Optimized MEMS Microfluidic Device For Low-Power Blood Component Segregation

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Abstract

Dielectrophoresis (DEP) occurs due to the movement of particles in a non-uniform electric field, resulting from the continuous interaction between the particle dipole and the spatial gradient of the electric field. DEP is a commonly utilized technique for particle manipulation in microfluidic devices and is employed in the separation of microparticles such as malignant blood cells, DNA, and other nanoparticles. Besides DEP, other techniques, like centrifugation, are used for particle sorting. DEP is particularly advantageous for sorting blood cells due to its microscale manipulation capabilities and favorable scaling system.

This work involves a computational analysis of the separation of blood components, primarily RBCs, WBCs, and platelets. The separation process is based on the properties of blood cells, including their significantly differing sizes and dielectric properties. Various studies and experiments have presented models with specific electrode shapes, inlets, and outlets to achieve cell separation. Modifying the shape and physical dimensions of the electrodes can enable cell separation at a low voltage, as particles are influenced by the electric potential applied to the electrodes and deflect within the channel medium. This study examines the effects of changes in shape, applied voltage, and physical dimensions using two model designs. A comparative analysis of these models with existing ones is conducted, leading to the development and analysis of an optimized design for efficient blood particle separation. The design, modeling, and simulations are performed using the Finite Element Method (FEM).

Introduction

The mechanisms of life vary among all creatures and animals. The system that supplies energy to individuals primarily relies on the fluid circulating within their bodies. Human blood, which is a major combination of RBC, WBC, platelets, and plasma, functions as the fluid of vitality [1]. Blood consists of approximately 55% plasma, 45% other cells, and less than 1% platelets and WBC combined. Each component of blood performs

distinct functions. RBCs play a crucial role in the exchange of oxygen and carbon dioxide between tissues and lungs [2], while WBCs contribute to the immune system, providing resistance against infections and diseases. Platelets are involved in enhancing growth factors, promoting blood clotting, and aiding wound recovery [1]. Due to their vital roles in the human body, any significant imbalance in their quantities can have serious effects, leading to conditions such as thrombocytopenia (low platelet count) or thrombocythemia (high platelet count) [3, 4]. In such cases, blood transfusions can restore the required cell count in the patient's body and minimize risk. Although blood transfusions are rare, different types of transfusions are conducted based on the specific blood cell component [5]. These facts highlight the importance of sorting RBCs, WBCs, and platelets as they are the main components of blood. The centrifuge technique is used to separate RBCs, platelets, and plasma from each other. Platelet transfusions help reduce mortality rates. rate due to marrow failure [6]. Dielectrophoresis technology can be used for the separation of RBC, WBC and platelets cells efficiently. Microfluidic devices can be modelled to segregate and manipulate blood cells and other biological particles like bacteria. It can be easily organized, as it holds the ups in case of particle size, manu- facturing techniques, power requirement, high level of analysis, diagnosis obtained and greater controlling system [7, 8].

Related Works

As per previous studies, the throughput of the microfluidic model is increased on designing electrodes in the form of an array at the inner side of microchannel with the electric field applied. Inlet and outlet with appropriate angle elevation are considered as an important factor along with size and dielectric properties of particle. There have been comparative studies regarding this, where modelling of microfluidic device is formulated and simulated. Taking previously modelled studies into consideration, particularly, the model designed by Ali [15], as shown in Fig. 1, is used as the reference model for designing the current paper designs. The modifications are made to the electrode design concerning their size, shape and dimensions. The table shown in table 1 shows the numerical values of dielectric properties of blood cells and fluid. Here, we are intended to use a smaller number of electrodes to obtain higher efficiency with low voltage. In this work, two different model designs are considered. The design has changes in their inlet and outlets, number of electrodes configured and dimensions of the same are compared to each other. Figures 2 and 3 show the designs considered in this work.

