WIRE CLOTH ELECTRODES: A STUDY OF ELECTRIC FIELD FOR DIELECTROPHORETIC SEPARATION OF CELLS

Z. Zainal Abidin[1], A.G Liew Abdullah[1], Z. Yunus[2] and G.H Markx[3]
[1]Dept. of Chemical Engineering and Environmental, Faculty of Engineering, UPM, 43400 Selangor, Malaysia
[2]STRIDE, MINDEF, Taman Bukit Mewah Fasa 9, 43000, Kajang, Selangor
[3]School of Chemical and Analytical Science, University of Manchester, M60 1QD Manchester, U.K
Email: zurina@eng.upm.edu.my

ABSTRACT

Dielectrophoresis (DEP) could provide a simple and efficient way of separating cell. However, it has been limited to small scale by the use of microelectrodes fabricated from photolithography. As an alternative, the weaving of cloth with interlacing conducting and insulating threads was investigated as a novel way of making microelectrode arrays to improve the process. In this work, a simulation using FEMLAB 3.1 was conducted to study the electric field pattern on the model wire cloth system and hence its performance in cells collection. When the wire cloth system was modeled as only conducting wires, the electric field strength was found to be highest at the edge of the electrode and decays exponential with distance from the edge. However, for wire cloth electrode made up of stainless steel wire and polyester yarns, the presence of the polyester yarns disturbs the field pattern and created non-uniformities. This is good since greater uniformities promote better cell collection for separation. For wire cloth with polyester yarn having an electrical permittivity lower than medium permittivity, the electric field is stronger inside the yarns compared to edges of electrodes, and also at other locations. For an insulating thread with higher electrical permittivity than suspending medium, the stronger electric fields are in the vicinity of the wires and yarns instead of inside the yarn itself. Shapes of the electrode also affect the non uniformities generated inside the wire cloth system. The simulation results for wire cloth system are very encouraging compare to wires alone and hence promise a great prospect for its uses in DEP separation.

***Keywords**: cell separation, dielectrophoresis, wire cloth, textile technology*

INTRODUCTION

Advances made in many bio-related areas such as cell biology, bioprocessing and others has generated a demand for a highly efficient and improved cell separation techniques. One of the methods available is the manipulation of the behaviour of a particle or cell in a non-uniform electric field or otherwise known as dielectrophoresis (DEP) (Pohl, 1978; Pethig, 1996). When suspended in a fluid medium, the particle or cell can exhibit positive or negative DEP due to the dipole associated with charge distribution at the fluid/particle interface. Dielectrophoresis has shown many applications such as in monitoring and purifying cell cultures (Becker et al., 1994; Docoslis et al., 1994; Markx et al., 1994), detection and removal of toxic pathogens from water (Suehiro et al., 2003), separation of dead and live cells (Li et al., 2002; Markx et al., 1994) and the removal of human breast cancer from CD34+ from stem cells (Huang et al., 1999). DEP has the advantage of being non-invasive and can be conducted under sterile conditions. More importantly, DEP can be integrated with other methods to achieve improved separation since the physical properties exploited by DEP have little impact in other cell separation methods.

Currently, the application of DEP uses microelectrodes fabricated using photolithography technique. The high field intensities which are important for DEP application have become possible due to the small dimensions of the microelectrode. Furthermore, it reduces the heat and enhances heat dissipation. However, the size of the substrate limits the capability of the microelectrodes to microlitres. This is rather unattractive for industrial application which requires for more sample volumes to be processed. The use of wire cloth suggests a potential alternative to meet the need of this large scale application.

Therefore, in this paper, we first study the electric field pattern of the wire cloth electrode system by simulation to promote better understanding of DEP process and hence assess its efficiency for cells separation at large scale. The wire cloth model consists of conducting wires running perpendicular to lengths of insulating wire which is similar to the microelectrodes fabricated by photolithography on glass slides.

