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Biomedical Applications of Electric Field Dependent Microfluidic Flow

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Abstract— Mixing and manipulating the fluid in microchannels have been a persistent challenge in the manufacturing of micro devices used in the field of bio electronics and microfluidic engineering. Both active and passive mixers are used for mixing fluid in microchannels. Tracing the fluid flow and its concentration at different time durations has been a tedious job if done practically. Simulation provides an easy way for checking the fluid concentration as time dependent study. In this paper, Simulation of electro osmotic mixer is done using comsol and electro osmosis principle is used here to mix fluids. Fluid flow under different potential is studied as time dependent and stationary study. A time-dependent electric field applied to this microfluidic system results in electro-osmosis and agitates the parallel streamlines in the otherwise highly ordered laminar flow.

Keywords— Microchannels; electroosmosis; active and passive mixers; Navier Stoke's equation; comsol..

I. INTRODUCTION

Human race is stepping in an artificial intelligence world where robots will be sharper as compared to human beings. We are now to enter in a world where if any part of human stops working it will be easily replaceable by a microstructure. It's the bioelectronics world where microfluidic body parts are replacing human parts which are not functional. To make a precise device, it's required to have control on fluid flow and mixing. For the development of electronic medical diagnostic kits, its required to have a precise control on the ingredients to be supplied and an efficient mechanism for the proper mixing of the chemicals before its application at the precise point. We are working on the application of microfluidic for the development of an efficient mixer for the microfluidic electronic bandage. Microfluidics is that branch of fluid dynamics but dealing with devices efficient of handling only fluids in micro, pico or nano litres.

Fluid dynamics is the science of motion of liquids and gases and their interaction with solid bodies. It touches every aspect and field of life and widely used in science and engineering. Fluid dynamics finds its use in manufacturing of medicines, biology, nano engineering, bio electronics, homeland security etc [1]-[15]. Fluid dynamics is a expanding field in microfluidic devices as fluid is considered to be the lifeline of all living organisms. So understanding its need and impact through small microfluidic channels will open new way of understanding living bodies to the way of biomicrofluidics. Understanding fluid dynamics of microfluidic devices is same as understanding the complexity of fluid dynamics of living organisms. Most of the matter in the world exists in turbulence. It's the turbulent behaviour of the matter that generates an application for it [5], [7]. It's required to convert the laminar behaviour of fluid into turbulence whether by external means or by changing the dimensions of the microfluidic channels for proper control and mixing of fluids in the microfluidic devices. Controlling the flow through microfluidic channels make use of either active or passive methods. Active methods make use of electrical and electronic devices controls microfluidic systems in a better way as compared to the passive but require external sources to actuate the valve. The common control methods in microfluidic systems are relay logic circuits, programmable controllers and air logic controls. Air logic controls can perform any function normally handled by relays, pressure, time delays, limit switches etc. The compressed air is the medium of controlling flow in microfluidic devices instead of the electric current. Flow of fluids through these small devices is laminar, so it's a necessity to mix the fluids efficiently which is a little bit difficult in microfluidic channels. Micro laboratories for biochemical applications often require rapid mixing of different fluid streams for the development of new compounds and mixtures to be used in medical field. Microfluidic devices are having a significant impact and the experiments are going in the field of biomedical diagnostics, drug development, and chemical and food industries. Microfluidic devices are the means of mixing samples and various ingredients in a more specific ratio. There are two types of mixers available, active as well as passive mixers. In passive mixers, mixing is done by taking the dimensional characteristics of the channels into consideration. The length of the channels needs to be long so as to mix the fluids properly. The small flow of fluids through microchannels increases surface to volume ratio. Turbulent mixing does not occur in microfluidics with ease so some other ways of mixing the fluids need to be considered to achieve proper mixing. Reynold's number and peclet number are means of evaluating the performance of mixers. Reynold's number is the ratio of inertial forces to viscous forces or fluid momentum to the viscous friction force.

$$R_e = VL_h/u$$

Where V is the average flow velocity, L_h is the hydraulic diameter and u is the kinematic viscosity. For Reynolds value less than 2300, the value is laminar and for value >2300, the flow is turbulent [7]-[12]. The flow is laminar in microfluidic