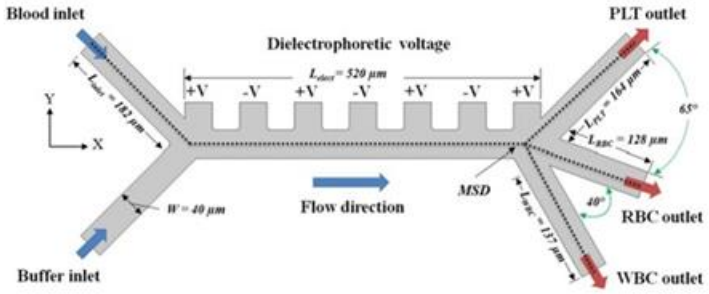

Figure 1: Reference model design

Table 1: Blood cells and fluid dielectric properties

Dielectric Property	RBC	Platelets	WBC	Fluid
Diameter of Particle (μm)	7	2	12	--
Conductivity (S/m)	0.31	0.25	0.65	0.055
Permittivity (ε)	59	50	60	80
Shell Conductivity σ_s (S/m)	1×10^{-6}	1×10^{-6}	27.4×10^{-6}	--
Shell Permittivity (ε^*_s)	4.44	6.8	6	--
Shell Thickness (μm)	0.009	0.008	0.007	--

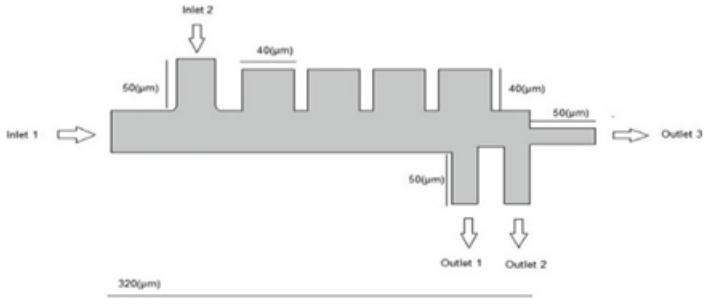

Figure 2: Model design 1

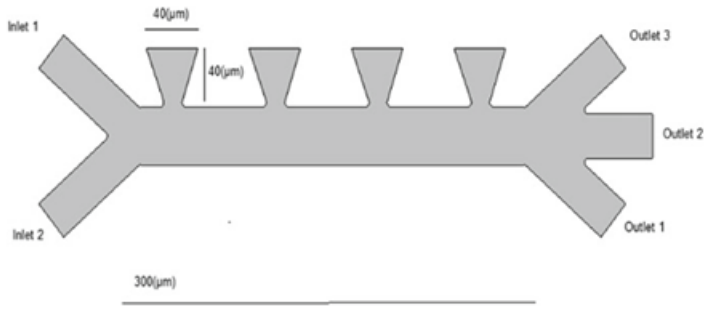

Figure 3: Model design 2

Figure 2 features a model with a channel length of 240 µm and a width of 40 µm. Two inlets are designed perpendicular to each other. The upper side of the channel contains a planar electrode array, with dimensions of 40 µm in height and 40 µm in width. These dimensions match those used in Figure 1 of paper [15]. Although the electrode dimensions remain the same, the number of electrodes is reduced by half, and three outlets are designed. The particle deflections vary based on the applied potential, due to the significant differences in their size and conductivities. Blood fluid flows through inlet2, buffer flows through inlet1, and the outlets are designed to separately collect RBCs, WBCs, and platelets.

Figure 3, on the other hand, employs differently shaped electrodes compared to the planar ones. The main channel has a length of 300 µm and a width of 40 µm. Inlet1 is angled at 140° to the channel, while inlet2 is at a mirror angle to inlet1 but in the opposite direction. Three outlets are located at the other end of the channel: outlet1 at the lower end, outlet2 in line with the channel, and outlet3 at the upper end. The flow rates of fluid through inlet1 and inlet2 for both designs are 135 µm/s and 853 µm/s, respectively. These models are simulated at different voltages to achieve the separation of RBCs, WBCs, and platelets through the dielectrophoresis force in the microchannel of the device.