THEORY

Dielectrophoresis works because of the existence of the non-uniform electric field which is vitally determined by the electrode configuration. Following established theory (Pohl, 1978; Pethig, 1979; Jones, 1995), the DEP force, F_{DEP} acting on a spherical particle of radius r suspended in a fluid of absolute dielectric permittivity ε_m is given by:

$$F_{DEP} = 2\pi r^3 \varepsilon_0 \varepsilon_m Re(fcm) \nabla E^2 \quad (1)$$

where *Re(fcm)* is the real part of the Clausius Mossoti factor, ∇E^2 is the square of the electric field gradient, ε_m is the medium conductivities and ε_0 is the free space permittivity (8.854 x 10^{-12} Fm^{-1}).

$$f_{cm} = \frac{(\varepsilon_p^* - \varepsilon_m^*)}{(\varepsilon_p^* + 2\varepsilon_m^*)} \quad (2)$$

where ε_p^* *and* ε_m^* are the frequency-dependent complex dielectric permittivities of the particle and its suspending medium and are defined by:

$$\varepsilon_p^* = \varepsilon_p - j\frac{\sigma}{\omega} \quad (3)$$

where ε_p are the permittivity of the particle and its suspending medium. σ is the conductivity and ω is the angular frequency, ($\omega = 2\pi f$). Clausius Mossoti factor depends on the applied frequency and also the electric properties of the particle relative to the medium. Theoretically, it should have a value between +1.0 to -0.5 which means that the DEP force can be positive and negative.

From Equation 1, DEP force is proportional to the value of ∇E^2 which means reversing the polarity of the applied voltage will not affect the direction of the force. ∇E^2 only depends on the electrode geometry and the voltage and can be calculated using the following formula (Pethig, 1996):

$$\nabla|E|^2 = \nabla i\,(E_k.E_k) = 2.E_k.\,(\nabla i\,E_k) = 2\,E_k\,(\nabla E)_{ki} \quad (4)$$

where *i* and *k* refer to the component in x, y and z directions, (*i*=*x*, *y*, *z* and *k*=*x*, *y* and *z*).

MATERIALS AND METHODS

A study of the electric field pattern generated by all the electrodes was done to improve the understanding of the systems. This analysis was conducted using the Electromagnetic module available in FEMLAB 2.3 (Comsol, UK) software. The electric field was modeled as a DC field in contrast to the application which uses AC field.

Figure 1 shows the actual wire cloth system prepared using textile technology, while Figure 2 depicts the model wire cloth system redrawn and used in the simulation study. The models of the wire cloth system with and without the polyester warp were done in 2-D forms. Circles were drawn to represent the wire while a square slab was drawn to represent the yarns. The yarns were drawn to wrap the wire alternately above and below. The wire was alternately connected to the electric potential of 30 $V_{pk\text{-}pk}$ and also ground. Finally the fluid was drawn to encapsulate the whole wire cloth area inside the chamber as being done in experimental work.

The simulation was done for several systems which include 2-D model of conducting wires only, model of conducting wires and yarn of lower electrical permittivity of 3.5 (compared to medium conductivity of water, ε_m=80) and finally model of conducting wires and yarn of higher electrical permittivity of 500.

The results from FEMLAB were extracted and analysed. A simple program written in MATLAB 6.5.1., was used to calculate the values of $\nabla|E|^2$ and hence DEP force as a tool to study its efficiencies.

ISSN 1823-1039 ©2007 FEIIC

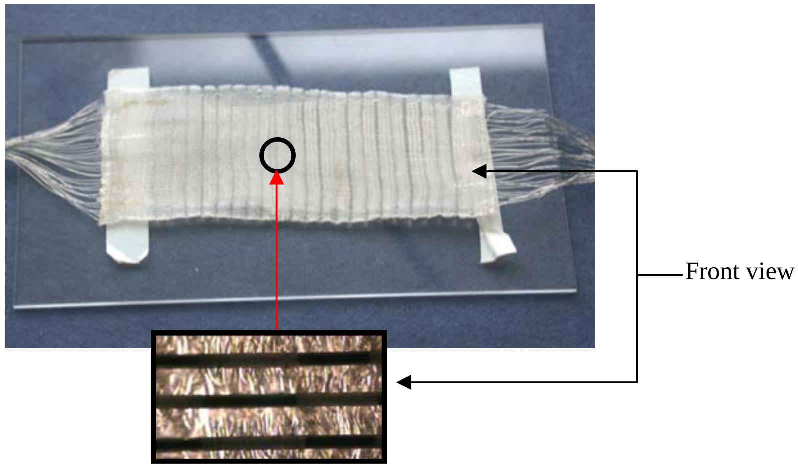

Figure 1: Actual wire cloth electrode. The small insert picture is the wire cloth electrode viewed under microscope at 20x magnification. It can be seen wires running horizontally while the yarns run vertically.

