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FEM Based Elasto-Electric Analysis of Elastomers for Pharmaceutical Applications

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Elastomer materials are very important due to weak intermolecular forces and very low Young's modulus and have high failure strain. Due to these properties, they are used in a large number of applications especially in pharmaceutical industry and medical / surgical equipment etc. Electrostatic discharge on such material is a potential hazard for the operator who is dealing with elastomers. In the research presented here, a detailed analysis on the elasto-electric analysis of 03x elastomers is analyzed in detail by using Finite Element Method (FEM). A CAD model is generated in accordance with an early research on elasto-electric study of Silicon material. Subsequently FEM based analysis is carried out to study vital electrostatics properties like Surface deformation and surface potential distribution developed on the application of external forces on 03x types of elastomers i.e. Silicon Rubber, Nitrile (NBR) and Poly Vinyl Chloride (PVC). The whole study is carried out in COMSOL multi-physics software. Analysis showed that the electric field developed on the surface of the elastomer is dependent on the deformation on non-linear nature and depends upon the material properties. FEM based results show that Silicon Rubber develops maximum deformation and electric potential of three chosen materials up to 50mm and 3150V respectively. Based on the conducted analysis, Silicon Rubber is widely recommended for its utilization in Pharmaceutical applications requiring electrostatics.

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Keywords: Pharmaceutical; elastomer; levitation; elasto-electricity; silicon rubber; electrostatic charges; electric potential.

1. INTRODUCTION

Elastomer materials are the polymer that have both viscosity and elasticity. These materials also have very weak intermolecular forces with very low Young's modulus and high failure strain. Elastomer materials have a large number of applications. They are used in fabrication of soft fluidic robots through various morphologies composed of Silicon rubber [1]. Another application lies in its usage as transducers through thin elastomeric membranes with electronic insulated methodology [2]. Dielectric elastomer actuators (DEA) are concentrating through Non-viscoelastic elastomers due to having fast and reliable actuations [3]. Elastomers also have very important application in urethane – during the process of metal forming [4]. Metal forming processes uses elastomers as a flexible tool and then they are used in various processes include in shaping / casting the metal for its formation to a desired shape. Another application lies in the use of elastomers as thermoplastic [5]. Thermo-plastic elastomers have various properties like light weight, high strength, process ability and low cost which makes them usable for various applications i.e. from household to aeronautics sectors.

Silicone tube is a majorly used material in the pharmaceutical industry for the purpose of fluid transfer, peristaltic pumping and filling operations. Such materials are are UV stable, thermally and chemically stable, and hyrdrophic (easy to sterilize). One another application of elastomer is its use as a medical / surgical equipment during various surgical procedures. Specifically, as medical gloves, various types of elastomers are used for the manufacturing with a numerous methodologies depending upon the usage [6-17]. Typically, these gloves are made from polymers which includes latex, nitrile rubber, neoprene, polyvinyl chloride etc. Some of these gloves are manufactured without the end application of cornstarch powdered to avoid lubrication [6] [7] [8]. Some are used for high grip applications [9] [10] [11]. Other application of these gloves are in the Clean Rooms where there is a requirement of vulcanized gloves for various chemical applications [12] [13] [14] [15]. During their manufacturing, these gloves undergo different manufacturing processes [16] [17] to make them suitable for the application they are being produced. Typical processes involved during the production of gloves [18] are compounding, latex dipping, beading, vulcanization, leaching, stripping, quality control, packing and sterilization. The process is highly automated with the exception of packing and sterilization where the product is manually treated and there despite a fully cured process, there is a slight risk of contamination due to contact based mechanism.

Therefore, there is a need of a mechanism of levitation during the production of these elastomers products which can avoid the physical contact of the end product. Other applications of contact-less manipulation lies in the manufacturing industries of optical parts production [19] [20] [21] [22]. The optical parts for various applications like panels for LCD (liquid crystal displays), optical lens etc. are very sensitive and thus will be hugely benefitted with the micro-scale levitation scheme. The manipulation schemes of the micro-scale end effectors can be implemented on mobile platforms which involves the movement of the objects through mobile robots [23] [24] [25] which requires the incorporation of smart filters [26].