Methodology

The polarized particle interacts with the non-uniform electric field in a medium and results in dielectrophoretic force acting on the particle [9]. With the proper DEP design the separation, orientation and trapping of particles can be obtained at a pre-defined point [10]. DEP force is manipulated based on the physical dimension, dielectric properties of particle in the suspended medium. DEP can be brought into action with application of AC or DC voltage. Since DC requires high voltage for the generation of required DEP force, it sets as a drawback for the simulation of the particles. Therefore, alternating voltage can be considered as the suitable method to generate the electric field compatible to drive the particles in a medium [9]. Dielec- trophoresis force leads to the formation of dipole at the opposing end of the particles in the presence of electric field depending on their dielectric properties [11], and the particle may experience different amount of forces on them. The force acting on a dipole in an electric field is given as,

Results & Discussion

FEM software is utilized to simulate the models. The particle trajectories in the channel vary depending on the potential applied to the electrodes. The electrodes are subjected to alternating polarity, resulting in particle movement due to the dielectrophoretic force generated by the non-uniform electric field. The field strength within the channel is influenced by the dimensions and shape of the electrodes. In model design 1, as shown in Fig. 2, which uses planar electrodes, a higher electric field strength at a specific point is observed compared to the electrodes in model design 2 in Fig. 3. The electrode dimensions affect the electric field strength inside the channel. As the field strength increases, particles in the channel experience greater forces and are more significantly deflected. Additionally, particle size contributes to the varying forces experienced, leading to

different trajectories in the medium. The diameter of WBC cells is greater than that of both RBC and platelet cells, with platelets being the smallest of the three. In model design 1, the smaller platelets are deflected less compared to RBC and WBC cells. RBC and WBC cells deflect more from the electrodes, but there is minimal difference between them, and they move cohesively in the transverse channel. In model design 2, the field strength is lower at the top end of the channel near the electrode, resulting in a lower DEP force. In this design, RBC and WBC cells are deflected at the same rate, whereas platelets are deflected less. The time taken by the particles to reach the outlets after separation is also considered in this analysis.

The computation results indicate that Model design 1 requires less time to separate the particles due to experiencing more force for a given voltage, resulting in faster movement within the channel. In contrast, Model design 2 takes more time to complete the cell separation. The electric potential distribution in the model designs is depicted in Figures 4 and 5.