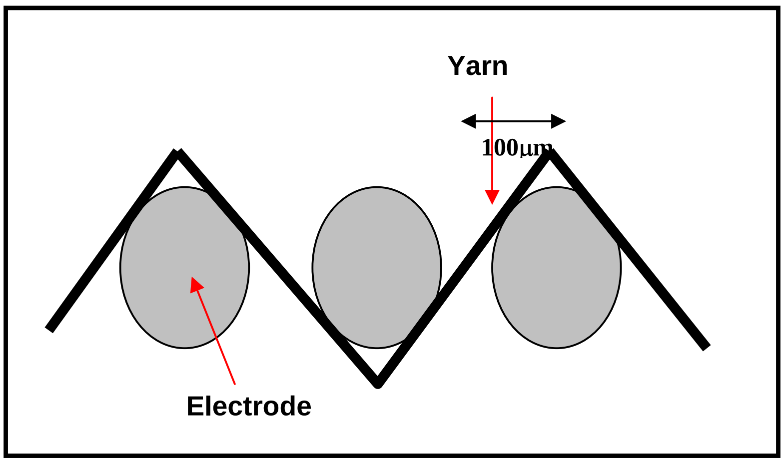

Figure 2: Front view of model wire cloth electrode system used in simulation work

RESULTS AND DISCUSSIONS

A model of the cloth with wire electrodes of 100 µm in diameter and a 150 µm gap size was simulated in 2-D using FEMLAB. The wire electrodes were alternately connected to the ground and electric potential. . The 2-D representation of this can be seen in Figure 3. When there is no polyester yarn, the variation of the electric field of the electrode in a wire mesh is similar to that of a planar microelectrode system (Pethig, 1996). The highest electric field strengths are found at the edges of the electrodes. As one moves away from the edge of electrodes, the electric field strength becomes weaker. These results are further illustrated in Figure 4 when an analysis of the electric field pattern was done along a line drawn through the middle of electrode system (red line in Figure 3).

Subsequent analysis conducted includes the study of the electric field pattern in a system with polyester yarns having a relative permittivity of 3.5 (lower than ε_m). The electric field distributions can be seen in Figure 5. In comparison to Figure 3 for wires with no yarns, the presence of the polyester yarns clearly distorted the electric field lines creating field of non uniformities inside the system. The electric field surrounding the yarns is being concentrated at the yarns, thus creating a reduced electric field strength in the vicinity of the yarns. These can be clearly seen in Figure 6 when an electric field analysis was done along the red line (see Fig. 5).

In a further investigation, the use of yarns with a high electrical permittivity of 500 (higher than ε_m) was studied and the electric field patterns inside the wire cloth are shown in Figure 7. The presence of the yarns again distorted the electric field lines to create non-uniformities. In this case however, stronger electric fields can be seen in the vicinity of the wires and yarns instead of inside the yarn itself. The analyzed result along the red line (see Fig. 7) is shown in Figure 8.

Unlike a planar microelectrode system by photolithography which is widely used now, the electric field in a wire cloth acts in three dimensions. In the planar microelectrodes, only the surface exposed to the liquid can be used for cells collection whereas for the wire cloth, all surfaces can be potential sites for cells collections. Furthermore, greater non-uniformities formed by the wire cloth implied a better performance in cell trapping compared to system without yarns. This would definitely be an added advantage, boosting the performance of the wire cloth in DEP separation of cells compared to small scale microelectrodes by photolithography. Results in Figure 5 and 7 suggested that wire cloth with higher permittivity yarns will perform better compared to yarns with lower permittivity. This is because yarns with higher permittivity will give greater distortion of the field pattern, creating higher values of ∇E^2 at the bead vicinity that can help to attract more cells in the system.

The highest electric field strength generated by this system is comparable to the electric field strength recorded with the microelectrodes systems (Pohl, 1978) which means that the wire cloth should improve the current small scale DEP separation of cells.

