Effects of wire diameter, yarns size and wire configuration to wire cloth electrode produced from textile technology for dielectrophoresis application

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Abstract. Dielectrophoresis (DEP) is one of an alternative way for cell separation. It has mainly been limited to processing small volumes due to constrain in fabrication of microelectrode over large surface areas. This work focuses on optimizing the wire cloth electrode fabricated from the use of textile technology. The plain-weave wire cloth consists of stainless steel wires as the microelectrode arrays and polyester yarn as the insulator. The study involved producing wire cloth electrode with variations of wire diameters, yarn sizes and wire configuration (single or double twisted). Simulation using FEMLAB software was conducted to study the electric field generated from the wire cloth. The performance of the finished wire cloth electrode was then tested by conducting a small-scale separation experiment. It was found that larger diameter wire electrode and smaller yarn size resulted to higher electric field strength. In regards to wire configuration, double twisted wire led to higher electric field intensity and better nonuniformity with 1.25% and 9.29% higher cell separation yield recorded than single wire for 100μm and 71μm, respectively.

1. Introductions
Biochemical and bioprocessing has gained an overwhelming recognition due to need for rapid and robust technologies. More and more industries nowadays were moving towards developing process based on biochemical and biotechnology because of their inherent advantages [1]. However, when dealing with bioprocessing, the usual constraint is the downstream processing or the bioseparation which is the recovery and purification of the desired product from the upstream process whereby the percentage of recovery is low. These kinds of trends and challenges in modern bioseparation have led to various discoveries and novel approaches in the techniques used.

Dielectrophoresis (DEP) is one of an alternative way for bioseparation, particularly cell separation. DEP is a motion of particles caused by the interaction of cell induced dipole in non-uniform AC electric fields [2]. It has certain advantages over other methods mostly because of its high resolution or selectivity. Additionally, by DEP, cell viability can be maintained and the process can be conducted under sterile condition. Previous works regarding DEP involved separating live and dead cells or monocytes [3,4], manipulating cells using travelling electric fields [5,6], and application in the water [7] and wastewater treatment [8]. In nanotechnology, numerous works have been done regarding viruses [9,10]. Alternatively, research on the use of higher throughput have increased with 3-
dimensional insulator [7] or electrode separator [3,11,12], wire cloth electrode separator [13], filter chip separator [14] and integrated microfluidic chip [15].

DEP has been limited to processing small throughput due to restriction in fabrication of microelectrode for large surface areas which mostly used lab-on-a-chip device and printed circuit board. Hence, the preparation of microelectrode using textile technology is implemented to overcome the throughput issue. While previous study [13] proved to be effective for fungi species such as yeast (Saccharomyces cerevisiae), this study targeted smaller microorganism using bacteria Escherichia coli with improvement of the microelectrode gap which involved wire diameter, yarn size and wire configuration. Electric field generated from the wire cloth system is simulated using FEMLAB and wire cloth performance is investigated following its production.

2. Materials and Methods
The studies were grouped into the production of wire cloth, the simulation of the electric field and the separation experiment.

2.1. Production of wire cloth
A simple plain-weave pattern is chosen for the wire cloth design in which stainless steel wire (Ormiston Wire Ltd, UK) with diameter of 71µm and 100µm was used as weft whilst the warp consisted of the textured multifilament polyester yarns (Hualon Recron Pte Ltd, Nilai, Malaysia) with yarn density of 58 decitex and 83 decitex (respective diameter of 10µm and 16µm). The maximum weft density of the weaving machine was 93 pick per inch (PPI). In general, weaving process was done in stages started with warping, followed by threading and weaving.

2.1.1. Warping. The yarns were taken from yarn cones assembled in parallel lines by rewinding process to give a warp. The warp density of 30 ends per inch for a total of 4 inches was used. The prepared warp was then transferred to a weaver beam of a weaving machine (Swiftec Mfg., Kajang, Malaysia).

2.1.2. Threading. The threading stage involved positioning the warped yarn into series of slot of the weaving machine (shafts, heddles and reed) according to the pattern required. The weaving machine has 4 shafts with mounted heddles on each shaft. For the plain weave pattern, the first yarn of the prepared warp was hooked in the eye of the first heddle on shaft 4. Then the subsequent yarns were threaded through all the first heddles on shaft 3, shaft 2 and finally shaft 1. This sequence of threading made one complete cycle. Once a cycle was finished, the same procedures were repeated onto the next set of heddles on all shafts following its order until all the yarn warps were threaded. After the heddles, the warp ends were inserted into each dent in the reed (30 dents/ inch) to regulate the yarn spaces.

