V$ and $\zeta_{membrane} = 0.1\ V$, respectively. The membrane has single nanochannel, single nanopore, respectively integrated to source inlet and sink outlet reservoirs.

Numerical values	inlet/outlet	nanochannel	nanopore
atomic mass of potassium ions	39.1 g/mol	39.1 g/mol	39.1 g/mol
atomic mass of chlorine ions	35.5 g/mol	35.5 g/mol	35.5 g/mol
concentration of the potassium ions	0.1 mM	1.75 mM (0.074 V)	1.75 mM (0.074 V)
concentration of the potassium ions	0.1 mM	4.8 mM (0.1 V)	4.8 mM (0.1 V)
concentration of the chlorine ions	0.1 mM	0.0058 mM (0.074 V)	0.0058 mM (0.074 V)
concentration of the chlorine ions	0.1 mM	0.002 mM (0.1 V)	0.002 mM (0.1 V)
concentration of the KCl	0.2 mM	1.76 mM (0.074 V)	1.76 mM (0.074 V)
concentration of the KCl	0.2 mM	4.8 mM (0.1 V)	4.8 mM (0.1 V)
mole of the potassium ions	10^{-6} mol	2.6×10^{-13} mol (0.074 V)	6.3×10^{-21} mol (0.074 V)
mole of the potassium ions	10^{-6} mol	7.2×10^{-13} mol (0.1 V)	1.7×10^{-20} mol (0.1 V)
mole of the chlorine ions	10^{-6} mol	8.7×10^{-16} mol (0.074 V)	2×10^{-23} mol (0.074 V)
mole of the chlorine ions	10^{-6} mol	3×10^{-16} mol (0.1 V)	7.4×10^{-24} mol (0.1 V)
mole of the KCl	2×10^{-6} mol	2.6×10^{-13} mol (0.074 V)	6.3×10^{-21} mol (0.074 V)
mole of KCl	2×10^{-6} mol	7.2×10^{-13} mol (0.1 V)	1.7×10^{-20} mol (0.1 V)

Concentration of the Chlorine Ions Inside the Nanochannel:

$$c_{nanochannel}^{Cl^-} = c_{inlet}^{Cl^-} \exp\left(\frac{\zeta_{membrane}(-z)e}{k_B T}\right) \tag{76}$$

The concentration of the chlorine ions inside the nanochannel is 0.0058 mM.

Concentration of KCl $\left(c_{nanochannel}^{KCl}\right)$ Inside the Nanochannel:

The concentration of the potassium chloride electrolyte solution inside the nanochannel is,

$$c_{nanochannel}^{KCl} = c_{nanochannel}^{K^+} + c_{nanochannel}^{Cl^-} = 1.76 \text{ mM}.$$

Charge of the Potassium Ions Inside the Nanochannel:
The charge of the potassium ions inside the nanochannel is calculated from the concentration of the potassium ions inside the nanochannel and the volume of the nanochannel.

$$q_{nanochannel}^{K^+} = c_{nanochannel}^{K^+} zFV_{nanochannel} \tag{77}$$

The charge of the potassium ions inside the nanochannel is 2.6×10^{-8} C.

Space Charge Density of the Potassium Ions Inside the Nanochannel:
The space charge density of the potassium ions inside the nanochannel is calculated from the charge of the potassium ions inside the nanochannel and the volume of the nanochannel. The space charge density of the potassium ions inside the nanochannel is 173334 C/m^3.

Charge of the Chlorine Ions Inside the Nanochannel:
The charge of the chlorine ions inside the nanochannel is calculated from the concentration of the chlorine ions inside the nanochannel and the volume of the nanochannel.

$$q_{nanochannel}^{Cl^-} = c_{nanochannel}^{Cl^-} zFV_{nanochannel} \tag{78}$$

The charge of the chlorine ions inside the nanochannel is 8.4×10^{-11} C.

Space Charge Density of the Chlorine Ions Inside the Nanochannel:
The space charge density of the chlorine ions inside the nanochannel is calculated from the charge of the chlorine ions inside the nanochannel and the volume of the nanochannel. The space charge density of the chlorine ions inside the nanochannel is 560 C/m^3.

Charge of KCl Inside the Nanochannel:
The charge of KCl inside the nanochannel,

$$q_{nanochannel}^{KCl} = q_{nanochannel}^{K^+} + q_{nanochannel}^{Cl^-} = 2.6 \times 10^{-8} \text{ C}.$$

Space Charge Density of KCl Inside the Nanochannel:
The space charge density of KCl inside the nanochannel is calculated from the charge of KCl inside the nanochannel and the volume of the nanochannel. The space charge density inside the nanochannel is 173894 C/m^3. The parameters of the potassium chloride electrolyte solution for surface potential of the membrane having single nanochannel 0.074 V are given in Table 13.

Table 13. Parameters of the KCl list 2 for membrane with surface potential $\zeta_{membrane} = 0.074\ V$ and $\zeta_{membrane} = 0.1\ V$, respectively. The membrane has single nanochannel, single nanopore, respectively integrated to source inlet and sink outlet reservoirs.

Numerical values	inlet/outlet	nanochannel	nanopore

charge of the potassium ions	0.097 C	2.6×10^{-8} C (0.074 V)	$6 \times 10^{-16} C$ (0.074 V)
charge of the potassium ions	0.097 C	7×10^{-8} C (0.1 V)	$1.6 \times 10^{-15} C$ (0.1 V)
charge of the chlorine ions	0.097 C	8.4×10^{-11} C (0.074 V)	2×10^{-18} C (0.074 V)
charge of the chlorine ions	0.097 C	3×10^{-11} C (0.1 V)	7.2×10^{-19} C (0.1 V)
charge of the KCl	0.194 C	$2.6 \times 10^{-8} C$ (0.074 V)	6×10^{-16} C (0.074 V)
charge of the KCl	0.194 C	7×10^{-8} C (0.1 V)	$1.6 \times 10^{-15} C$ (0.1 V)
space charge density of the potassium ions	9700 C/m³	173334 C/m³ (0.074 V)	166670 C/m³ (0.074 V)
space charge density of the potassium ions	9700 C/m³	4.7×10^{5} C/m³ (0.1 V)	4.5×10^{5} C/m³ (0.1 V)
space charge density of the chlorine ions	9700 C/m³	560 C/m³ (0.074 V)	556 C/m³ (0.074 V)
space charge density of the chlorine ions	9700 C/m³	200 C/m³ (0.1 V)	200 C/m³ (0.1 V)
space charge density of the KCl	19400 C/m³	173894 C/m³ (0.074 V)	167226 C/m³ (0.074 V)
space charge density of the KCl	19400 C/m³	4.7×10^{5} C/m³ (0.1 V)	4.5×10^{5} C/m³ (0.1 V)
mobility	-	5.3×10^{-8} (Am/N) (0.074 V)	5.3×10^{-8} (Am/N) (0.074 V)
mobility	-	7.1×10^{-8} (Am/N) (0.1 V)	7.1×10^{-8} (Am/N) (0.1 V)
velocity (Smoluchowski model)	-	10.5 mm/s (0.074 V)	10.5 mm/s (0.074 V)
velocity (assumed)	-	40 mm/s (0.074 V)	40 mm/s (0.074 V)
velocity (Smoluchowski model)	-	14.2 mm/s (0.1 V)	14.2 mm/s (0.1 V)
velocity (assumed)	-	60 mm/s (0.1 V)	60 mm/s (0.1 V)
acceleration (assumed)	-	120 mm/s² (0.074 V)	120 mm/s² (0.074 V)
acceleration (assumed)	-	180 mm/s² (0.1 V)	180 mm/s² (0.1 V)

Smoluchowski Model to Calculate the Velocity of the Potassium Chloride Electrolyte

$$u_{nanochannel} = -\mu_E E_{nanochannel} \tag{79}$$

$$E_{nanochannel} = \frac{-\Delta V}{L_{nanochannel}} \tag{80}$$

We consider applied voltage = 1 V. We consider ΔV = 1 V.

Mobility of KCl

$$\mu_E = \frac{\epsilon_{water}\epsilon_0\zeta_{membrane}}{\mu} \tag{81}$$

The mobility of KCl inside the nanochannel is 5.3×10^{-8} (Am/N). The velocity of KCl inside the nanochannel is 10.5 mm/s.

Current of the Potassium Ions Inside the Nanochannel:

$$I_{nanochannel}^{K^+} = \frac{u_{nanochannel} q_{nanochannel}^{K^+}}{L_{nanochannel}} + \frac{m_{nanochannel}^{K^+} a_{nanochannel} u_{nanochannel}}{Voltage} \quad (82)$$

We assume the velocity of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel is 40 mm/s. We assume is the acceleration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel is 120 mm/s^2.

Mass of the Potassium Ions Inside the Nanochannel:
The mass of the potassium ions inside the nanochannel is calculated from the mole of the potassium ions inside the nanochannel and the atomic mass of the potassium.

$$m_{nanochannel}^{K^+} = mole_{nanochannel}^{K^+} \times atomic\ mass\ of\ potassium \quad (83)$$

Mole of the Potassium Ions Inside the Nanochannel:
The mole of the potassium ions inside the nanochannel is calculated from the concentration of the potassium ions inside the nanochannel and the volume of the nanochannel.

$$mole_{nanochannel}^{K^+} = c_{nanochannel}^{K^+} V_{nanochannel} \quad (84)$$

The mole of the potassium ions inside the nanochannel is 2.6×10^{-13} mol. The mass of the potassium ions inside the nanochannel is 10^{-14} kg. The current of the potassium ions inside the nanochannel is 0.2 mA. The parameters of the potassium chloride electrolyte solution for surface potential of the membrane having single nanochannel 0.074 V are given in Table 14.

Table 14. Parameters of the KCl list 3 for membrane with surface potential $\zeta_{membrane} = 0.074\ V$ and $\zeta_{membrane} = 0.1\ V$, respectively. The membrane has single nanochannel, single nanopore, respectively integrated to source inlet and sink outlet reservoirs.