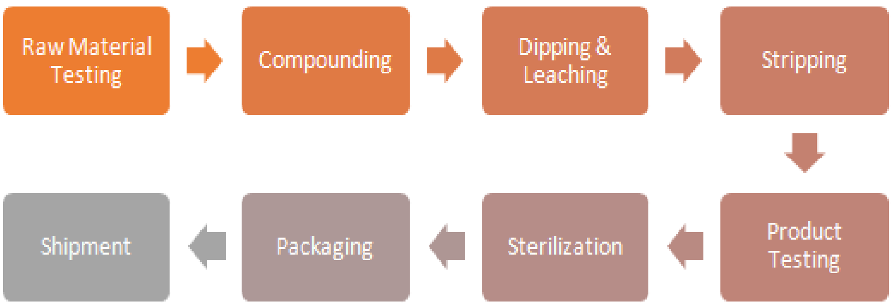


Fig. 1. Process diagram for elastomer based glove production [18]

In the research presented here, a detailed analysis on the elasto-electric behavior of various elastomers have been carried out using FEM (finite element method) based techniques keeping in view the prime objective of levitating the elastomer. Levitation is defined to be the process by which the object is held aloft, without physical support, in a stable position. In order to levitate any elastomer object through electric / magnetic field, electrical properties like electric field and charge distribution density on the surface is a very important parameter. This behavior can be achieved through the elastic properties of the elastomer. The same properties of 03x types of elastomers i.e. Silicon Rubber, Nitrile (NBR) and Poly Vinyl Chloride (PVC) are studied in this work on COMSOL multi-physics software. At initial level, a model has been developed in COMSOL keeping in view the study carried out in [27]. Afterwards the same study has been carried out and the results are regenerated in order to evaluate / validate the developed model. Later on, a study on surface potential distribution has been carried out to extend the study on electrical properties required for levitation on the same Silicon Rubber material. Subsequently, the same study has been carried out on elastomer materials NBR and PVC in order to evaluate the surface charge distribution on these materials.

1.1 Related Work

Elastomer materials are usually undergo irregular electrical and mechanical loadings. Common examples are in insulators and tires. Recent development presents various research being carried out in electric field induced in elastomers by change in shapes. Detailed work on the complex surface morphology and of a tube of vulcanized natural rubber has been presented in [27]. Electric field effect develops a non-linear deformation which is modelled but is not studied at molecular level. Electrostatic potential developed on rubber surfaces was computed with respect to the stretching frequency using Kelvin electrodes. The results show that the potential varies due to change in the stretching frequency. Schematic diagram for measurement of electrostatic potential is shown in Fig. 2.

Another development for conversion of the mechanical energy into electrical potential through periodic stretching of rubber tubing is presented in [28]. The mechanism for collecting electricity is shown in Fig. 3. Surface of the rubber presents periodic and reversible electrostatic variations with the tubing length depending upon the type of elastomer and the pattern of vibrations. The developed amplitude also has direct impact on the humidity changes, however, pre-treatment of the elastomer nullifies this effect.

In one other research [29], electrostatic potential on rubber is presented as a function of repeated strain for the lifetime period of the sample is presented. Two factors, i.e. hygro-electricity and mechano-chemical are the main contributors in the electrostatic potential development on the elastomer surfaces. The results explained that over a longer period, significant negative potential is displayed on the rubber surface in the absence of any externally applied voltage.

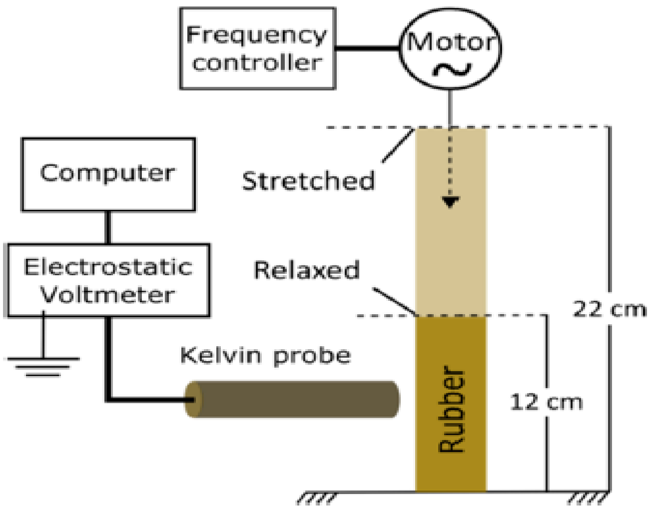


Fig. 2. Schematic diagram for electrostatic potential in silicon rubber [27]