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tubes as diffusion is the only criteria for mixing in microfluidics so it's difficult to obtain proper mixing and for turbulence to occur the length of microfluidic channels are to be long. Diffusion of small molecules can occur in a matter of seconds where as for bigger molecules to diffuse, it requires the use of secondary sources [16]-[18]. It require time from minutes to hour for proper mixing to occur. Passive mixers required long mixing channels to mix the fluids flowing in parallel stream through microfluidic channels. Sometimes its not feasible to use long channels for passive mixing. The geometries of the channels differ w.r.t the proportion of fluids to be mixed [19]-[35]. Passive mixers required very thin alternating layers as they decrease the average diffusion length for the molecules between the different fluids. Passive mixers required geometrical stirring. About nine passive mixers had been purposed by different researchers. Lamination passive mixers required wedge, spilt and Y shaped inlets required mixing time of 1 ms and 1, 500 and 13000 um length. Intersecting channels working on mixing techniques of unbalanced splits and collisions channels, rhombic channels with flat angles, unbalanced split and recombine channels with asymmetric sub channels required mixing length of 5500, 15000 and 10300 um [35]-[50]. Convergent divergent channels with split and recombination channels with convergent divergent walls, convergent divergent channels, convergent divergent channels with pulsatile flow required mixing length of 6720, 22000 and 24000 um. 3D structures working on mixing techniques interconnected multi channels network, 3D crossing manifold, 3D periodic perturbation, 3D spiral, H shaped sub channels, 3D triangle required mixing length of 10000, 250, 50000, 2340, 21000, 300 etc. Embedded barriers working on mixing techniques static mixing elements, obstruction pairs, rib shaped, inserted diamond obstacles, simple periodic geometric features, shifted trapezoidal blades 185, 4200, 1344, 10000, 14000 and 5000 um length. Twisted channels working on mixing techniques clamped capillaries required 313.6 um. Tesla structures working on mixing techniques of Modified and 3D tesla required mixing length of 2370 and 11200 um [50]-[56]. An active mixer provides the better way of mixing fluids but involve the use of active devices or moving parts to stir the fluids. Active microfluidic mixers enhance the mixing performance by the use of external sources or by agitating the fluid flow using pressure or electric field. Eight active microfluidic mixers have been purposed by different researchers. The active mixers work on the principle of acoustic/ ultrasonic actuation, dielectrophoretic force actuation, electro kinetic time pulsed actuation, pressure perturbation, electrodynamic force, thermal actuation, magneto hydrodynamic flow, electrokinetic stability. The active microfluidic mixers provides better mixing than passive mixers but the use of moving parts is not suitable at the micro level. So we are experimenting electro- osmotic effect for mixing fluids. Four electrodes are applied near the end of the rectangular mixing chambers. The electro-osmotic effect is perpendicular to the main direction of flow. Time dependent electric field is applied to initiate turbulence and resulting electro-osmosis perturbs the highly ordered laminar flow in microfluidics.

In our research we are using the micromixer having fed with two fluids of different concentration through the micromixer geometry as shown in figure 1. The micromixer geometry mixes combines two fluids entering from different inlets into a single 10 um wide channel. The fluid enters a rectangular shaped mixing chambers where electrodes are placed near the corners of the mixing chambers. Finally a point probe is set in the domain area of the mixer and effect of velocity and concentration gradient with respect to time are studied at it.

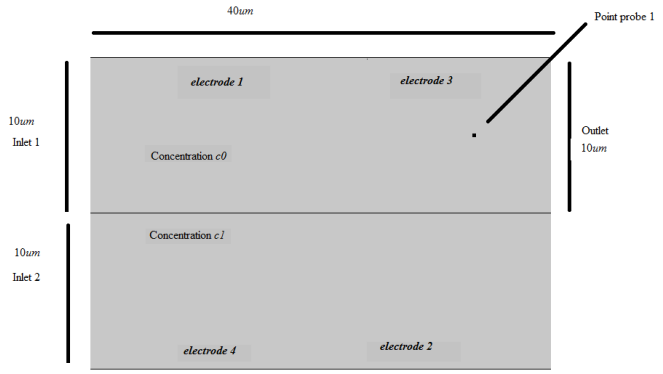

Fig.1 Geometrical outline of the micromixer

Figure 1 shows the micromixer with four symmetric electrodes on the wall of mixing chambers. Fluid is applied through the inlets of 10 um dimensions and obtained at the outlet of 10 um dimensions. The Navier stokes equation is used for determining the laminar flow through the microchannels.