2.1.3. Weaving. Each weaving cycle involves shedding, picking and beating. During shedding process, the warp threads which were under tensioned by the heddles were separated into 2 layers to form a tunnel with half of the heddle shafts (shaft 2 & 4) to be at the top layer and the other half (shaft 1 & 3) to be at the bottom layer. Then, in the picking process, the stainless steel wire, acting as the weft part were individually inserted into the tunnel prior to the beating in which the reed is drove forward to tighten the newly inserted weft. Simultaneously, this action caused the heddle frames on shaft 1 and 3 to be raised up while the heddles frames on shaft 2 and 4 to be lowered, locking the weft with warp and forming a new tunnel alternating the initial configurations. These steps were repeated until the required length of wire cloth was obtained. For this study, variation of yarn size (58 and 83 decitex), wire diameter (71µm and 100µm) and wire configuration (single and double twisted) were used.
2.2. Simulation study on the electric field pattern

A study of the electric field strength and pattern generated by electrodes of the wire cloth was performed using FEMLAB 3.0 (COMSOL™) using the Electromagnetic module [13,16]. The electric field was simulated with parameters that were wire diameter, yarn size and wire configuration. The yarn was drawn to wrap the wire alternately above and below mimicking the plain weave pattern. A rectangle shape was drawn to represent the water that encapsulated the wire cloth area.

2.3. Separation experiment

After the wire cloth production, its effectivity was investigated using the separation experiment in which the data acquired includes the visual of the separation as well as the percentage of the separation achieved. Prior to the experiment, all variation of wire cloth produced were trimmed and tested for any connectivity issue and proceeded for a small chamber construction using microscope glass slides.

2.3.1. Cell preparation. Escherichia coli (Biotechnology Lab, Universiti Putra Malaysia) was cultured overnight in nutrient broth (Oxoid, UK) at 37°C in a 150 rpm incubator shaker (Stuart, Fisher Scientific, UK). The cell was then harvested, centrifuged at 5000 rpm (Heraeus, Thermo Scientific, USA) and washed four times with distilled water. Early concentration of cells suspended in distilled water was measured through 600nm wavelength of a UV spectrophotometer (Thermo Electron Corporation, UK).

2.3.2. Experimental setup. The flow diagram for the experiment is shown schematically in figure 1. The DEP chamber was placed under a camera-equipped microscope (Leica Qwin, Germany) to observe and capture visuals of dielectrophoresis of bacteria cells through the software provided. The aforementioned E. coli cells suspension was placed in a syringe and the syringe was positioned at the syringe pump. Once the chamber was filled with distilled water, the cells was pumped into the chamber and immediately 1 MHz frequency and 20 Vpk-pk voltage was applied to the system using the frequency generator (TG120, Thurlby Thandar Instruments, UK). The visuals of the DEP was captured through the software of the microscope camera and afterwhile, the experiment was stopped, the DEP sample was processed and the yield was analyzed using spectrophotometer.

![Figure 1. The schematic diagram of the separation experiment as explained in section 2.3.2.](image)

3. Results and Discussion

The discussion covers all the said effects which are yarn size and wire diameter and configuration towards the wire cloth product, the simulation study as well as to the separation experiment.
3.1. Wire cloth product
The objective for the fabrication of wire cloth was to determine the best combination of settings needed to produce an optimized wire cloth for dielectrophoresis application. The key factor was to obtain the smallest gap between electrodes for a more efficient separation.

3.1.1. Effect of wire diameter. The distance between the electrodes was optimized using 71 µm and 100 µm stainless steel wires. As can be seen in Figure 2, the electrode wires are the black bold lines in the horizontal direction, whilst the multifilament polyester yarns are perpendicular to it. The increment of the wire diameter caused the gap between the wires decreased, hence stronger dielectrophoretic force experienced by the cells [9,17]. This is due to the weft setting fixed to 93 PPI (picks per inch) in which the machine beats exactly 93 wires for every inch produced resulted either smaller or larger gap based on the compression of weft which in this case the electrode wires. Table 1 summarized the average gap calculated from all wire cloth produced.