To compare different electrode configurations, electrodes of diamond, square and triangular shaped were drawn with a gap of 150 μm. The electric field distributions are plotted in Figure 9. Diamond-shaped electrode gave the highest electric field value of 1.07×10^5 Vm^{-1} followed by triangle, 9.98×10^4 Vm^{-1} and finally square, 9.5×10^4 Vm^{-1}. Circular electrodes meanwhile gave a value of 1×10^5 Vm^{-1}. Square and circular electrode shapes clearly show a wider coverage of area with high electric field strength compared to the other shapes. This is in agreement with the work by Wakizaka et al. (2004). The results also suggest that the use of different cross sectional shape of the yarns can also affect the non-uniformities created inside the wire cloth system and hence capability of cells collections.

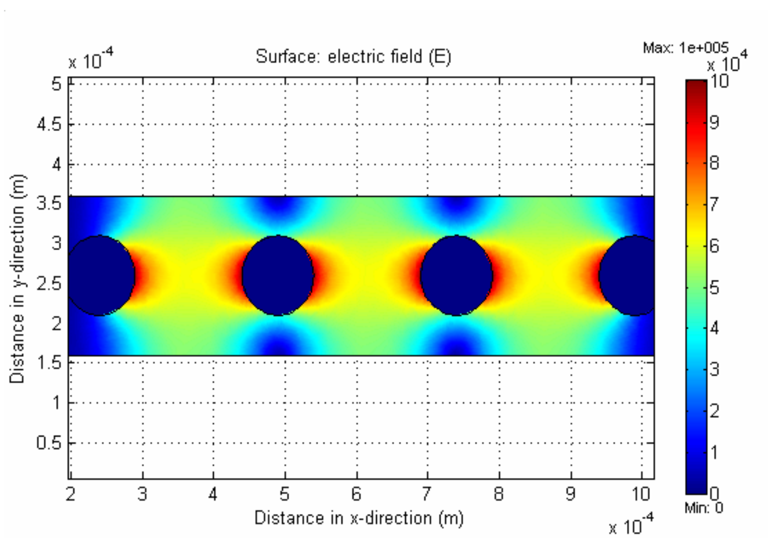

Figure 3: The 2-D representation of the electric field variation in a wire electrode system simulated at 30 V_{pk-pk}. The strongest electric field strength as shown in red can be seen near the electrode edges. As one moves away from the edge of electrodes, the electric field strength becomes weaker.

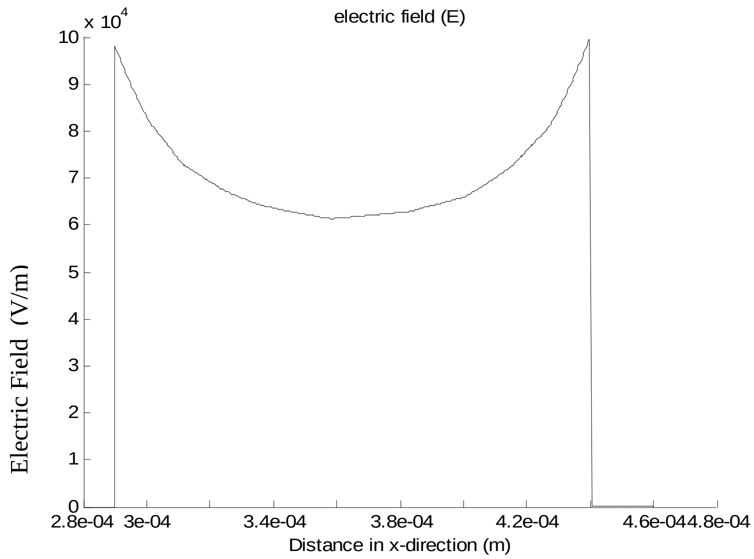

Figure 4: Electric field plot between wires (refer to red line in Figure 3) for a wire system for a 2-D model.