$$\rho\partial u/\partial t-\nabla.\eta(\nabla u+(\nabla u)^{T})+\rho u.\nabla u+\nabla p=0 \quad \text{---------- (1)}$$

$$\nabla.u=0 \quad \text{---------- (2)}$$

Here η denotes the dynamic viscosity (kg/(m·s)), u is the velocity (m/s), ρ equals the fluid density (kg/m3), and p refers to the pressure (Pa).

Here an assumption is made that entrance is the point where flow is fully developed laminar. The mixed fluid flows freely out of the right end boundary, where vanishing total stress components normal to the boundary are specified.

$$n.[\ -pI+\eta(\ \nabla u+(\ \nabla u)T\ )]=0 \quad \text{---------- (3)}$$

Solid surfaces acquire a surface charge when on contact with an electrolyte. A charged solution is formed closed to the liquid solid interface in response to the spontaneously formed surface charge. An electric double layer is formed because of the charged groups located on the surface facing the solution. On applying electric field, electro-osmotic flow is generated displacing the charged liquid in the electric double layer. Due to this, force is imposed on the positively charged solution close to the wall surface, and the fluid starts to flow in the direction of the electric field. Viscous transport results in this direction due the velocity gradients perpendicular to the wall. The velocity profile becomes uniform in the cross section perpendicular to the wall in the absence of other forces. This model replaces the thin electric double layer with the Helmholtz-Smoluchowski relation

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between the electro-osmotic velocity and the tangential component of the applied electric field

$$u= \varepsilon w\, \zeta 0/ \eta\, V\, T\, \nabla \text{ ----------(4)}$$

In this equation, εw is fluid's electric permittivity (F/m), ζ0 is zeta potential at the channel wall (V), and V equals the potential (V). This equation is applicable for all boundaries except inlets and the outlets.

For no concentration gradients in the ions carrying the current, current balance in the channel with Ohm's law and the balance equation for current density is given by

$$\nabla. (\varsigma \nabla V) = 0 \text{ -----------(5)}$$

Here ς is conductivity (S/m) and $\varsigma\nabla V$ is the current density (A/m^2). The electric potentials on the four electrodes are sinusoidal in time 5 with the maximum value (V0 = 0V,0.1 V, 1V) and the frequency (8 Hz), alternate in polarity are applied and its impact is studied differently. The potentials on electrodes 1 and 3 are $V0 \sin(2\pi ft)$, whereas those on electrodes 2 and 4 are $-V0\sin(2\pi ft)$. Except these four points all the other boundaries of the structure are insulated. The insulation boundary condition

$$-\varsigma \nabla V. n=0 \text{ ----------(6)}$$

sets the normal component of the electric field to zero. Upper inlet has cconcentration, c0; at the lower inlet has concentration c1. After the application of the potential we have to study whether the solution is properly mixed. The mixed solution flows out from the right outlet by convection, and all other boundaries are assumed insulated. It should be noted that the concentration of the mixed fluid will differ from the actual concentration of the two fluids. Convection-diffusion equation describes the concentration of the dissolved substances in the fluid,

$$\partial c/ \partial t + \nabla. (- D\nabla c) = R- u .\nabla c \text{ --------(7)}$$

Where c is the concentration, D is the diffusion coefficient, R, the reaction rate, and u ,the flow velocity. In this model R = 0 means concentration are independent of the reactions. Fluid on contact with an electrolyte (most solid surfaces) acquire a surface charge. And applying an electric field, generates electro osmotic flow and displaces the charged liquid in the electric double layer. It imposes a force on the positively charged solution close to the wall surface, and the fluid flows in the direction of the electric field [57]-[60].