![Figure 2](image_url)

**Figure 2.** The wire cloth under the light microscope with magnification of 10x and 40x. The electrode diameter used was single 71µm (a) and 100µm (b) with similar yarn size.

| Wire Diameter (µm) & configuration | Average Real Gap (µm) |
|-----------------------------------|-----------------------|
|                                   | 58 dtx | 83 dtx |
| 71 single                         | 146    | 198    |
| 71 double                         | 94     | 104    |
| 71 double (twisted)               | 126    | 139    |
| 100 single                        | 119    | 150    |
| 100 double                        | 39     | 70     |
| 100 double (twisted)              | 69     | 122    |

3.1.2. Effect of wire configuration.
Next, the effect of wire configuration to the wire cloth was studied. The wire diameter used were both 71 µm and 100 µm with three comparable wire configurations; single wire, double wire and double wire twisted. Figure 3 shows the images of the electrodes for double configuration with significant change of wire gap from previous single configuration. The 100 µm double wire obtained smaller electrode gap compared to 71 µm double wire because double configuration makes the diameter value doubled. This leads to the aforementioned compression of the weft that resulted to the small electrode gap value. Similarly, the usage of double twisted wire for the 100µm wires (figure 4b) still gave smaller gap than the 71µm double twisted (figure 4a). Numerically, for a 93PPI of weft setting, 14% gap difference was recorded from both wire diameters (table 1).
Figure 3. The double non-twisted wire cloth under the light microscope with magnification of 10x and 40x. The electrode diameter used was single 71 µm (a) and 100 µm (b) with similar yarn size.

Figure 4. The double twisted wire cloth under the light microscope with magnification of 10x and 40x. The electrode diameter used was single 71 µm (a) and 100 µm (b) with similar yarn size.

3.1.3. Effect of yarn size.
Polyester yarns comprised of very fine and slightly elastic filaments, very flexible for weaving stainless steel wire and helped reducing the distance between the wires. Two polyester yarn size of 58 dtex and 83 dtex were used in order to compare the electrode gap achieved. Referring to table 1, although different yarn sizes were used, the pattern of its corresponding real gap values was not quite faraway with the smallest electrode gap again produced by 100 µm double wire. Other than the gap, the significance of using smaller yarn size was to promote better electric field intensity around the system during DEP process which is discussed next.

3.2. Electric field simulation of the wire cloth electrode
In discussing dielectrophoresis theoretically, the main factors affecting its process were the electric field strength and electric field non-uniformity. Again, the electric field generated with variation of wire diameter, wire configuration and yarn size were modelled with the terminal wires alternately connected to the electric potential (20 Vpk-pk) and ground [13].

3.2.1. Effect of different wire diameter.
As shown in figure 5, the blue circle represents cross-section of the alternate charged and ground wire electrodes while the zigzag shape represents the polyester yarn with the red area indicates high electric field strength. Figure 5(a) simulated the 71 µm wire cloth system while the 100 µm wire was represented by figure 5(b). Maximum values of electric field generated were $1.340 \times 10^6$ V m$^{-3}$ and $1.341 \times 10^6$ V m$^{-3}$ respectively showed that the diameter influence the electric field strength in the wire cloth system which was the smaller the gap, the higher the electric field achieved.
Figure 5. The simulation of single 71µm(a) and 100µm(b) wire cloth system. Maximum value of electric field obtained were 1.340×10^6 V^2 m^{-3} and 1.341×10^6 V^2 m^{-3} respectively.

3.2.2. Effect of different wire configuration. \( \mathbb{E}^2_{\text{rms}} \) defines the average local non-uniform electric field strength and gradient, and is dependent on the applied voltage as well as the electrode geometry and size. Hence, some alteration to the wire arrangement might modify the electrode geometry for instance the introduction of the twisted wire configuration. From the simulation done, the highest value of electric field obtained was 2.042×10^6 V^2 m^{-3} through 100µm double twisted wire. Table 2 summarizes the maximum electric field attained for all the simulated wire cloth.

| Wire Setting  | Yarn Diameter (µm) | Max Electric Field (V^2 m^{-3}) |
|---------------|--------------------|---------------------------------|
| 71 µm single  | 16                 | 1.340×10^6                     |
| 100 µm single | 16                 | 1.341×10^6                     |
|               | 10                 | 1.591×10^6                     |
| 100 µm twisted| 10                 | 2.042×10^6                     |

The twisted wire configuration furthermore produced diverse range of non-uniformity due to its different geometry. The contour option was selected during simulation yielded patterns as seen in figure 6. For the single wire, the contour generated repetitive define patterns while the twisted wire induced more coverage with inconsistent patterns. This was beneficial to dielectrophoresis as the cells required non-uniformities to achieve a good degree of separation [18,19].