Numerical values	inlet/outlet	nanochannel	nanopore
number of potassium ions	6×10^{17}	16×10^{10} (0.074 V)	3795 (0.074 V)
number of potassium ions	6×10^{17}	44×10^{10} (0.1 V)	10239 (0.1 V)
number of chlorine ions	6×10^{17}	53×10^{7} (0.074 V)	13 (0.074 V)
number of chlorine ions	6×10^{17}	18×10^{7} (0.1 V)	5 (0.1 V)
number of KCl	12×10^{17}	16×10^{10} (0.074 V)	3808 (0.074 V)
number of KCl	12×10^{17}	44×10^{10} (0.1 V)	10244 (0.1 V)
mass of potassium ions	3.9×10^{-8} kg	10^{-14} kg (0.074 V)	2.5×10^{-22} kg (0.074 V)

mass of potassium ions	3.9×10^{-8} kg	2.8×10^{-14} kg (0.1 V)	6.7×10^{-22} kg (0.1 V)
mass of chlorine ions	3.6×10^{-8} kg	3×10^{-17} kg (0.074 V)	7×10^{-25} kg (0.074 V)
mass of chlorine ions	3.6×10^{-8} kg	1.1×10^{-17} kg (0.1 V)	2.6×10^{-25} kg (0.1 V)
mass of KCl	7.5×10^{-8} kg	10^{-14} kg (0.074 V)	2.5×10^{-22} kg (0.074 V)
mass of KCl	7.5×10^{-8} kg	2.8×10^{-14} kg (0.1 V)	6.7×10^{-22} kg (0.1 V)
applied voltage	1 V		
current of the potassium ions	-	0.2 mA (0.074 V)	4.8 pA (0.074 V)
current of the potassium ions	-	0.84 mA (0.1 V)	19.6 pA (0.1 V)
current of the chlorine ions	-	0.68 μA (0.074 V)	0.016 pA (0.074 V)
current of the chlorine ions	-	0.37 μA (0.1 V)	0.009 pA (0.1 V)
current of the KCl	-	0.2 mA (0.074 V)	4.8 pA (0.074 V)
current of the KCl	-	0.85 mA (0.1 V)	19.6 pA (0.1 V)

Number of the Potassium Ions Inside the Nanochannel:

The number of the potassium ions inside the nanochannel is calculated from the mole of the potassium ions and Avogadro number.

$$N_{nanochannel}^{K^+} = mole_{nanochannel}^{K^+} N_{Avogadro} \tag{85}$$

The number of the potassium ions inside the nanochannel is 16×10^{10} elements.

Current of the Chlorine Ions Inside the Nanochannel:

$$I_{nanochannel}^{Cl^-} = \frac{u_{nanochannel} q_{nanochannel}^{Cl^-}}{L_{nanochannel}} + \frac{m_{nanochannel}^{Cl^-} a_{nanochannel} u_{nanochannel}}{Voltage} \tag{86}$$

Mass of the Chlorine Ions Inside the Nanochannel:

The mass of the chlorine ions inside the nanochannel is calculated from the mole of the chlorine ions inside the nanochannel and the atomic mass of the chlorine.

$$m_{nanochannel}^{Cl^-} = mole_{nanochannel}^{Cl^-} \times atomic\ mass\ of\ chlorine \tag{87}$$

Mole of the Chlorine Ions Inside the Nanochannel:

The mole of the chlorine ions inside the nanochannel is calculated from the concentration of the chlorine ions inside the nanochannel and the volume of the nanochannel.

$$mole_{nanochannel}^{Cl^-} = c_{nanochannel}^{Cl^-} V_{nanochannel} \tag{88}$$

The mole of the chlorine ions inside the nanochannel is 8.7×10^{-16} mol. The mass of the chlorine ions inside the nanochannel is 3×10^{-17} kg. The current of the chlorine ions inside the nanochannel is 0.68 μA.

Number of the Chlorine Ions Inside the Nanochannel:
The number of the chlorine ions inside the nanochannel is calculated from the mole of the chlorine ions and Avogadro number.

$$N_{nanochannel}^{Cl^-} = mole_{nanochannel}^{Cl^-} N_{Avogadro} \tag{89}$$

The number of the chlorine ions inside the nanochannel is 53×10^{7} elements.

Current of KCl Inside the Nanochannel:
The current of the potassium chloride electrolyte solution inside the nanochannel,

$$I_{nanochannel}^{KCl} = I_{nanochannel}^{K^+} + I_{nanochannel}^{Cl^-} = 0.2\ mA$$

mass of the potassium chloride electrolyte solution inside the nanochannel

The mass of the potassium chloride electrolyte solution inside the nanochannel is calculated as the sum of the mass of the potassium ions and mass of the chlorine ions inside the nanochannel. The mass of the potassium chloride electrolyte solution inside the nanochannel is 10^{-14} kg.

Mole of KCl Inside the Nanochannel:
The mole of KCl inside the nanochannel is,

$$mole_{nanochannel}^{KCl} = mole_{nanochannel}^{K^+} + mole_{nanochannel}^{Cl^-}$$

The mole of KCl inside the nanochannel is 2.6×10^{-13} mol.

Number of KCl Inside the Nanochannel:
The number of KCl inside the nanochannel is,

$$N_{nanochannel}^{KCl} = N_{nanochannel}^{K^+} + N_{nanochannel}^{Cl^-}$$

The number of KCl inside the nanochannel are 16×10^{10} elements. We assume the relative permittivity of the membrane having single nanochannel is 2.9. The relative permittivity corresponds to surface potential of 0.074 V.

We consider the surface potential of the membrane having single nanochannel is 0.1 V. The inlet concentration of the potassium ions is 0.1 mM, chlorine ions is 0.1 mM and total concentration of potassium chloride electrolyte solution is 0.2 mM. The Gouy-Chapman equation gives the relation between the surface potential of the membrane having single nanochannel with the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel. The concentration of the potassium ions inside the nanochannel is 4.8 mM. The concentration of the chlorine ions inside the nanochannel is 0.002 mM. The concentration of the potassium chloride electrolyte solution inside the nanochannel is 4.8 mM. The charge of the potassium ions inside the nanochannel is calculated from the concentration of the potassium ions and the volume of the nanochannel. The charge of the potassium ions inside the nanochannel is 7×10^{-8} C. The space charge density of the potassium ions inside the nanochannel is 4.7×10^{5} C/m^3. The charge of the chlorine ions inside the nanochannel is calculated from the concentration of the chlorine ions and the volume of the nanochannel. The charge of the chlorine ions inside the nanochannel is 3×10^{-11} C. The space charge density of the chlorine ions inside the nanochannel is 200 C/m^3. The charge of the potassium chloride electrolyte solution inside the nanochannel is 7×10^{-8} C. The space charge density of KCl inside the nanochannel is 4.7×10^{5} C/m^3. The mole of the potassium ions inside the nanochannel is 7.2×10^{-13} mol. The mass of the potassium ions inside the nanochannel is 2.8×10^{-14} kg. The number of the potassium ions inside the nanochannel are 44×10^{10} elements. The velocity of the potassium chloride electrolyte solution inside the nanochannel is calculated from the Smoluchowski model [11]. The mobility of the potassium chloride electrolyte inside the nanochannel is 7.1×10^{-8} (Am/N). The velocity of the potassium chloride electrolyte solution inside the nanochannel is 14.2 mm/s. We assume the velocity of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel is 60 mm/s. We assume the acceleration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel is 180 mm/s^2. We obtain the ionic current of the potassium ions inside the nanochannel is 0.84 mA. The mole of the chlorine ions inside the nanochannel is 3×10^{-6} mol. The mass of the chlorine ions inside the nanochannel is 1.1×10^{-17} kg. The number of the chlorine ions inside the nanochannel are 18×10^{7} elements. We obtain the ionic current of the chlorine ions inside the nanochannel is 0.37 μA. The mole of KCl inside the nanochannel is 7.2×10^{-13} mol. The mass of KCl inside the nanochannel is 2.8×10^{-14} kg. The number of KCl inside the nanochannel are 44×10^{10} elements. The current of KCl inside the nanochannel is 0.85 mA. We assume the relative permittivity of the membrane having single nanochannel is 4.3. The relative permittivity corresponds to surface potential of 0.1 V.

Nanopores

The length of the nanopore is 5 μm and the diameter of the nanopore is 30 nm. The volume of the nanopore ($V_{nanopore}$) is 3.6×10^{-21} m^3.

Gouy-Chapman Equation for Nanopore:

We consider the surface potential of the membrane having single nanopore is 0.074 V. The inlet concentration of the potassium ions is 0.1 mM, chlorine ions is 0.1 mM and total concentration of potassium chloride electrolyte solution is 0.2 mM. The Gouy-Chapman equation gives the relation between the surface potential of the membrane having single nanopore with the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanopore.

Concentration of the Potassium Ions Inside the Nanopore:

$$c_{nanopore}^{K^+} = c_{inlet}^{K^+} \exp\left(\frac{\zeta_{membrane} ze}{k_B T}\right) \tag{90}$$

where $\zeta_{membrane}$ is 0.074 V. The concentration of the potassium ions inside the nanopore is 1.75 mM.

Concentration of the Chlorine Ions Inside the Nanopore:

$$c_{nanopore}^{Cl^-} = c_{inlet}^{Cl^-} \exp\left(\frac{\zeta_{membrane} (-z) e}{k_B T}\right) \tag{91}$$

The concentration of the chlorine ions inside the nanopore is 0.0058 mM.

concentration of KCl inside the nanopore

$$c_{nanopore}^{KCl} = c_{nanopore}^{K^+} + c_{nanopore}^{Cl^-}$$

The concentration of KCl inside the nanopore is 1.76 mM.

Charge of the Potassium Ions Inside the Nanopore:
The charge of the potassium ions inside the nanopore is calculated from the concentration of the potassium ions and the volume of the nanopore.

$$q_{nanopore}^{K^+} = c_{nanopore}^{K^+} zFV_{nanopore} \tag{92}$$

The charge of the potassium ions inside the nanopore is 6×10^{-16} C.

Space Charge Density of the Potassium Ions Inside the Nanopore:
The space charge density of the potassium ions inside the nanopore is calculated from the charge of the potassium ions inside the nanopore and the volume of the nanopore. The space charge density of the potassium ions inside the nanopore is 166670 C/m^3.

Charge of the Chlorine Ions Inside the Nanopore:
The charge of the chlorine ions inside the nanopore is calculated from the concentration of the chlorine ions and the volume of the nanopore.

$$q_{nanopore}^{Cl^-} = c_{nanopore}^{Cl^-} zFV_{nanopore} \tag{93}$$

The charge of the chlorine ions inside the nanopore is 2×10^{-18} C.