II. METHODOLOGY

Simulation effect of the varying sinusoidal potential on the concentration of the fluids are studied and compared. While designing the simulation study first of all model of the micromixer is designed and after it general physics pertaining the simulation experiment to be carried is added. He we had added laminar flow physics and inlet, outlet and boundary conditions are defined for the structure. On Intel core i3 dual core processor at clock frequency of 2.27ghz, it requires a time duration of 2 min 18 seconds to compute the results for finer mesh analysis.

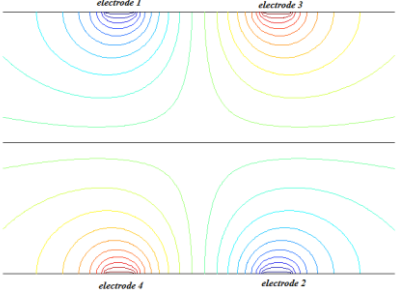

Fig. 2 showing electrode potential simulation results at V0max=0.1V

Fig. 2 shows the electric potential varying curves through out the geometry of the micromixer. Red lines shows the maximum positive potential existing at electrode potential 2 and 4 and maximum negative potential exists at electrode potential 1 and 3. The maximum potential is 0.09v and minimum potential is -0.01v. The distribution of potential stays the same through out. For V0 = 1V max., electric potential at 1 and 3 catches a maximum value of 0.85v and electrodes 2 and 4 catches a value of -0.95v. For V0max.=0, no electric potential contour are observed. Under the application of varying electrode potential we studied the varying velocity curves and average velocity at point probe in the domain area and compare the result. The concentration change for the varying potential is also noted and finally analysis is made as on which potential good mixing is provided.

III. RESULTS

Figure 3 to figure 6 shows the streamline velocity field at different time. Intervals for electric potential of V0max= +-0.1v applied at the alternate electrodes.

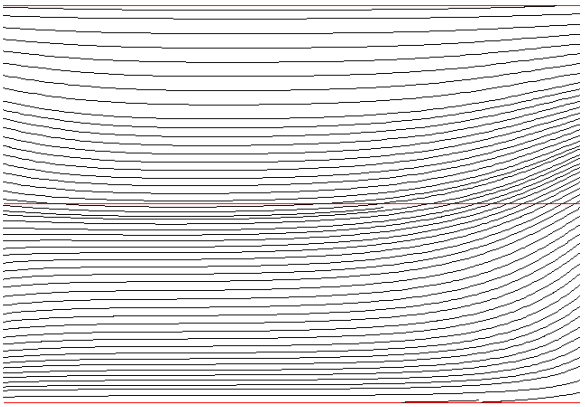

Fig.3 showing the streamline velocity field at time =0second showing no effect of electric potential on the streamline velocity field.

Fig. 3 shows that there is no turbulence effect introduced so far. The fluid flow is observing laminar flow characteristics.

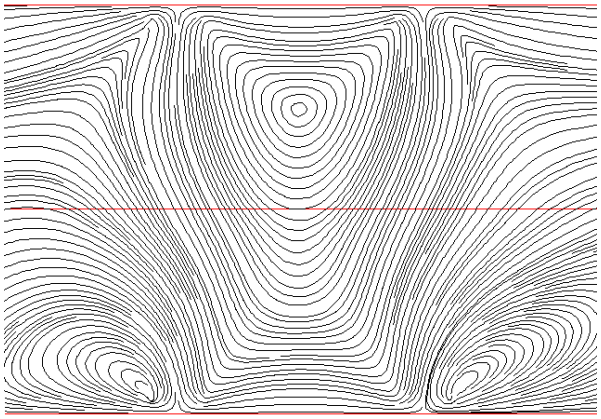

Fig. 4 showing the velocity field at time 0.025s showing the effect of electric potential on the streamline velocity field.

Fig. 4 shows that the turbulence effect is introduced with time and mixing of fluids of different concentration is observed.

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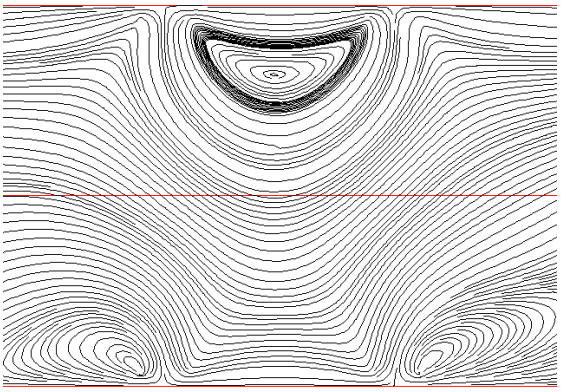

Fig. 5 showing the velocity field at time 0.05s showing the effect of electric potential on the streamline velocity field.