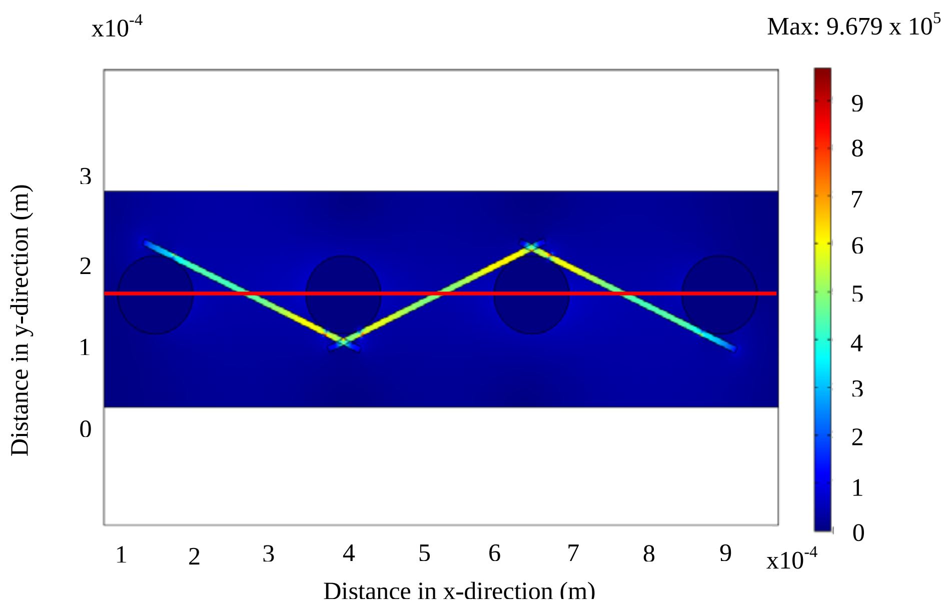

Figure 5: The 2-D electric field surface plot for a wire cloth system with a polyester yarn (ε_p =3.5). The presence of the yarn disturbs the electric field lines and causes a high electric field strength region to be generated at the yarns and reduce the field strength at the vicinity of the yarns.

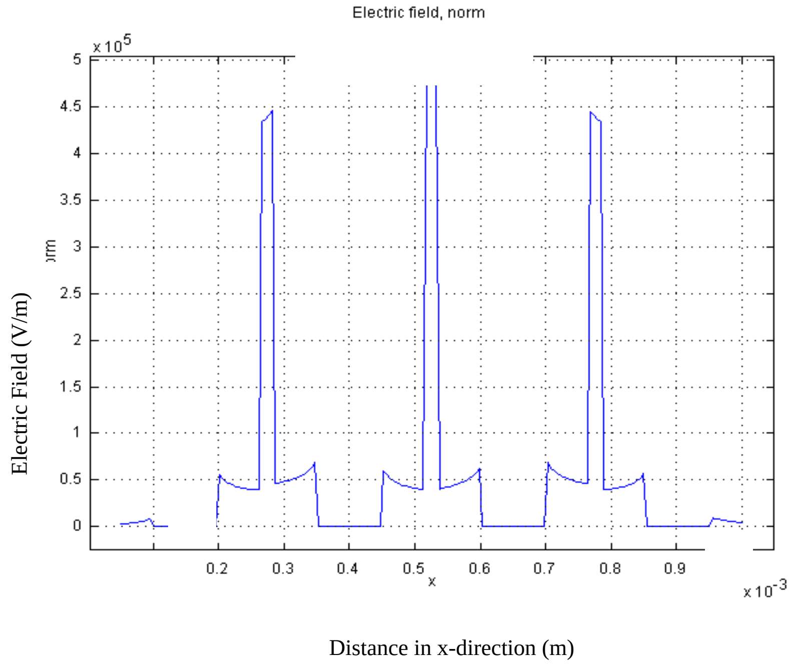

Figure 6: The electric field plot at the red line as in Figure 5 against the distance inside the chamber. This plot shows the electric field pattern describe in Figure 5 more clearly.