Space Charge Density of the Chlorine Ions Inside the Nanopore:

The space charge density of the chlorine ions inside the nanopore is calculated from the charge of the chlorine ions inside the nanopore and the volume of the nanopore. The space charge density of the chlorine ions inside the nanopore is 556 C/m^3.

Charge of KCl Inside the Nanopore:

The charge of KCl inside the nanopore is,

$$q_{nanopore}^{KCl} = q_{nanopore}^{K^+} + q_{nanopore}^{Cl^-} \tag{94}$$

The charge of KCl inside the nanopore is 6×10^{-16} C.

Space Charge Density of KCl Inside the Nanopore:

The space charge density of KCl inside the nanopore is calculated from the charge of KCl inside the nanopore and the volume of the nanopore. The space charge density of KCl inside the nanopore is 167226 C/m^3.

Smoluchowski Model to Calculate the Velocity of the Potassium Chloride Electrolyte:

The velocity of the potassium chloride electrolyte solution inside the nanopore is calculated from the Smoluchowski model [11].

$$u_{nanopore} = -\mu_E E_{nanopore} \tag{95}$$

$$E_{nanopore} = \frac{-\Delta V}{L_{nanopore}} \tag{96}$$

We consider applied voltage = 1 V. We consider ΔV = 1V.

Mobility of the Potassium Chloride Electrolyte:

$$\mu_E = \frac{\epsilon_{water}\epsilon_0\zeta_{membrane}}{\mu} \tag{97}$$

The mobility of KCl inside the nanopore is 5.3×10^{-8} (Am/N). The velocity of KCl inside the nanopore is 10.5 mm/s.

Current of the Potassium Ions Inside the Nanopore:

$$I_{nanopore}^{K^+} = \frac{u_{nanopore} q_{nanopore}^{K^+}}{L_{nanopore}} + \frac{m_{nanopore}^{K^+} a_{nanopore} u_{nanopore}}{Voltage} \tag{98}$$

where $u_{nanopore}$ is 40 mm/s. We assume acceleration is 120 mm/s^2.

Mass of the Potassium Ions Inside the Nanopore:

The mass of the potassium ions inside the nanopore is calculated from the mole of the potassium ions inside the nanopore and the atomic mass of the potassium.

$$m_{nanopore}^{K^+} = mole_{nanopore}^{K^+} \times atomic\ mass\ of\ potassium \tag{99}$$

Mole of the Potassium Ions Inside the Nanopore:
The mole of the potassium ions inside the nanopore is calculated from the concentration of the potassium ions inside the nanopore and the volume of the nanopore.

$$mole_{nanopore}^{K^+} = c_{nanopore}^{K^+} V_{nanopore} \tag{100}$$

The mole of the potassium ions inside the nanopore is 6.3×10^{-21} mol. The mass of the potassium ions inside the nanopore is 2.5×10^{-22} kg. The current of the potassium ions inside the nanopore is 4.8 pA.

Number of the Potassium Ions Inside the Nanopore:
The number of the potassium ions inside the nanopore is calculated from the mole of the potassium ions and Avogadro number.

$$N_{nanopore}^{K^+} = mole_{nanopore}^{K^+} N_{Avogadro} \tag{101}$$

The number of the potassium ions inside the nanopore is 3795 elements.

Current of the Chlorine Ions Inside the Nanopore:
The current of the chlorine ions inside the nanopore is,

$$I_{nanopore}^{Cl^-} = \frac{u_{nanopore} q_{nanopore}^{Cl^-}}{L_{nanopore}} + \frac{m_{nanopore}^{Cl^-} q_{nanopore} u_{nanopore}}{Voltage} \tag{102}$$

Mass of the Chlorine Ions Inside the Nanopore:

$$m_{nanopore}^{Cl^-} = mole_{nanopore}^{Cl^-} \times atomic\ mass\ of\ chlorine \tag{103}$$

Mole of the Chlorine Ions Inside the Nanopore:

$$mole_{nanopore}^{Cl^-} = c_{nanopore}^{Cl^-} V_{nanopore} \tag{104}$$

The mole of the chlorine ions inside the nanopore is 2×10^{-23} mol. The mass of the chlorine ions inside the nanopore is 7×10^{-25} kg. The current of the chlorine ions inside the nanopore is 0.016 pA.

Number of the Chlorine Ions Inside the Nanopore:

The number of the chlorine ions inside the nanopore is calculated from the mole of the chlorine ions and Avogadro number.

$$N_{nanopore}^{Cl^-} = mole_{nanopore}^{Cl^-} N_{Avogadro} \tag{105}$$

The number of the chlorine ions inside the nanopore is 13 elements.

Current of KCl Inside the Nanopore:
The current of KCl inside the nanopore is,

$$I_{nanopore}^{KCl} = I_{nanopore}^{K^+} + I_{nanopore}^{Cl^-}$$

The current of KCl inside the nanopore is 4.8 pA.

Mass of KCl Inside the Nanopore:
The mass of KCl inside the nanopore is calculated as the sum of the mass of the potassium ions and mass of the chlorine ions inside the nanopore. The mass of KCl inside the nanopore is 2.5×10^{-22} kg.

Mole of the Potassium Chloride Electrolyte Solution Inside the Nanopore:
The mole of the potassium chloride electrolyte solution inside the nanopore is given.

$$mole_{nanopore}^{KCl} = mole_{nanopore}^{K^+} + mole_{nanopore}^{Cl^-}$$

The mole of KCl inside the nanopore is 6.3×10^{-21} mol.

Number of KCl Inside the Nanopore:

$$N_{nanopore}^{KCl} = N_{nanopore}^{K^+} + N_{nanopore}^{Cl^-}$$

The number of the potassium chloride electrolyte inside the nanopore are 3808 elements. We assume the relative permittivity is 2.9. The relative permittivity corresponds to surface potential of 0.074 V. We consider the surface potential of the membrane having single nanopore is 0.1 V. The inlet concentration of the potassium ions is 0.1 mM, chlorine ions is 0.1 mM and total concentration of KCl is 0.2 mM. The Gouy-Chapman equation gives the relation between the surface potential of the membrane having single nanopore with the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanopore. The concentration of the potassium ions inside the nanopore is 4.8 mM. The concentration of the chlorine ions inside the nanopore is 0.002 mM. The concentration of the potassium chloride electrolyte solution inside the nanopore is 4.8 mM. The charge of the potassium ions inside the nanopore is calculated from the concentration of the potassium ions inside the nanopore and the volume of the nanopore. The charge of the potassium ions inside the nanopore is 1.6×10^{-15} C. The space charge density of the potassium ions inside the nanopore is 4.5×10^{5}

C/m^3. The charge of the chlorine ions inside the nanopore is calculated from the concentration of the chlorine ions inside the nanopore and the volume of the nanopore. The charge of the chlorine ions inside the nanopore is 7.2×10^{-19} C. The space charge density of the chlorine ions inside the nanopore is 200 C/m^3. The charge of KCl inside the nanopore is 1.6×10^{-15} C. The space charge density of KCl inside the nanopore is 4.5×10^{5} C/m^3. The mole of the potassium ions inside the nanopore is 1.7×10^{-20} mol. The mass of the potassium ions inside the nanopore is 6.7×10^{-22} kg. The number of the potassium ions inside the nanopore are 10239 elements. The number of the chlorine ions inside the nanopore are 5 elements. The number of KCl inside the nanopore are 10244 elements. The mobility of KCl is 7.1×10^{-8} (Am/N). The velocity from the theory is 14.2 mm/s. We assume the velocity is 60 mm/s. We assume the acceleration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanopore is 180 mm/s^2. The current of the potassium ions inside the nanopore is 19.6 pA. The mole of the chlorine ions inside the nanopore is 7.4×10^{-24} mol. The mass of the chlorine ions inside the nanopore is 2.6×10^{-25} kg. The current of the chlorine ions inside the nanopore is 0.009 pA. The mole of KCl inside the nanopore is 1.7×10^{-20} mol. The mass of KCl inside the nanopore is 6.7×10^{-22} kg. The current of KCl inside the nanopore is 19.6 pA. We assume the relative permittivity is 4.3. The relative permittivity corresponds to surface potential of 0.1 V.

In this section we show a difference of several orders of magnitude in the final obtained current between the single nanochannel and the single nanopore, respectively. The section provides comprehensive comparative analysis of the structural, transport mechanisms of nanochannels, nanopores to thoroughly explain the fundamental reasons for the current difference between the nanochannel and nanopore, respectively. The reason for the several orders of magnitude in the current difference between the single nanochannel and single nanopore is the structure of the single nanochannel is different compared to the single nanopore. The volume of the single nanochannel is larger than the volume of the single nanopore resulting in larger charge of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the single nanochannel compared to the single nanopore, respectively. The volume of the single nanochannel is larger than the volume of the single nanopore resulting in larger mol, number, mass and current of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the single nanochannel compared to the single nanopore, respectively.

RESULTS AND DISCUSSION

Fig. 4 shows the concentration of the potassium chloride electrolyte solution, potassium ions and the chlorine ions inside the single nanochannel. The concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the nanochannel match the literature [25]. Fig. 4 shows the concentration of potassium ions is higher inside the nanochannel than the inlet concentration of the potassium ions. The reason for the increase in the concentration of the potassium ions are because the potassium ions interact with the surface of the membrane having nanochannel. The parameter influencing the structure of the potassium ions inside the nanochannel is the surface potential. Fig. 4 shows the concentration of chlorine ions is lower inside the nanochannel than the inlet concentration of chlorine ions.

The low concentration of the chlorine ions inside the nanochannel is because of the surface potential.