Fig. 5 shows that the turbulence effect sustains ensuring more mixing introduced with time. However the shape of velocity contour varies showing random velocity patterns.

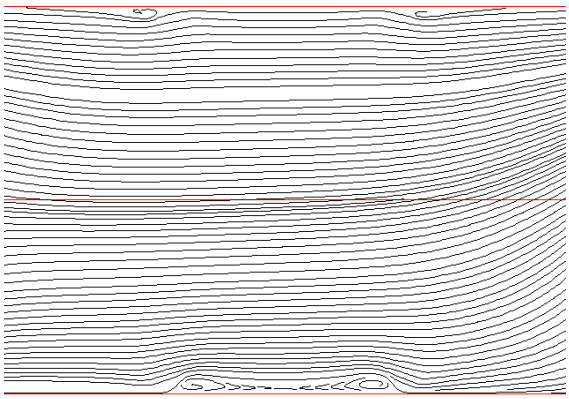

Fig. 6 showing the velocity field at time 0.25s showing the effect of electric potential on the streamline velocity field.

Fig. 6 shows that the there is no turbulence effect observed as the sinusoidal cycle repeats after 0.25s. Streamline velocity field with laminar characteristics is observed after 0.25 seconds ensuring working frequency of 8 hz.

Fig. 7 shows that at electrode potential of 0v, no turbulence is introduced and the fluid flow as such. Same streamlined constant velocity is observed at different intervals of time cycle after cycle.

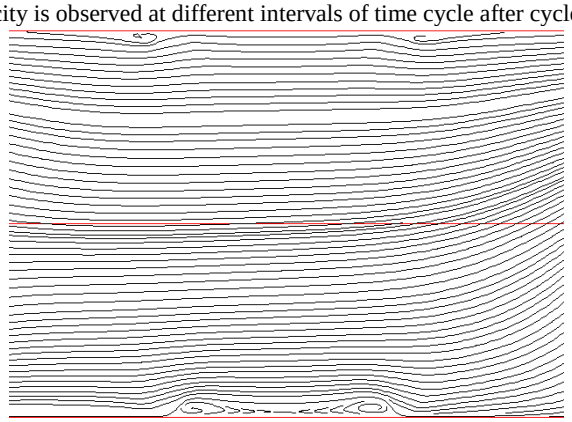

Fig. 6 showing the velocity field stays same throughout the time.

Figure 8 to Figure 10 shows the effect of electrode potential 1vmax. at the streamlined velocity field. Fig. 8 shows that there is no turbulence effect introduced so far. The fluid flow is observing laminar flow characteristics.

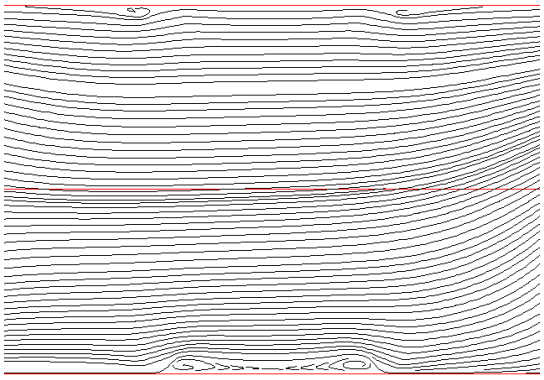

Fig.8 showing the streamline velocity field at time =0second showing no effect of electric potential on the streamline velocity field.