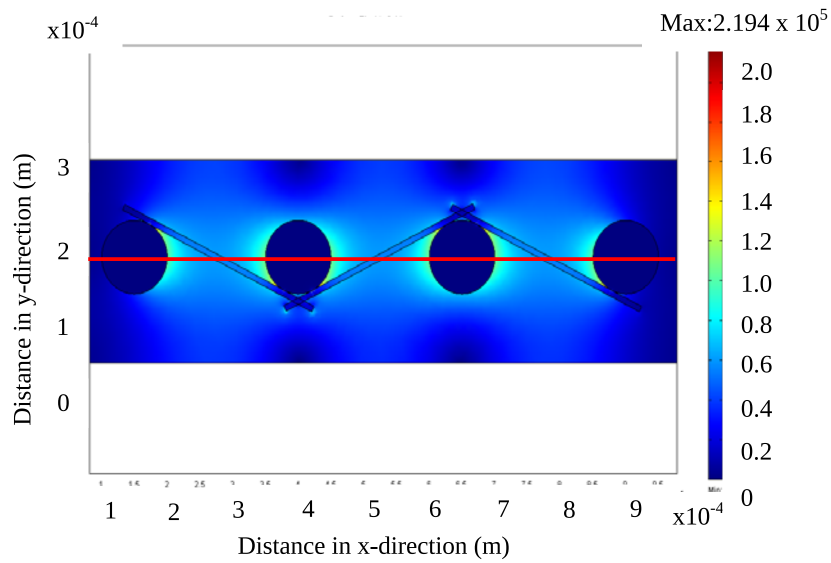

Figure 7: The electric field surface plot for a wire cloth with a yarn having a higher value of electrical permittivity (ε_p = 500). The electric fields are disturbed by the high permittivity yarns creating, a high electric field strength region in the surrounding medium instead of inside the yarn as in Figure 3.

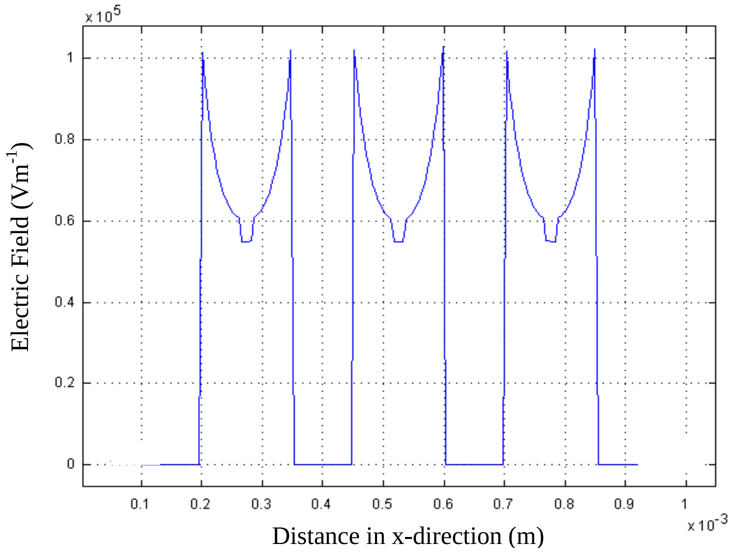

Figure 8: Electric field plot at the red line (shown in Figure 7). It presents a better picture of the electric field behaviour describes in Figure 7.