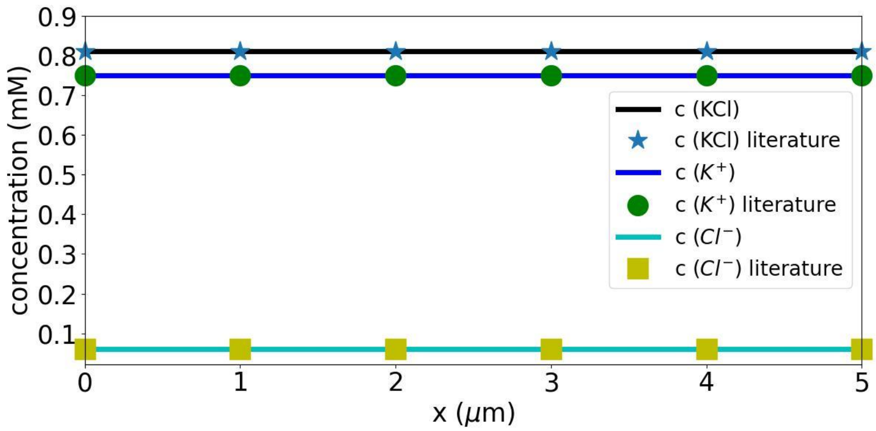


Figure 4. Concentration of the KCl electrolyte solution simulation (black solid line), literature results (*), potassium ions simulation (blue solid line), literature results (circle), chlorine ions simulation (purple solid line) and literature results (square). The concentration is calculated inside the nanochannel. The literature results are given in [25]. The surface potential of the membrane having single nanochannel is 0.052 V.

Fig. 4 shows the concentration of KCl inside the nanochannel.

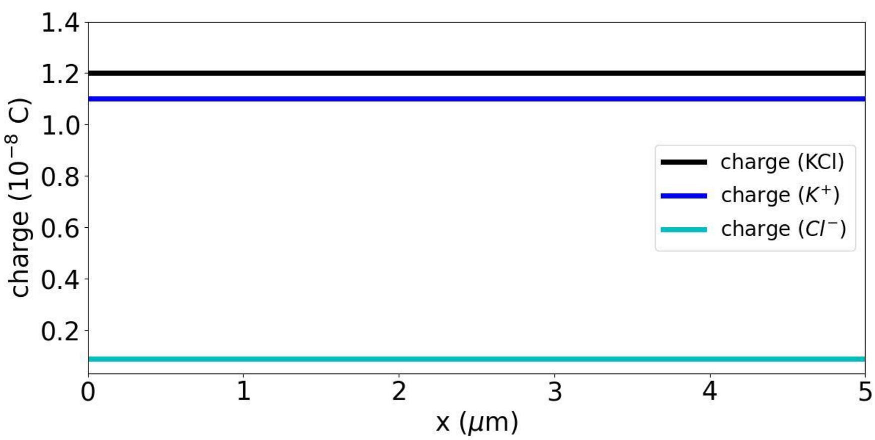


Figure 5. Charge of the KCl, potassium ions and the chlorine ions inside the single nanochannel. The surface potential of the membrane having single nanochannel is 0.052 V.

Fig. 5 shows the charge of the KCl inside the nanochannel. Here we consider the surface potential of the membrane having single nanochannel is 0.052 V. The charge of the potassium chloride electrolyte solution is given by the Faraday-concentration model discussed in our theory section. The charge of the potassium chloride electrolyte solution inside the nanochannel has a linear relation to the concentration of the potassium chloride electrolyte solution inside the nanochannel. Fig. 5 shows the charge of the potassium ions inside the nanochannel. The charge of the potassium ions inside the nanochannel also has a linear relation to the concentration of the potassium ions inside the nanochannel. Fig. 5 shows the charge of the chlorine ions inside the nanochannel. The charge of the chlorine ions inside the nanochannel also has a linear relation to the concentration of the chlorine ions inside the nanochannel. Further the charge of the potassium ions inside the nanochannel is higher owing to the surface potential. Furthermore, we show the selectivity of the potassium ions inside the nanochannel from the charge perspective.

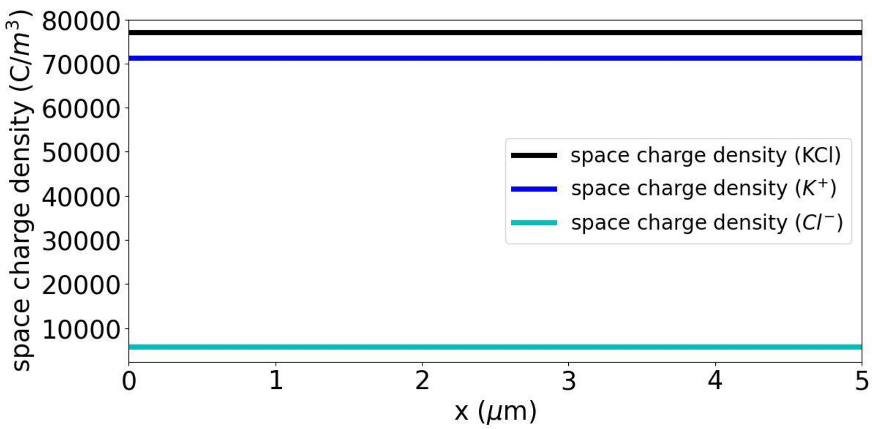


Figure 6. Space charge density of the KCl, potassium ions and the chlorine ions inside the single nanochannel. The surface potential of the membrane having single nanochannel is 0.052 V.

Fig. 6 shows the space charge density of the potassium chloride electrolyte solution inside the nanochannel. The space charge density of the potassium chloride electrolyte solution inside the nanochannel has linear relation with the charge of the potassium chloride electrolyte solution. The volume of the nanochannel gives the density effect to the charge. Fig. 6 shows the space charge density of the potassium ions inside the nanochannel. The space charge density of the potassium ions inside the nanochannel also has a linear relation with the charge of the potassium ions inside the nanochannel. Fig. 6 shows the space charge density of the chlorine ions inside the nanochannel. The space charge density of the chlorine ions inside the nanochannel also has a linear relation to the charge of the chlorine ions inside the nanochannel. The space charge density of the potassium ions inside the nanochannel is higher due to the surface potential. Fig. 7 shows the velocity of the potassium chloride electrolyte solution inside the nanochannel. The velocity of the potassium chloride electrolyte solution inside the nanochannel is dependent on the mobility of the potassium chloride electrolyte solution inside the nanochannel and the electric field. The mobility of the potassium chloride electrolyte solution is dependent on the surface potential, relative permittivity and viscosity of KCl. The calculated velocity of the potassium chloride electrolyte solution is in accordance with the literature [46, 47]. Fig. 7 shows the parabolic velocity because we distributed the electric field in grid locations to obtain the velocity. Fig. 7 shows the velocity results are grid independent.
Fig. 8 shows the mass of the potassium chloride electrolyte solution inside the single nanochannel. The mass of the potassium chloride electrolyte solution has a linear relation with the concentration of the potassium chloride electrolyte inside the nanochannel.

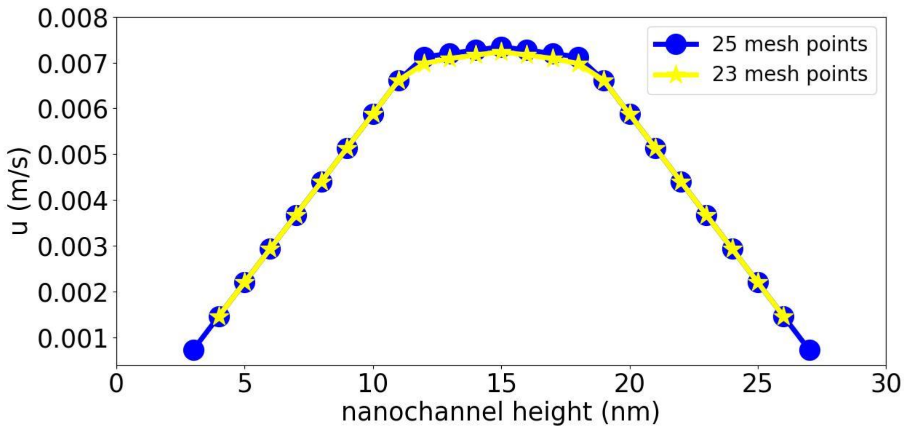


Figure 7. Velocity of the KCl inside the single nanochannel. The surface potential of the membrane having single nanochannel is 0.052 V.

Fig. 8 shows the mass of the potassium ions inside the nanochannel. The mass of the potassium ions inside the nanochannel also has a linear relation with the concentration of the potassium ions inside the nanochannel.

Fig. 8 shows the mass of the chlorine ions inside the nanochannel. The mass of the chlorine ions inside the nanochannel also has a linear relation to the concentration of the chlorine ions inside the nanochannel. Further the mass of the potassium ions inside the nanochannel is higher due to the surface potential.

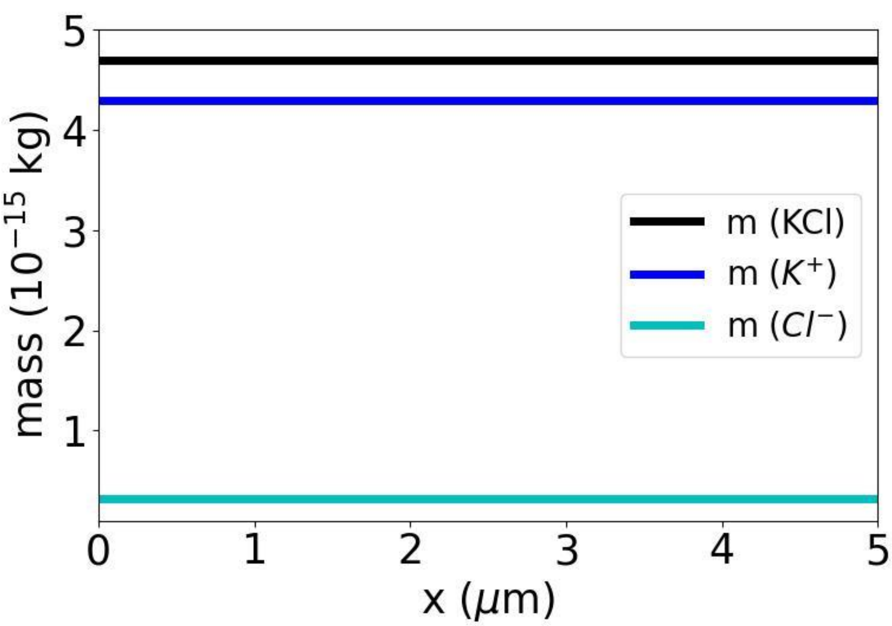


Figure 8. Mass of the KCl, potassium ions and the chlorine ions inside the single nanochannel. The surface potential of the membrane having single nanochannel is 0.052 V.