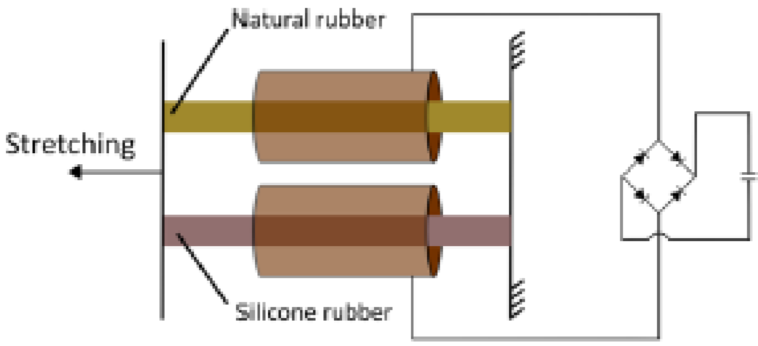


Fig. 3. Technique for electrostatics induction due to periodic stretching in natural rubber and silicon rubber [28]

Another work [30] develops a force-based actuation model which includes a coupling scheme between the Dielectric Elastomer Generators (DEGs) and Self-Priming Circuits (SPCs) to estimate the dynamics of the system. DEGs is a state of the art technology to convert the mechanical energy into electrical energy, whereas SPCs are a very likely resolution of storing a part of electrical output to supply as input for the purpose of boosting effect.

Some other related contributions presenting the development of electrostatic charges on elastomers with detailed analysis on developed stretches are presented in [31] [32] [33].

2. MATERIALS AND METHODS

A block of dimension 120 x 10 x 1 (mm) has been developed for the purpose of elasto-electric study with 03x different materials A, B and C. The model has been developed in COMSOL® multi-physics software [34]. Where COMSOL® is a FEM based simulation software used to analyze the multi-physics domains. For our study, we have used the physics of 1. Solid Mechanics and 2. Electrostatics. The developed model is shown in Fig.4.

The study has been carried out on 03x types of materials characterized as A, B and C. Material A is the one taken similar to the one used in the experimental study carried out in [27]. The properties of the 03x materials used for this work at STP (standard temperature and pressure) are presented below;

- Material 'A':
  - Composition: Silicon Rubber
  - Relative Permittivity (ε_r): 11.68
  - Young's Modulus (Y): 4.15 MPa
  - Density(ρ): 1280 Kg/m^3
  - Poisson's Ratio (u): 0.02
- Material 'B':
  - Composition: Nitrile (Acrylonitrile Butadiene (NBR))
  - Relative Permittivity (ε_r): 2.4
  - Young's Modulus (Y): 6.79 MPa
  - Density (ρ): 980 Kg/m^3
  - Poisson's Ratio (u): 0.48

- Material 'C':
  - Composition: Poly Vinyl Chloride (PVC)
  - Relative Permittivity (ε_r): 2.9
  - Young's Modulus (Y): 2900 MPa
  - Density(ρ): 1760 Kg/m^3
  - Poisson's Ratio (u): 0.4

The whole simulation has been carried out on an Intel™ Core™ i5-3230M @2.6 GHz CPU with 1GB Radeon™ Graphic Card and 6GB of RAM. In order to maintain the accuracy with the computational power, Mesh element size of 0.2 mm has been used with the maximum element growth rate of 1.5, curvature factor of 0.6 and resolution of narrow region is kept to be 0.5. Complete mesh consists of 146777 domain elements, 25290 boundary elements, and 1048 edge elements as shown in Fig.5.