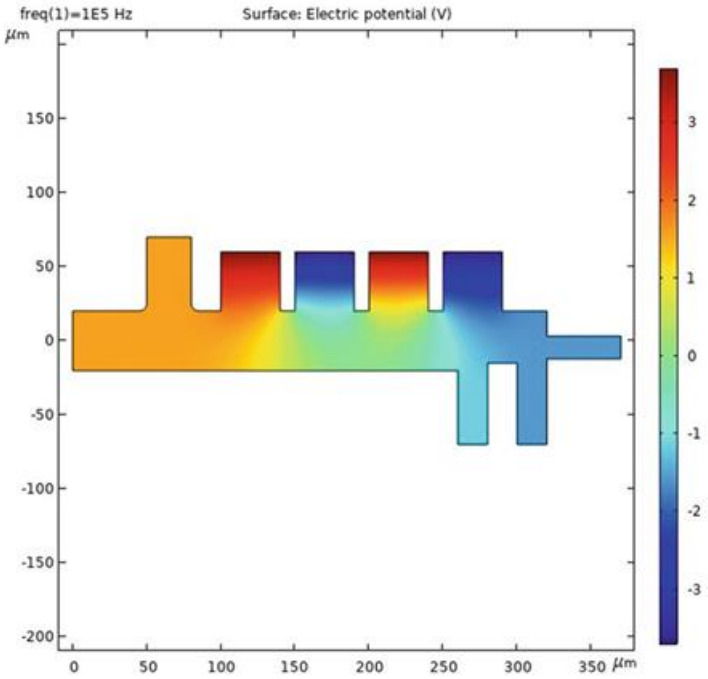

Figure 4: Model design 1 potential distribution

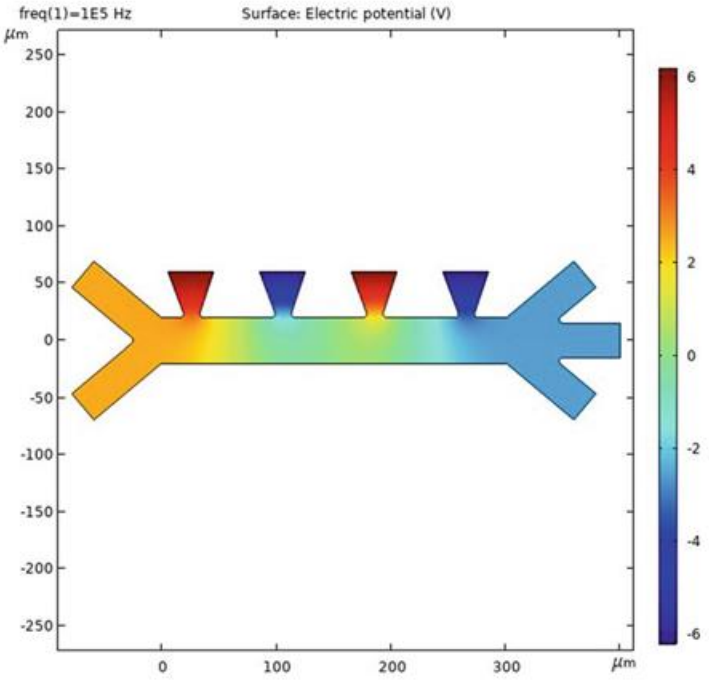

Figure 5: Model design 2 potential distribution

According to the theories, factors such as electrode design, dimension, outlet and inlet design, and the applied voltage can all influence the dielectrophoretic force induced. In paper [15], it is concluded that the separation of RBCs, WBCs, and platelets occurs at an applied voltage of 4 V to the electrodes. In this study, an attempt was made to achieve particle separation using different electrode shapes, with a reduced number of electrodes and minimal applied voltage. Applying varying voltages yielded different outcomes. Through numerous attempts, it was found that particles in Model design 1 separated at a voltage of 3.7 V, while Model design 2 achieved results at 6.2 V. Slight increases or decreases in these voltages resulted in RBC and WBC particles being collected in the same outlet, with platelets in a separate outlet. Hence, separation in these models is only possible at specific voltages, and applying other voltages could result in no particle separation. The figures 6 & 7 below illustrate the separation of blood cells at the aforementioned voltages in Model design 1 and Model design 2.