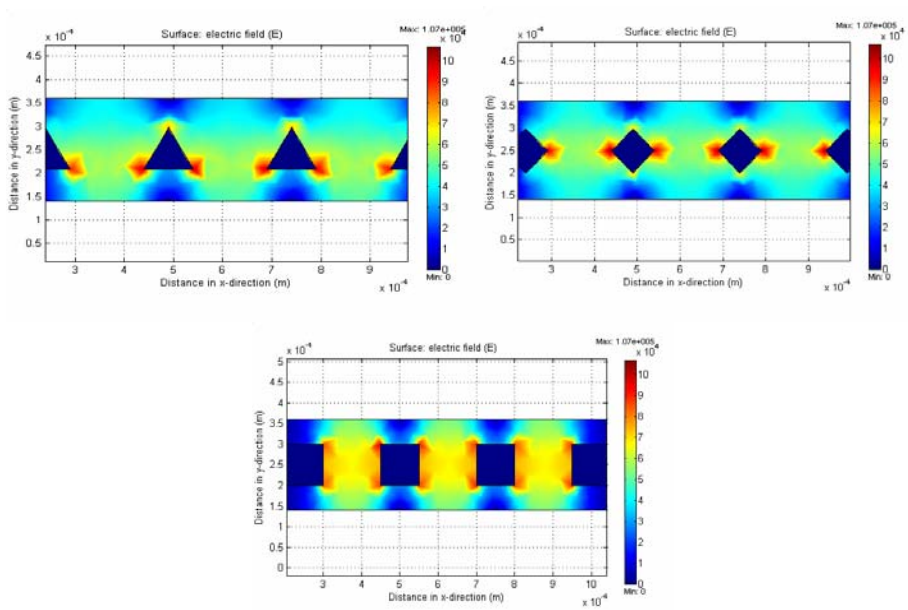

Figure 9: Electric field distributions for diamond, square and triangle electrodes shape. Diamond and triangle give a higher electric field strength compared to square. However, square electrode shows a wider coverage of area with high electric field strength.

CONCLUSIONS

Simulation work has been done to study the electric field pattern of wire cloth electrodes for large scale applications of dielectrophoretic separations. Wires without yarns show similar electric field behaviour to microelectrodes produced by photolithography. When conducting wires woven with yarns, the presence of the polyester yarns disturb the electric field pattern and created non uniformities which also can be potential sites for cells collections. The magnitude of the electric field is comparable to the small scale system and therefore promise great prospect in DEP separation of cells

ACKNOWLEDGEMENT

We wish to thank Universiti Putra Malaysia for financial support.

REFERENCES

[1] Pohl HA. (1978). Dielectrophoresis. Cambridge: Cambridge University Press.
[2] Pethig R. (1996). Dielectrophoresis: Using inhomogeneous AC electric fields to separate and manipulate cells. *Crit. Rev. Biotech*., **16**(4), 331-348
[3] Becker FF, Wang XB, Huang Y, Pethig R, Vykoukal J and Gascoyne PRC. (1994). The removal of human leukaemia cells from blood using interdigitated microelectrodes. *J. Phys. D: App. Phys*. 1994, **27**: 2659-2662.
[4] Docoslis A, Kalogerakis N, Behie LA and Kaler KVIS. (1994). A novel dielectrophoresis-based device for the selective retention of viable cells in cell culture media. *Biotech. Bioeng*., **54**: 239-250
[5] Markx GH, Huang Y, Zhou XF and Pethig R. (1994). Dielectrophoretic characterization and separation of microorganism. Microbiology, **140**: 585-591.
[6] Suehiro J, Zhou G, Imamura M and Hara M. (2003). Dielectrophoretic filter for separation and recovery of biological cells in water. *IEEE Trans. Ind. App*., **39**(5): 1514-1521.
[7] Li H and Rashid B. (2002). Dielectrophoretic separation and manipulation of live and heat-treated cells of Listeria on microfabricated devices with interdigitated electrodes. *Sens.Actu. B*, **86**(2-3): 215-221.
[8] Markx, GH, Talary, M and Pethig R. (1994). Separation of viable and non-viable yeast using dielectrophoresis. *J Biotech*., **32**: 29-37
[9] Huang Y, Yang J, Wang XB, Becker FF and Gascoyne PRC. (1999). Cutting Edge Communication: The removal of human breast cancer cells from hematopoietic CD34+ stem cells by dielectrophoretic field-flow-fractionation. *J Hema. Stem Cell Res*. **8**(5): 481-490.
[10] Pethig, R. (1979). Dielectric and Electronic Properties of Biological Materials, J. Wiley and Sons.
[11] Jones, T. B. (1995). Dielectrophoretic Force Calculation, *Journal of Electrostatics*, **6**: 69-82.
[12] Wakizaka , Y., Hakoda, M. and Shiragami, N. (2004) Effect of electrode geometry on dielectrophoretic separation of cells. *Biochemical Engineering Journal*, **20**: 13-19.

NOMENCLATURE

F_{DEP}	Force	(N)
r	Particle radius	(m)
ε_0	Free space permittivity	(Fm^{-1})
ε_m	Medium permittivity	(Fm^{-1})
$Re(f_{cm})$	Clasius Mossotti Factor	(-)
∇E^2	Squared electric field gradient	(V^2/m^3)
ε_p^*	Complex particle permittivity	(Fm^{-1})
ε_m^*	Complex medium permittivity	(Fm^{-1})
j	Imaginary number	(-)
σ	Particle conductivity	(Sm^{-1})
ω	Angular frequency	(Hz)
f	Frequency	(Hz)