Fig. 9 shows the current of the potassium chloride electrolyte solution inside the single nanochannel. The applied voltage is 1 V. The current provides the understanding of the transport mechanism of the potassium chloride electrolyte solution inside the nanochannel. The current of the potassium chloride electrolyte solution inside the nanochannel is dependent on the charge of the potassium chloride electrolyte solution inside the nanochannel and the mass of the potassium chloride electrolyte solution inside the nanochannel. In this study we observe that the charge of the potassium chloride electrolyte solution inside the nanochannel dominates the current of the potassium chloride electrolyte solution inside the nanochannel. Fig. 9 shows the current of the potassium ions inside the nanochannel. Fig. 9 shows the current of the chlorine ions inside the nanochannel. In this study we observe that the charge of the chlorine ions inside the nanochannel dominates the current of the chlorine ions inside the nanochannel. Further the current of the potassium ions inside the nanochannel is higher owing to the high charge of the potassium ions due to the surface interaction of the membrane with the potassium ions inside the nanochannel. The surface potential is the key parameter to calculate the current of the potassium ions inside the nanochannel. Further the current of the chlorine ions inside the nanochannel is less due to the smaller charge of the chlorine ions inside the nanochannel. This is because of the surface interaction of the membrane with the chlorine ions inside the nanochannel. The surface potential plays an important role to obtain the low current of the chlorine ions inside the nanochannel. The current of the potassium chloride electrolyte solution, potassium ions and the chlorine ions match the literature [25].

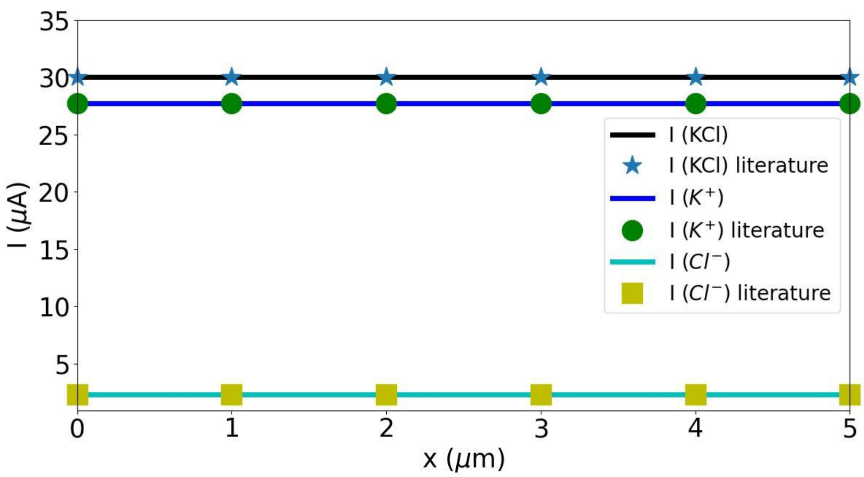


Figure 9. Current of the KCl simulation (black solid line), literature results (*), potassium ions simulation (blue solid line), literature results (circle), chlorine ions simulation (purple solid line) and literature results (square). The current is calculated inside the nanochannel. The literature results are given in [25]. The surface potential of the membrane having single nanochannel is 0.052 V.

On solving the Gouy-Chapman equation we obtain the concentration of the potassium ions, chlorine ions and potassium chloride electrolyte solution inside the single nanopore. Here we consider the surface potential of the membrane having single nanopore is 0.052 V. Fig. 10 shows the concentration of the potassium chloride electrolyte solution, potassium ions and the chlorine ions inside the single nanopore. Fig. 10 shows the concentration of potassium ions is higher inside the nanopore than the inlet concentration of the potassium ions. The reason for the increase in the concentration of the potassium ions is because the potassium ions interact with the surface of the membrane having single nanopore. The parameter influencing the structure of the potassium ions inside the nanopore is attributed to the surface potential of the membrane having nanopore. The surface potential is non-zero positive value. From the relation of Gouy-Chapman equation the concentration of the cation that is the concentration.

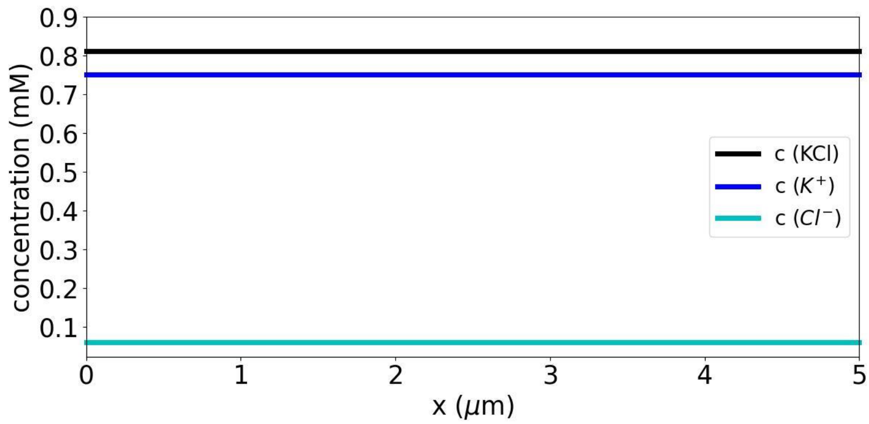


Figure 10. Concentration of the KCl, potassium ions and the chlorine ions inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

of the potassium ions increases with non-zero positive surface potential. Fig. 10 shows the concentration of chlorine ions is lower inside the nanopore than the inlet concentration of chlorine ions. The low concentration of the chlorine ions inside the nanopore is due to the surface potential. Fig. 10 shows the concentration of potassium chloride electrolyte solution inside the nanopore. The concentration of potassium chloride electrolyte solution inside the nanopore is the sum of the concentration of the potassium ions and chlorine ions inside the nanopore, respectively. The relation of adding the concentration of the potassium ions and chlorine ions to obtain the concentration of the potassium chloride electrolyte solution is same in the inlet reservoir. Further the high concentration of the potassium ions inside the nanopore shows that for the given surface potential of the membrane having single nanopore the nanopore is selective to the potassium ions than the chlorine ions. The selectivity is same as the potassium ion transference number. Fig. 11 shows the charge of the potassium chloride electrolyte solution inside the nanopore. The charge of the potassium chloride electrolyte solution is given by the Faraday-concentration model discussed in our theory section. The charge of the potassium chloride electrolyte solution inside the nanopore has a linear relation to the concentration of the potassium chloride electrolyte solution inside the nanopore. Fig. 11 shows the charge of the potassium ions inside the nanopore. The charge of the potassium ions inside the nanopore also has a linear relation to the concentration of the potassium ions inside the nanopore.

Fig. 11 shows the charge of the chlorine ions inside the nanopore. The charge of the chlorine ions inside the nanopore also has a linear relation to the concentration of the chlorine ions inside the nanopore. Further the charge of the potassium ions inside the nanopore is higher owing to the surface interaction of the membrane with the potassium ions inside the nanopore due to the surface potential. Further, the charge of the chlorine ions inside the nanopore is less due to the surface interaction of the membrane with the chlorine ions inside the nanopore. The surface potential plays an important role to obtain the low charge of the chlorine ions inside the nanopore. Furthermore, we show the selectivity of the potassium ions inside the nanopore from the charge perspective.

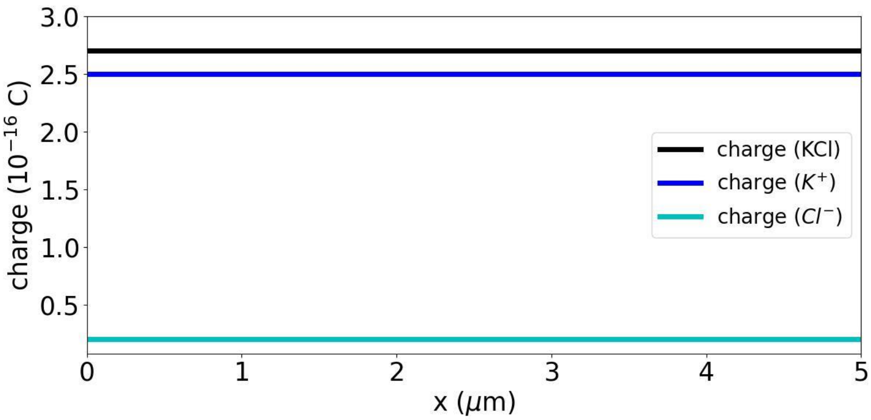


Figure 11. Charge of the KCl, potassium ions and chlorine ions inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

Fig. 12 shows the space charge density of the potassium chloride electrolyte solution inside the nanopore. The space charge density of the potassium chloride electrolyte solution is given by the Faraday-concentration model discussed in our theory section. The space charge density of the potassium chloride electrolyte solution inside he nanopore has linear relation with the charge of the potassium chloride electrolyte solution. The volume of the nanopore gives the density effect to the charge. Fig. 12 shows the space charge density of the potassium ions inside the nanopore. The space charge density of the potassium ions inside the nanopore also has a linear relation with the charge of the potassium ions inside the nanopore. Fig. 12 shows the space charge density of the chlorine ions inside the nanopore. The space charge density of the chlorine ions inside the nanopore also has a linear relation to the charge of the chlorine ions inside the nanopore. Further the space charge density of the potassium ions inside the nanopore is higher owing to the surface interaction of the membrane with the potassium ions inside the nanopore. This is due to the surface potential. Furthermore, the space charge density of the chlorine ions inside the nanopore is less due to the surface interaction of the membrane with the chlorine ions inside the nanopore. The surface potential plays an important role to obtain the low space charge density of the chlorine ions inside the nanopore.