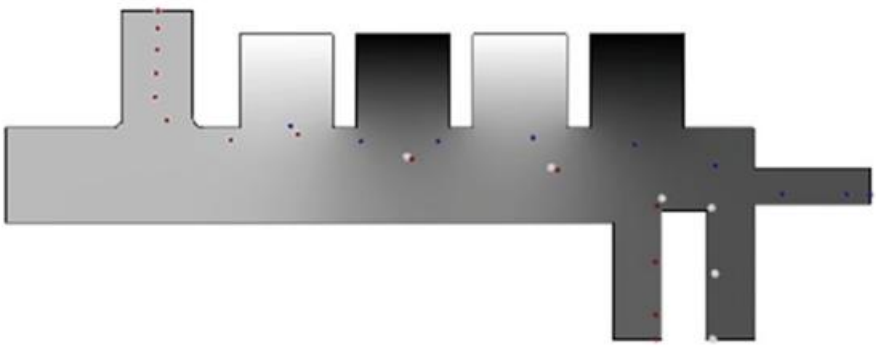

Figure 6: Separation of RBC, WBC and platelets in model design 1

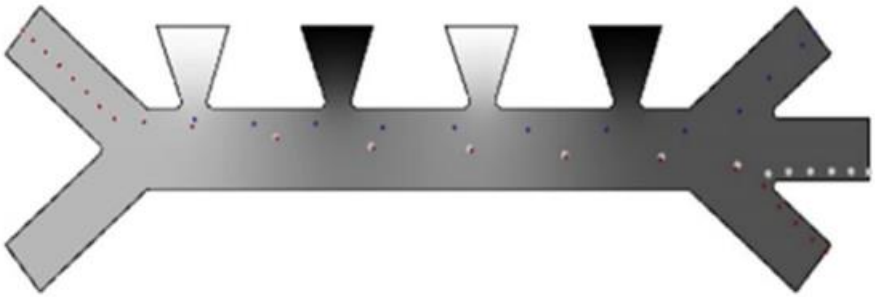

Figure 7: Separation of RBC, WBC and platelets in model design 2

Therefore, it can be concluded that altering the physical dimensions and shape of the electrodes affects the field strength distribution within the channel, leading to particle separation. Figure 8 illustrates the distribution of electric field strength inside the microfluidic channel for both model designs shown in Figures 6 and 7.

The results demonstrate that the shape and dimensions of the electrodes influence the field strength within the channel, affecting particle separation. To apply the required force to the particles, the voltage must be adjusted accordingly based on the electrode dimensions. This study leads to further work on the impact of changes in electrode dimensions. A comparative study using the reference model [15] is intended. The electrode dimensions in the reference model are 40 µm in height and 40 µm in width. Simulations were conducted by alternately reducing the height and width of the electrode to half their original value, while also decreasing the number of electrodes and channel length to approximately half of their reference values. The analysis focuses on the effects of changes in electrode width and height.

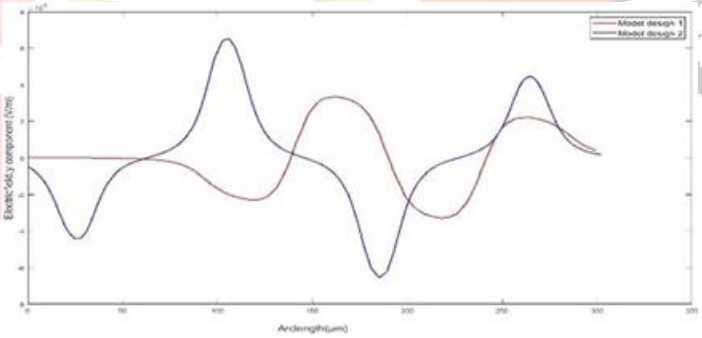

Figure 8: Electric field distribution versus channel length for designs 1 and 2

Figures 9 and 10 depict optimized model designs with electrode dimensions of 10 µm in height and 40 µm in width. The voltages at which particle separation is achieved are 1.6 V and 2.2 V, respectively. These model designs are observed to be more efficient than all other designs, as they require lower voltage, minimal channel length, and include one additional electrode. Figure 9 illustrates the distribution of electric field strength inside the microfluidic channel for both model designs shown in Figures 9 and 10.