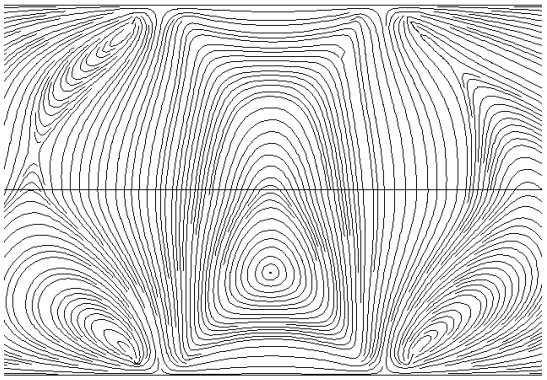

Fig. 9 showing the velocity field at time 0.025s showing the effect of electric potential on the streamline velocity field.

Fig. 9 shows that the turbulence effect ensures that mixing is introduced with time in the same manner as for Fig.4. However the shape of velocity contour varies showing random velocity patterns.

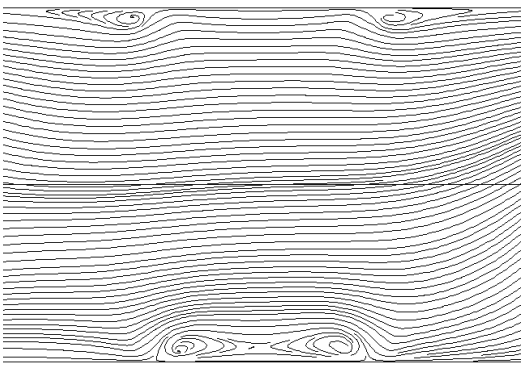

Fig. 10 showing the velocity field at time 0.25s showing the effect of electric potential on the streamline velocity field.

Fig. 10 shows that the there is no turbulence effect observed as the sinusoidal cycle repeats after 0.25s. Same velocity curves as that for Fig. 6 are obtained. Figure 11 to Figure 13 shows the time verses velocity field at point in the domain area. Fig. 11 shows the velocity field at electrode potential of V0max =1v.The maximum value of velocity 0.0897m/s is obtained at 0.09s and minimum value of velocity is 0.000123m/s obtained at 0.5s. Fig. 12 shows the velocity field at electrode potential of V0max =0v. The curve stays same through out. Fig. 13 shows the velocity field at electrode potential of V0max =0.1v.The maximum value of velocity .000**182**m/s is obtained at 0.4705s and minimum value of velocity is 0.000123m/s obtained at 0.2982s.

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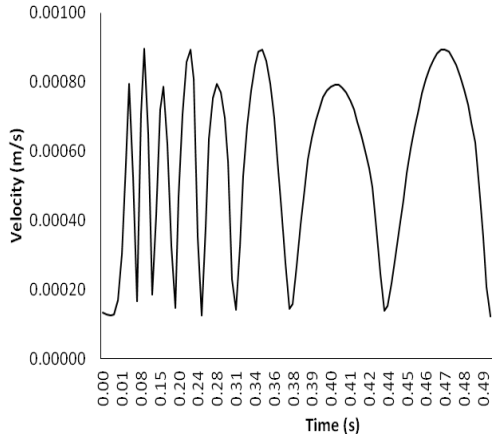

Fig. 11 showing the variation of velocity as a time dependent study for electrode potential of 1v.