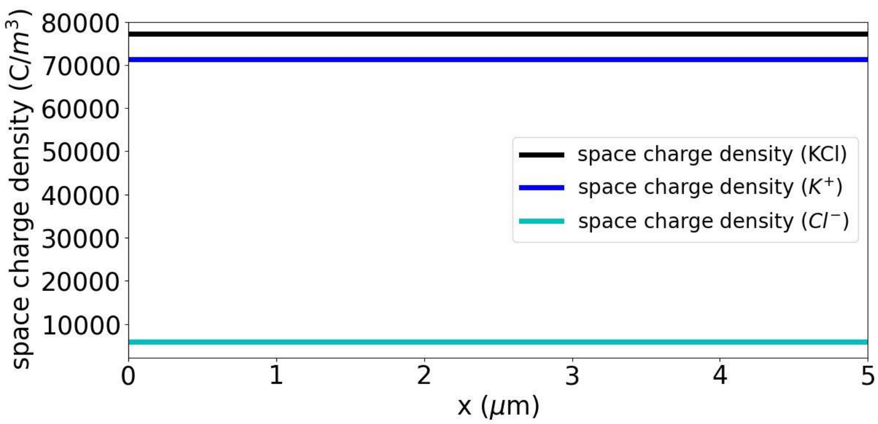


Figure 12. Space charge density of the KCl, potassium ions and chlorine ions inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

Fig. 13 shows the velocity of the potassium chloride electrolyte solution inside the nanopore. The velocity of the potassium chloride electrolyte solution inside the nanopore is dependent on the mobility of the potassium chloride electrolyte solution inside the nanopore and the electric field. The mobility of the potassium chloride electrolyte solution is dependent on the surface potential of the membrane having single nanopore, relative permittivity and viscosity of KCl. The calculated velocity of the potassium chloride electrolyte solution is in accordance with the literature [46, 47]. Fig. 13 shows the parabolic velocity profile because we distributed the electric field in grid locations to obtain the velocity. Fig. 13 shows the results are grid independent.

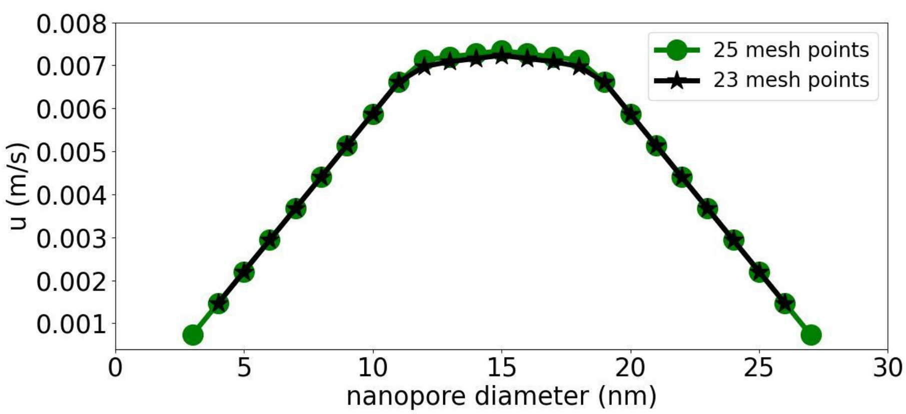


Figure 13. Velocity of the KCl inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

Fig. 14 shows the mass of the potassium chloride electrolyte solution inside the single nanopore. The mass of the potassium chloride electrolyte solution has a linear relation with the concentration of the potassium chloride electrolyte inside the nanopore. Fig. 14 shows the mass of the potassium ions inside the nanopore. The mass of the potassium ions inside the nanopore also has a linear relation with the concentration of the potassium ions inside the nanopore. Fig. 14 shows the mass of the chlorine ions inside the nanopore. The mass of the chlorine ions inside the nanopore also has a linear relation to the concentration of the chlorine ions inside the nanopore. Further, the mass of the potassium ions inside the nanopore is higher owing to the surface potential. Furthermore, the mass of the chlorine ions inside the nanopore is less due to the surface interaction of the membrane with the chlorine ions inside the nanopore. The surface potential plays an important role to calculate the low mass of the chlorine ions inside the nanopore.

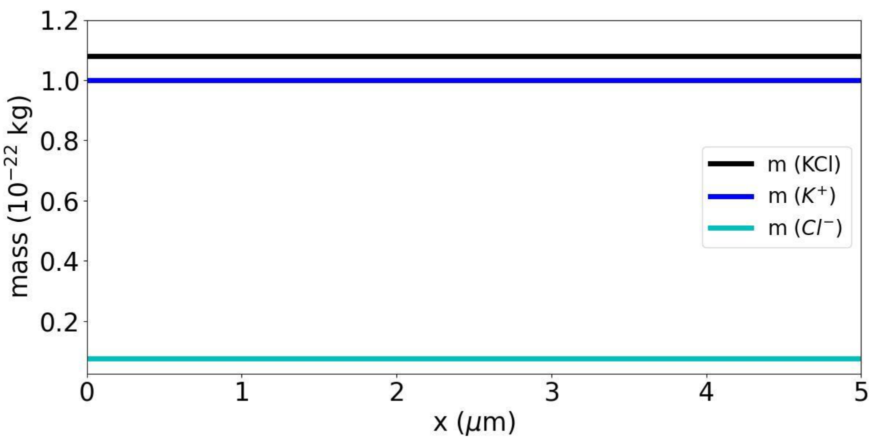


Figure 14. Mass of the KCl, potassium ions and the chlorine ions inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

Fig. 15 shows the current of the potassium chloride electrolyte solution inside the single nanopore. The applied voltage is 1 V. The current provides the understanding of the transport mechanism of the potassium chloride electrolyte solution inside the nanopore. The current of the potassium chloride electrolyte solution inside the nanopore is dependent on the charge of the potassium chloride electrolyte solution inside the nanopore and the mass of the potassium chloride electrolyte solution inside the nanopore. In this study we observe that the charge of the potassium chloride electrolyte solution inside the nanopore dominates the current of the potassium chloride electrolyte solution inside the nanopore. The mass of the potassium chloride electrolyte solution inside the nanopore is small. Fig. 15 shows the current of the potassium ions inside the nanopore. In this study we observe that the charge of the potassium ions inside the nanopore dominates the current of the potassium ions inside the nanopore. The mass of the potassium ions inside the nanopore is small. Fig. 15 shows the current of the chlorine ions inside the nanopore. In this study we observe that the charge of the chlorine ions inside the nanopore dominates the current of the chlorine ions inside the nanopore. The mass of the chlorine ions inside the nanopore is small. The current of the potassium ions inside the nanopore is higher owing to the high charge of the potassium ions due to the surface interaction of the membrane with the potassium ions inside the nanopore. The surface potential plays an important contribution. The current of the chlorine ions inside the nanopore is less due to the smaller charge of the chlorine ions inside the nanopore. This is because of the surface interaction of the membrane with the chlorine ions inside the nanopore.

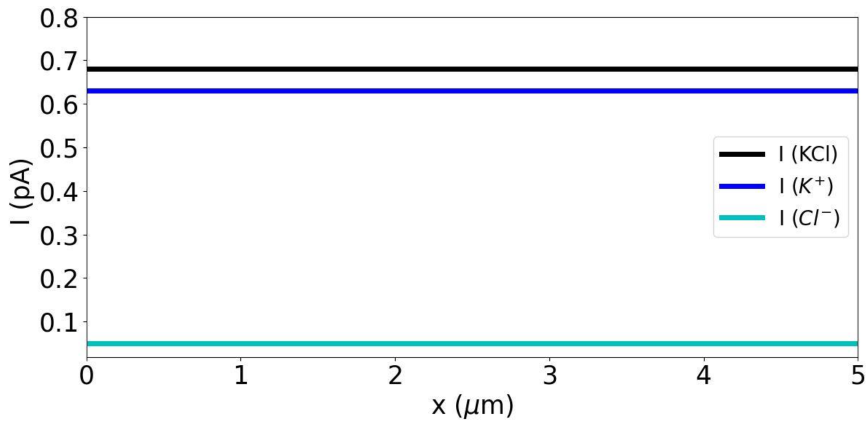


Figure 15. Current of the KCl, potassium ions and chlorine ions inside the nanopore. The surface potential of the membrane having single nanopore is 0.052 V.

Fig. 16 shows the device simulation software to obtain the structure and transport mechanism parameters for potassium chloride electrolyte solution inside the single nanochannel. The surface potential of the membrane having single nanochannel is included in the software.

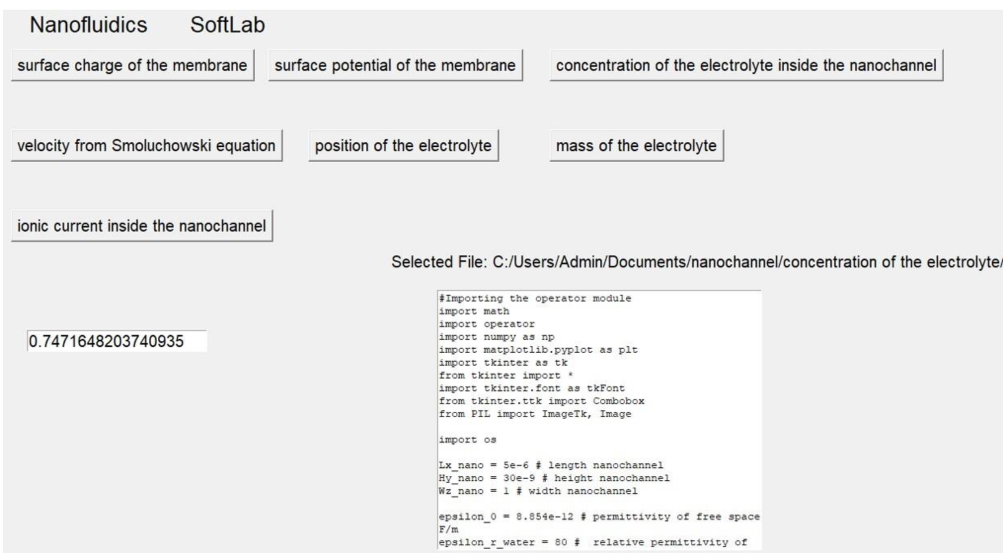


Figure 16. Device simulation for the membrane having single nanochannel integrated to cm/mm source-sink fluidic reservoirs. The GUI model is used.

Fig. 17 shows the device simulation software to obtain the structure and transport mechanism parameters for potassium chloride electrolyte solution inside the single nanopore. The surface potential of the membrane having single nanopore is included in the software.