3.2.3. Effect of warp size (polyester yarn).

Next, the simulation done using a smaller yarn size of 58 dtx resulted to a higher value of electric field produced compared to 83 dtx yarn size with values of 1.341×10^6 V^2 m^{-3} and 1.591×10^6 V^2 m^{-3} each (table 2). This was due to the fact that the yarns has its own permittivity value (=3.0) and this property was responsible for distorting the electric potential and electric field of a DEP system. As the yarn also act as an insulator, its size determined the intensity of the electric field distortion experienced by the wire cloth, hence the higher electric field value for smaller yarn. Research [14,17] proved that a higher permittivity of insulator resulted to a lower electric field and vice versa.

3.3. Separation experiment

After theoretical simulation of the wire cloth behavior, they were brought to test for separation experiment for further understanding. A small DEP chamber was prepared using glass slides to
evaluate the performance of the wire cloth for *E. coli* collection. The observation consisted of both microscopic views of the DEP as well as quantitative results derived from the number of cells collected. Figure 7 shows a successful DEP with pearl chain formation (as indicated by the red circles) of bacteria cells seen at the edge of the electrodes; the formerly neutral-charged cell experienced permittivity complex relative to the medium (which was water), hence resulted to the cells movement towards the high field region of electrode that was known as the positive dielectrophoresis (positive DEP) [4].

![Figure 6](image)

**Figure 6.** The contours represents the non-uniformity of electric field simulation of (a) 100µm single wire and (b) 100µm double twisted wire

In terms of the wire cloth efficiency, the yield was calculated [20] by percentage of cells experiencing positive DEP during the separation experiment illustrated as in Figure 8. The percentage cells collected was compared through the three parameters which were the wire diameters, yarn size and wire configurations. Figure 8(a) proved that larger wire diameter led to smaller electrode gap that resulted a stronger DEP force experience by the cells, hence the higher yield. This led to higher accumulation of cells at the electrodes that form pearl chain.
Similarly, stronger DEP force in the smaller yarns system cause a higher cell collection (figure 8(b)). Lastly, the wire configuration reflected a different pattern compared to the simulation study done in the previous section. While double twisted wires offered the most yield (Figure 8(c)), the double wire (non-twisted) gave lowest yield due to the electrode heating that possibly caused the cells to be non-viable and not responsive to the DEP force [21]. The double twisted wire features on the other hand was good in heat dissipation.

![Figure 7. The 40x magnification of wire cloth for single 71μm electrode during DEP with (a) The image of the system after the introduction of cell suspension prior to DEP process, and (b) The positive DEP of E. coli after voltage of 20Vpk-pk was applied.](image)

![Figure 8. The percentage cells (yields) collected in comparison with regards to (a) wire diameter, (b) yarn size and (c) wire configuration.](image)

### 4. Conclusions

There were variable stages of determining a better DEP process in a higher throughput system in which this study covered from the wire cloth electrode production, the wire cloth simulation study towards the DEP experiment. The electrode diameter and configuration as well as yarn size maintained the important relationship for a more high-throughput friendly microelectrode in which smaller physical gap was desired. In the simulation study of the electric field intensity, the maximum electric field achieved was $2.042 \times 10^6 \text{V}^2\text{m}^{-3}$ through double 100μm twisted wire. We have established that smaller electrode gap from greater wire diameter led to a higher electric field strength and double twisted configuration yields better electrode non-uniformity. Polyester yarn on the other hand served
as a double-edge sword of holding the steel wire in the desired manner in wire cloth production as well as to distort the electric field, promoting more non-uniformities in which smaller yarn size was better as it lessens the insulative element of the system generating greater electric field intensity. From the experimental results it can be concluded that a larger wire diameter and smaller yarn size produced smaller electrode gap that led to higher electric field strength which caused larger DEP force for better cell separation. The twisted configuration on the other hand showed most efficient separation of all three wire configurations due to its non-uniformity of the electric field yields that triggered a better DEP force. The double wire configuration did better in reducing electrode gap but resulted to electrode heating that caused possible cell death. Thus, the use of twisted wire geometry by further enhancing the non-uniformity coverage for the cell separation without compromising the heating effects.

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5. References

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