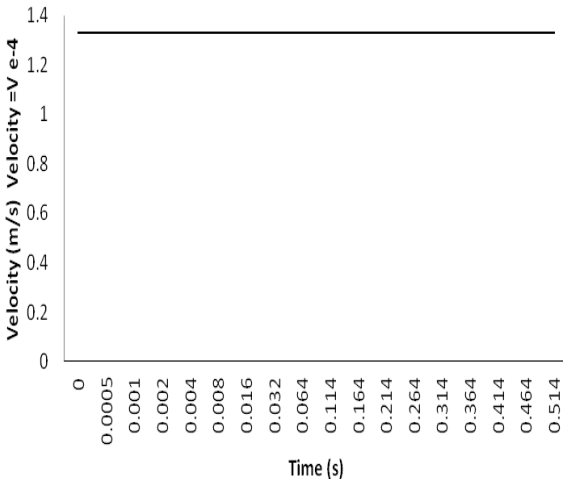

Fig. 12 showing constant velocity independent of time at electrode potential 0

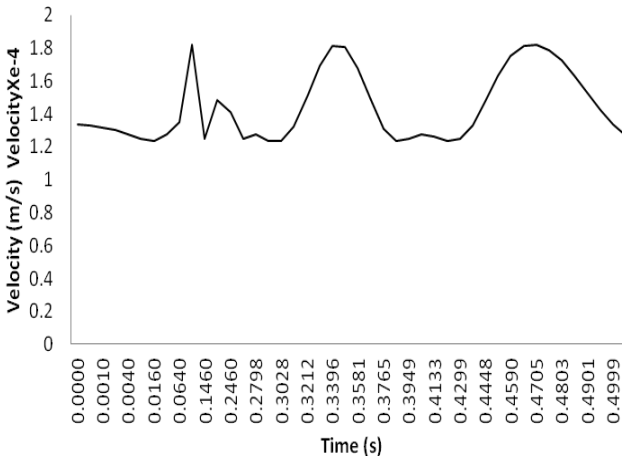

Fig. 13 showing the variation of velocity as a time dependent study for electrode potential Vmax. 0f 0.1v.

Figure 14 to figure 16 shows the concentration gradient at different intervals of time under the effect of electrode potential of value V0max=1v.

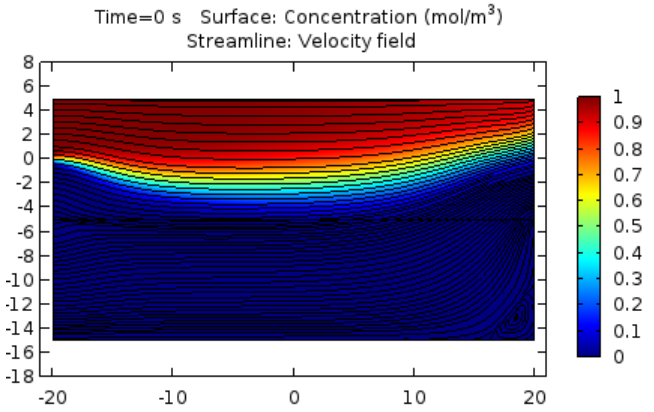

Fig. 14 showing concentration gradient at time =0s

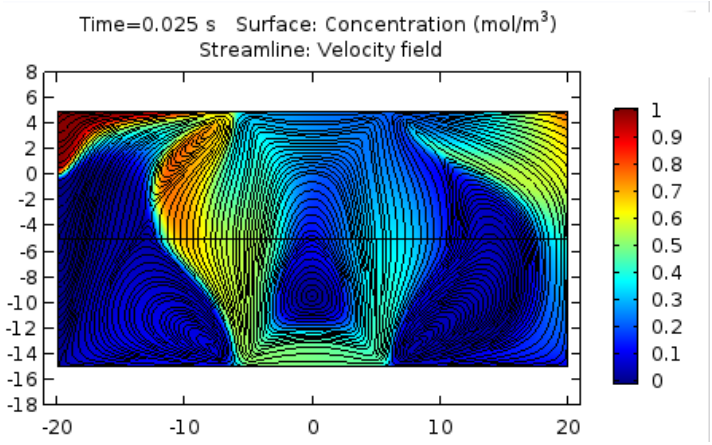

Fig. 15 showing concentration gradient at time =0.025s

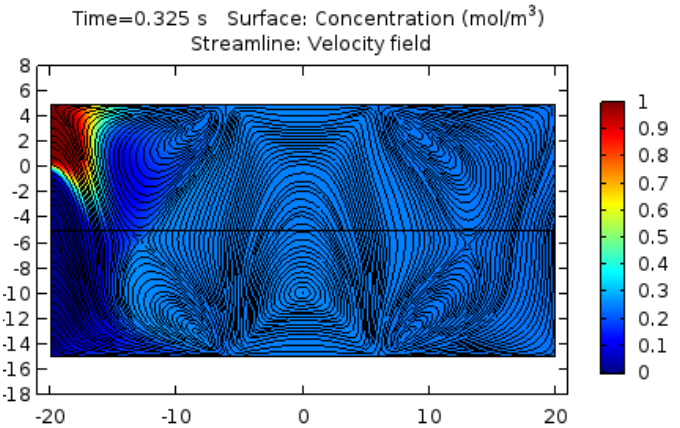

Fig. 16 showing concentration gradient at time =0.325s

Figure 17 to figure 19 shows the concentration gradient for different intervals of time under the effect of electrode potential of 0.1v.