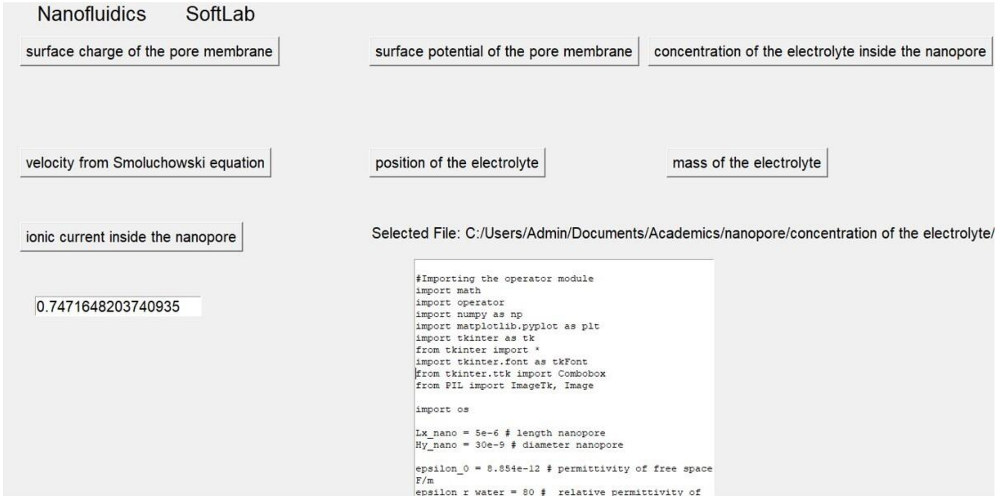
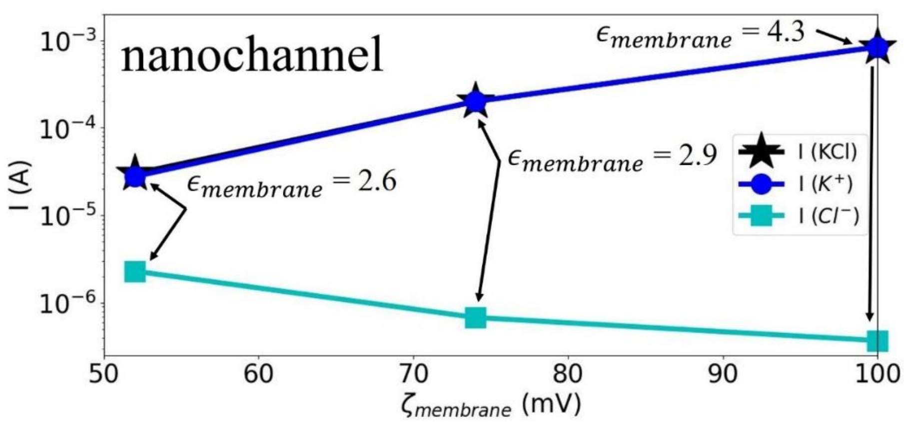


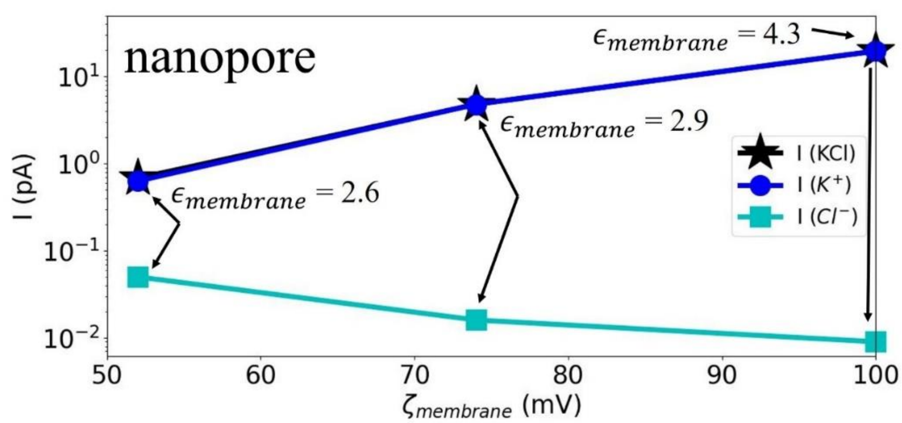
Figure 17. Device based simulation for the membrane having single nanopore integrated to cm/mm source-sink fluidic reservoirs. The GUI model is used.

The current of the potassium chloride electrolyte solution, potassium ions and chlorine ions inside the single nanochannel as a function of membrane surface potential is shown in Fig. 18a. Further the current of the potassium chloride electrolyte solution, potassium ions and chlorine ions inside the single nanopore as a function of membrane surface potential is shown in Fig. 18b. Fig. 18a shows the current of the potassium ions inside the nanochannel is higher compared to the current of the chlorine ions inside the nanochannel. The current of the potassium ions inside the nanochannel is high because of the high charge of the potassium ions due to the surface potential of the membrane with the potassium ions inside the nanochannel. Further, the current of the chlorine ions inside the nanochannel is less due to the smaller charge of the chlorine ions inside the nanochannel. This is because of the surface interaction of the membrane with the chlorine ions inside the nanochannel. The surface potential is the key parameter to calculate the current of the chlorine ions inside the nanochannel. The mass of the potassium ions, mass of the chlorine ions inside the nanochannel contribution to the current of the potassium ions and current of chlorine ions, respectively are small. The observations are consistent for all the surface potential of the membrane having single nanochannel studied here. Furthermore, we show the selectivity of the potassium ions inside the nanochannel from the current perspective for all the surface potential of the membrane having single nanochannel. The assumed relative permittivity of the membrane having single nanochannel for the corresponding surface potential of the membrane having single nanochannel is shown in Fig. 18a.

Fig. 18b shows the current of the potassium ions inside the nanopore is higher compared to the current of the chlorine ions inside the nanopore. The current of the potassium ions inside the nanopore is high because of the high charge of the potassium ions due to the surface interaction of the membrane with the potassium ions inside the nanopore. The surface potential is the key parameter to calculate the current of the potassium ions inside the nanopore. Further, the current of the chlorine ions inside the nanopore is less due to the smaller charge of the chlorine ions inside the nanopore. This is because of the surface interaction of the membrane with the chlorine ions inside the nanopore. The surface potential is the key parameter to calculate the current of the chlorine ions inside the nanopore. The mass of the potassium ions, mass of the chlorine ions inside the nanopore contribution to the current of the potassium ions and current of chlorine ions, respectively are small. The observations are consistent for all the surface potential of the membrane having single nanopore studied here. Furthermore, we show the selectivity of the potassium ions inside the nanopore from the current perspective for all the surface potential of the membrane having single nanopore. The assumed relative permittivity of the membrane having single nanopore for the corresponding surface potential of the membrane having single nanopore is shown in Fig. 18b.



(a)



(b)

Figure 18. (a) Current of the KCl, potassium ions and chlorine ions inside the nanochannel as a function of membrane surface potential (b) Current of the KCl, potassium ions and chlorine ions inside the nanopore as a function of membrane surface potential.

We observe difference of several orders of magnitude in the final obtained current between the nanochannel and the nanopore as shown in Fig. 18a and Fig. 18a, respectively. We provide comprehensive comparative analysis of the structural and transport mechanisms of nanochannels, nanopores to thoroughly explain the current difference in our earlier section.

The significant difference of the current between the nanochannel and nanopore is because of the volume of the nanochannel considered is larger than the volume of the nanopore, respectively.

NANOFLUIDICS ELECTRONICS CALCULATOR

Practical Guide to Design Nanofluidics Electronics Calculator

In this article we develop the GUI for the nanofluidics electronics calculator as shown in Fig. 19. Each button of the nanofluidics electronics calculator is considered as an ON/OFF switch. In the design we represent the standard calculator numbers and operators on the buttons of the nanofluidics electronics calculator. When a button is pressed the switch is in the ON state. The wiring is internal. The wire terminals are connected from the button to the battery. The battery is internal unit of the nanofluidics electronics calculator. In the ON state the battery is the inlet supplying the voltage to the single nanochannel made on the membrane integrated between the source-sink reservoirs. The single nanochannel made on the membrane integrated between the two reservoirs are internal unit of the calculator. The wire terminals are connected from the same button to the DC pump. The DC pump is internal unit of the calculator. In the ON state the DC pump drives the potassium chloride electrolyte solution from the potassium chloride electrolyte solution tank. The potassium chloride electrolyte solution in the tank is internal unit of the calculator. The potassium chloride electrolyte solution is pumped to the branched flow pipes to the inlet source, outlet sink reservoirs to complete fill the source and sink reservoirs. The unit discussed above is internal unit of the calculator.

Ag/AgCl electrodes are placed on the inlet source, outlet sink reservoirs to measure the current inside the single nanochannel integrated between the source and sink reservoirs system. The unit discussed above is internal unit of the calculator. The inlet voltage and the current of the potassium chloride electrolyte solution are respectively measured from two digital multimeter. The two digital multimeter are internal unit of the calculator.

The outlet reservoir having the potassium chloride electrolyte solution is transported in different flow pipe to an o-ring integrated to thin film membrane material etched in millimeter size shape of the number same as the number pressed on the button. The etched thin film in the shape of the number is the display. The procedure is repeated to design the nanofluidics electronics calculator to numbers 0 to 9.

The outlet reservoir having the potassium chloride electrolyte solution is transported in different flow pipe to an o-ring integrated to thin film membrane material etched in millimeter size shape of the operator same as the operator pressed on the button. The etched thin film in the shape of the operator is the display. The operator buttons include add +, subtract -, multiply *, division /, equal to = and solution Ans.

The etched thin film membrane in the shape of the number and etched thin film in the shape of the operator are the outlet units of the calculator.

The etched thin film has an end sealant capped transparent thin film membrane material.

The end sealant capped transparent thin film membrane material is the outlet unit of the calculator.

The calculator performs the addition of two input numbers only between 0 to 9 and 0 to 9, respectively.

The outlet reservoir having the potassium chloride electrolyte solution is transported in different flow pipe to an o-ring integrated to thin film membrane material etched in millimeter size shape of the number same as the answer number obtained from addition available as the number pressed on the button. The etched thin film in the shape of the answer number is the display.

The calculator performs the subtraction, multiplication and division for any two input numbers only between 0 to 9 and 0 to 9, respectively. The outlet reservoir having the potassium chloride electrolyte solution is transported in different flow pipe to an o-ring integrated to thin film membrane material etched in millimeter size shape of the number same as the answer number obtained from subtraction, multiplication and division available as the number pressed on the button. The etched thin film in the shape of the answer number is the display.