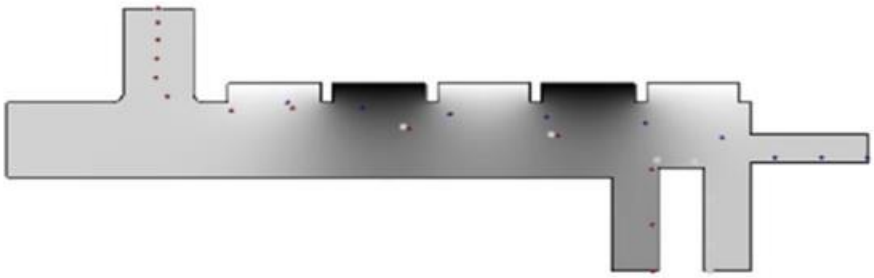

Fig. 9 Particle separation in design 1 with optimized electrode design

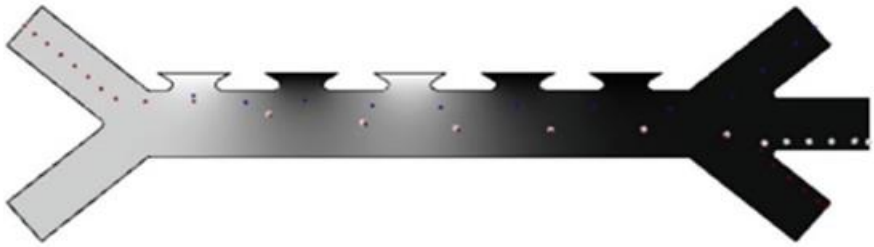

Fig. 10 Particle separation in design 2 with optimized electrode design

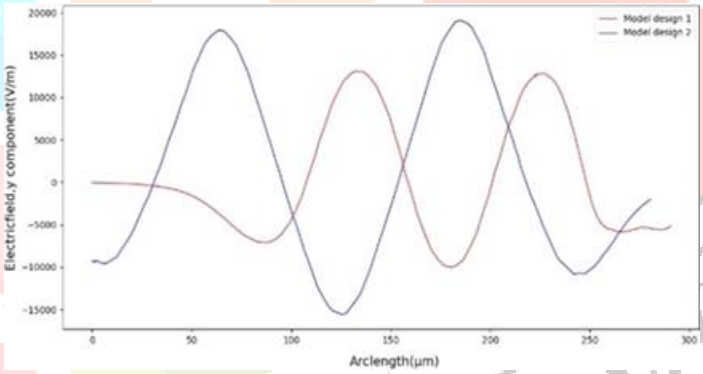

Fig. 11 Electric field distribution versus channel length for optimized design 1 and 2

The table 2 provides a comparison of the number of electrodes used, the voltage required for cell separation, and the electrode dimensions. This comparison clearly indicates that electrode physical dimensions, shape, channel length, and applied voltage are crucial parameters to consider when designing a microfluidic device for particle segregation.

Table 2: Comparison of model designs

Parameters	Basic Design		Reduced Height		Reduced Width		Optimized Design	
	Model Design 1	Model Design 2	Model Design 1	Model Design 2	Model Design 1	Model Design 2	Model Design 1	Model Design 2
Height of Electrode (μm)	40	40	20	20	40	40	10	10
Width of electrode (μm)	40	40	40	40	20	20	40	40
Channel length (μm)	240	300	240	300	240	300	240	300
Number of electrodes	4	4	4	4	4	4	5	5
Voltage required for separation (V)	3.7	6.2	2.4	4.3	5.6	7.3	1.6	2.2

Conclusion

This paper presents the separation of RBCs, WBCs, and platelets using the Finite Element Method (FEM) based on model designs. The model designs were simulated and analyzed using equations related to the dielectrophoretic force applied to the microfluidic device, fluid flow rates, and dielectric properties of the fluid and cells. The separation is based on the size of the particles under consideration. The simulation was conducted on two different model designs with variations in electrode dimensions, shape, and array length. Additionally, changes were made to the inlet and outlet positions for particle separation.

The results indicate that cell separation is achieved at low voltages when the electrode height is reduced, and the width is increased. The optimized voltage values for model design 1 and model design 2 are 1.6V and 2.2V, respectively, for the segregation of particles with one extra electrode. Since the channel length remains unchanged, adding one electrode does not alter the device's physical dimensions. Among both designs, model design 1 achieved separation at very low voltage while maintaining the same physical device dimensions. Thus, these models can be used in applications where minimum voltage, low power, and compact size with high efficiency are critical constraints in the design of microfluidic devices.

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