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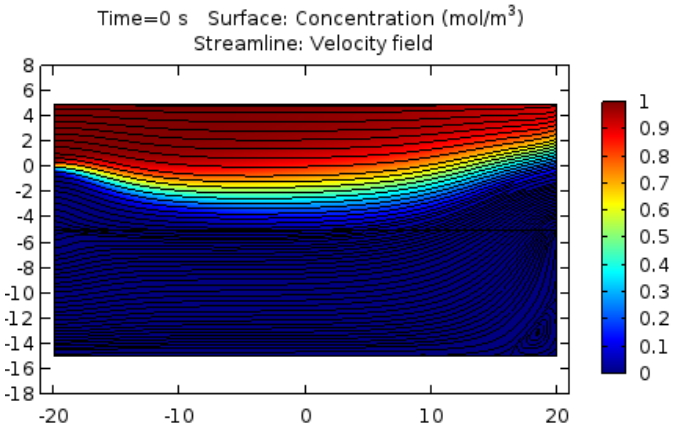

Fig.. 17 showing concentration gradient for electrode potential v0max =0.1v at time =0s depicting the same pattern as for electrode potential of V0max 1v

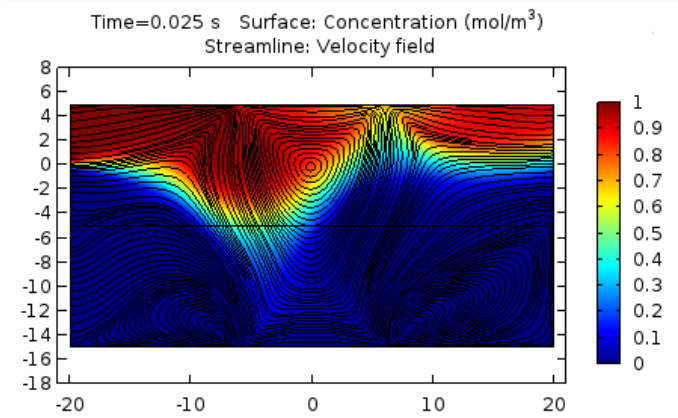

Fig.. 18 showing concentration gradient for electrode potential v0max =0.1v

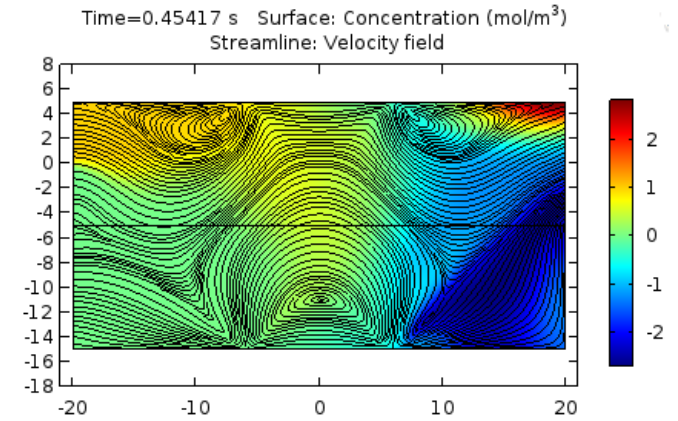

Fig.. 19 showing concentration gradient for electrode potential v0max =0.1v depicting the proper mixing and almost uniform distribution of concentration.

IV. Conclusion

On Intel core i3 dual core processor at clock frequency of 2.27ghz, a time duration of 2 min 18 seconds is required for each set of computation for varying electric potentials at constant concentration. Under condition of non applicability of electric field, flow continues to be laminar through out the mixer and whatever mixing occurs in the mixer is merely because of diffusion and no turbulence effect is there in the absence of the electric potentials. The finest mesh analysis with the same processor cannot be computed out for the same parameters. Electro osmotic mixing provides better mixing of the ingredient fluids entered through the inlets as compared to non electro osmotic mixing. It has been analysed from the results that with increasing electrode potential, the turbulence increases with increase in velocity and more proper mixing of fluids with different concentrations.

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