The answer number for the division is ensured to be number, decimal point followed by another number in accordance to the answer number.
Hence the calculator answer number has floating point numbers. The etched thin film in the shape of the answer number is the display.

We ensure the answer number in the calculator are only two digits.

The etched thin film in the shape of the answer number will display only two digits.

The button turns to OFF sate after some time releasing the potassium chloride electrolyte solution in another pipe to the tank.

Performance of the GUI Simulation Based Nanofluidics Electronics Calculator
Fig. 19 shows the nanofluidics electronics calculator using single nanochannel. The buttons include the numbers, 0 to 9. The buttons include operators add +, subtract -, multiply *, division /, equal to = and solution Ans. The calculator includes the button C to clear and for the display to show 0. Fig. 19 shows number 5 on the display of the calculator. Fig. 19 shows the current of the potassium chloride electrolyte solution inside the single nanochannel integrated to the source and sink reservoirs system. The current is shown on another display. The current shown in Fig. 19 is only related to the button having number 5. Here the current is in μA range for the nanochannel that is discussed in the earlier section.

Our GUI simulation of the calculator can take input of any number of digits as given number. Our GUI simulation performs the addition, subtraction, multiplication and division for any number of digits given as input. Our simulation-based calculator displays the current for the input number, input operator, equal to =, Ans buttons and output number, respectively. Further, the calculator displays the output number on the calculator screen. Furthermore, our calculator is run on Windows Power-Shell terminal screen. The input calculator numbers and the operator are printed on the terminal.

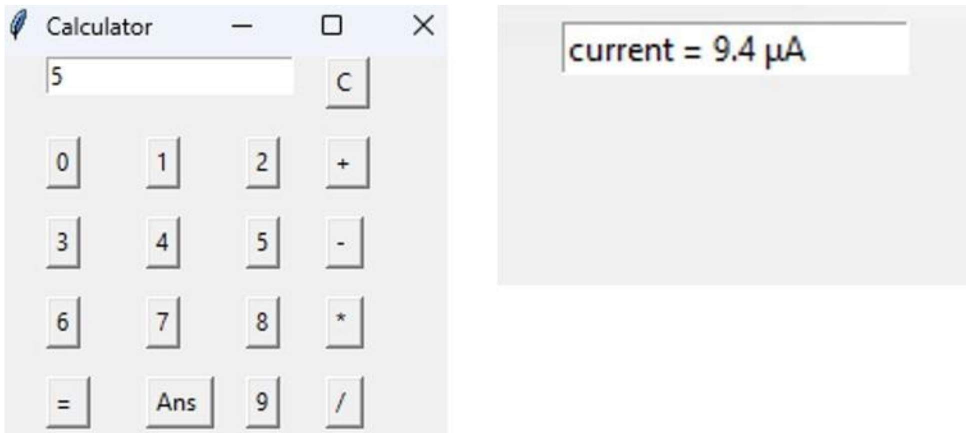


Figure 19. Nanofluidics electronics calculator with single nanochannel integrated to source-sink reservoirs as components. The calculator has buttons. The buttons are represented as switches. Each button is related to their own ionic current obtained from the single nanochannel.

Fig. 20 shows the nanofluidics electronics calculator using single nanopore. The buttons include the numbers, 0 to 9. The buttons include operators add +, subtract -, multiply *, division /, equal to = and solution Ans. The calculator includes the button C to clear and for the display to show 0. Fig. 20 shows number 5 on the display of the calculator.

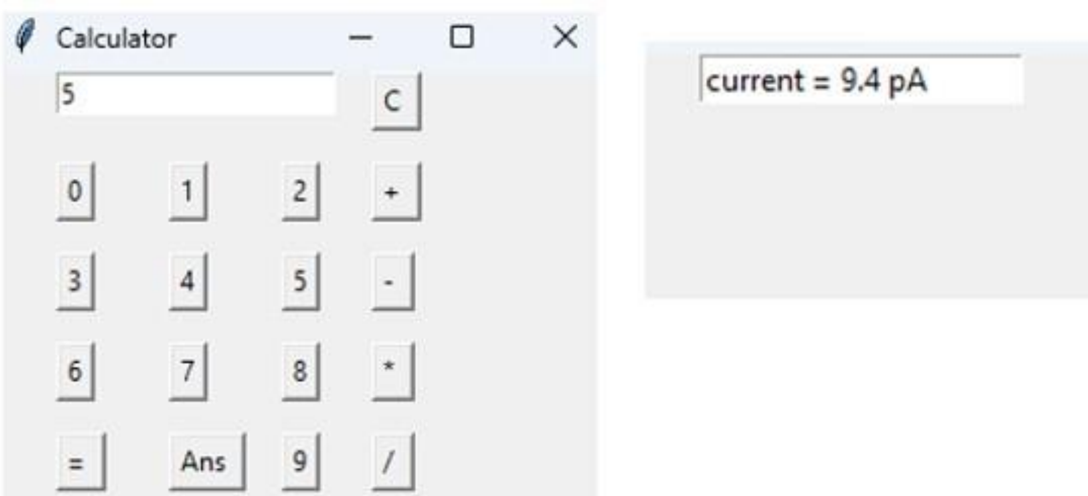


Figure 20: Nanofluidics electronics calculator with single nanopore integrated to source-sink reservoirs as components. The calculator has buttons. The buttons are represented as switches. Each button is related to their own ionic current obtained from the single nanopore.

Fig. 20 shows the current of the potassium chloride electrolyte solution inside the single nanopore integrated to the source and sink reservoirs system. The current is shown on another display. The current shown in Fig. 20 is only related to the button having number 5. Here the current is in pA range for the nanopore that is discussed in the earlier section. Our GUI simulation of the calculator can take input of any number of digits as given number. Our GUI simulation performs the addition, subtraction, multiplication and division for any number of digits given as input. Our simulation-based calculator displays the current for the input number, input operator, equal to =, Ans buttons and output number, respectively. Further, the calculator displays the output number on the calculator screen. Furthermore, our calculator is run on Windows PowerShell terminal screen. The input calculator numbers and the operator are printed on the terminal.

We discuss adjusting key parameters can optimize device performance of our calculator. In our study we consider fixed concentration of potassium chloride electrolyte solution, potassium ions, chlorine ions, fixed input voltage, fixed charge of the potassium chloride electrolyte solution, potassium ions, chlorine ions, fixed space charge density of the potassium chloride electrolyte solution, potassium ions, chlorine ions, fixed velocity of the potassium chloride electrolyte solution, fixed mobility of the potassium chloride electrolyte solution, fixed mass of potassium chloride electrolyte solution, potassium ions, chlorine ions, fixed mole of potassium chloride electrolyte solution, potassium ions, chlorine ions, fixed number of potassium chloride electrolyte solution, potassium ions and chlorine ions.

Here we consider fixed current of the potassium chloride electrolyte solution, potassium ions and chlorine ions. Here we consider fixed dimensions of the membrane having single nanochannel and nanopore, respectively. Here we consider fixed dimensions of the single nanochannel and single nanopore, respectively. Here we consider different surface potential of the membrane having single nanochannel and single nanopore respectively.

In regards to adjusting key parameters to optimize the device performance of the calculator the concentration of potassium chloride electrolyte solution take between 0.2 mM to 2 M, concentration of potassium ions take between 0.1 mM to 1 M, the concentration of chlorine ions take between 0.1 mM to 1 M, the mass of the potassium chloride electrolyte solution take between 6 g to 1 kg, mass of the potassium ions take between 3 g to 500 g and mass of the chlorine ions take between 3 g to 500 g. The voltage take between 1 V to 5 V. The velocity of the potassium chloride electrolyte solution take between 100 μm/s to 120 mm/s. In regards to single nanochannel have one of the dimensions from 1 nm to 500 nm and single nanopore have the diameter from 1 nm to 500 nm. Take the surface potential of the membrane having single nanochannel from 0 V to 0.2 V. Adjusting key parameters can optimize device performance for industrial-grade neuromorphic computers.

CONCLUSIONS

Our experiments measured the surface potential of the polycarbonate track etched membrane having multiple nanopores and graphene/copper membrane having multiple nanopores. In this study we develop GUI simulations to study the structural, transport mechanisms of nanochannels, nanopores for different surface potential of the membrane having single nanochannel and single nanopore, respectively. The surface potential of the membrane is the key parameter in our study. We observe difference of several orders of magnitude in the final obtained current between the nanochannel and the nanopore because of the volume of the nanochannel considered is larger than the volume of the nanopore, respectively. Further, we calculate the velocity of the potassium chloride electrolyte solution inside the nanochannel and nanopore from the Smoluchowski model. Furthermore, we present practical guide to design nanofluidics electronics calculator. We develop GUI simulation of nanofluidics electronics calculator using single nanochannel and single nanopore, respectively. Our model and results can be used to guide the practical design and performance improvement of neuromorphic computing devices. There is scope for the future work of fabrication of the nanofluidics electronics calculator using single nanochannel and single nanopore, respectively. In this study we limit ourselves to measure the surface potential for two membranes that needs to be addressed in the future.

Author Contributions

S. Ragulranjith: Conceptualization; methodology; validation; investigation; software; data curation; formal analysis; writing – original draft.
Nandigana V. R. Vishal: Conceptualization; supervision; funding acquisition; software; visualization; resources; writing – review and editing.

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Conflict of Interest Statement

The authors declare no potential conflict of interest.

Data Availability Statement

1. The device simulation code of the single nanochannel and single nanopore are provided. 2. The tabular values, python code for 23 grid points, 25 grid points of the velocity of the potassium chloride electrolyte solution inside the single nanochannel and single nanopore are provided. We ensure the velocity of the potassium chloride electrolyte solution inside the single nanochannel and single nanopore are grid independent. 3. The method details to obtain the position of the lumped potassium chloride electrolyte solution evolving with simulation time inside the single nanochannel and single nanopore are provided. The codes to obtain the position of the lumped potassium chloride electrolyte solution evolving with simulation time inside the single nanochannel and single nanopore are provided. 4. The GUI code for nanofluidics electronics calculator using the current obtained from single nanochannel integrated to source-sink reservoirs system and single nanopore integrated to source-sink reservoirs system are provided.

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