For the whole study, we have applied a fixed constrain on one surface of block and applied a surface load F_A (Eq. 1) on the other surface as described in Fig.4.

Where;

$$F_A = \frac{F_{tot}}{Area} \quad \text{Eq. 1}$$

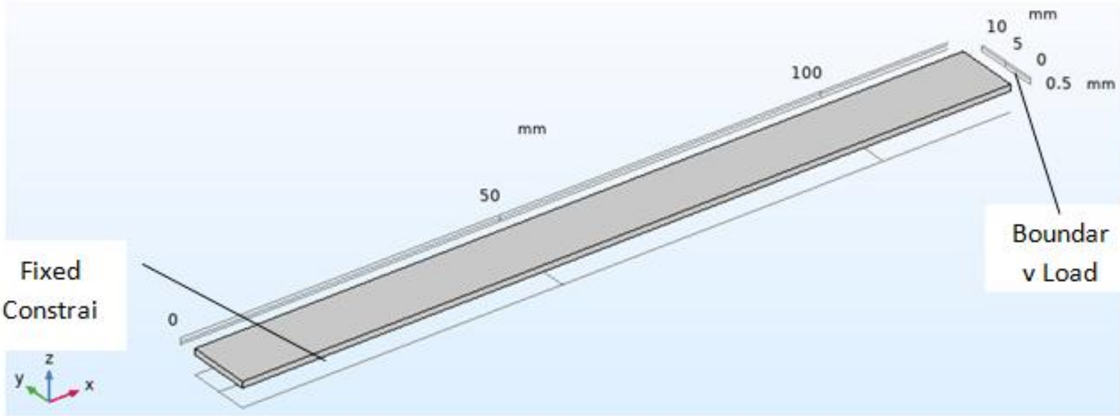


Fig. 4. CAD model of plate for the study of elasto-electric properties with 03x types of material

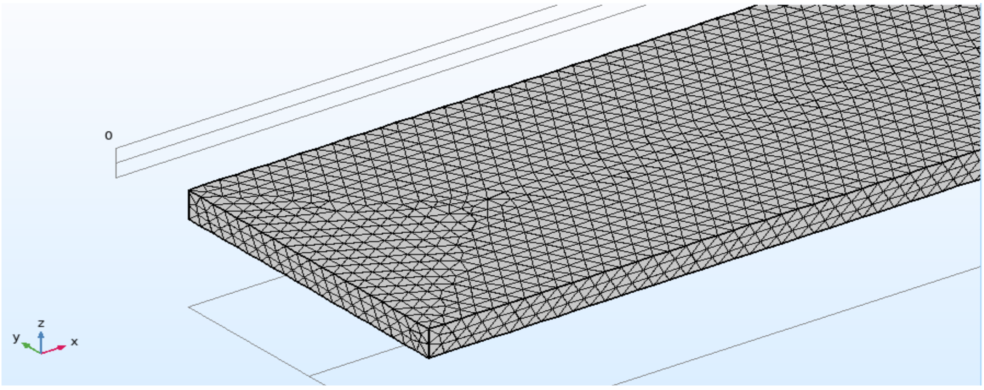


Fig. 5. Tetrahedral meshing with total 146777 domain elements, 25290 boundary elements, and 1048 edge elements

Where the whole system is assumed to be linear elastic model for material for solid mechanics physics according to the Eq. 2 for linear elastic material;

$$\frac{\partial^2 \boldsymbol{u}}{\partial t^2} = \nabla.(FS)^T + F_V \qquad \text{Eq. 2}$$

For the study of electrostatic, the charge conservation is given according to Eq. 3;

$$\rho_v = \epsilon_0 \epsilon_r E\,.\nabla \qquad \text{Eq. 3}$$

3. RESULTS

Following are the results attained from the above-mentioned materials and method;

3.1 With Silicon Rubber

Upon the application of total force of 10,000 N load on the surface mentioned in Fig. 4, following deformation and surface voltages shown in Fig. 6 are attained.

The graphical results of deformation and electric potential are presented in Fig. 7.

3.2 With Nitrile (Acrylonitrile Butadiene (NBR))

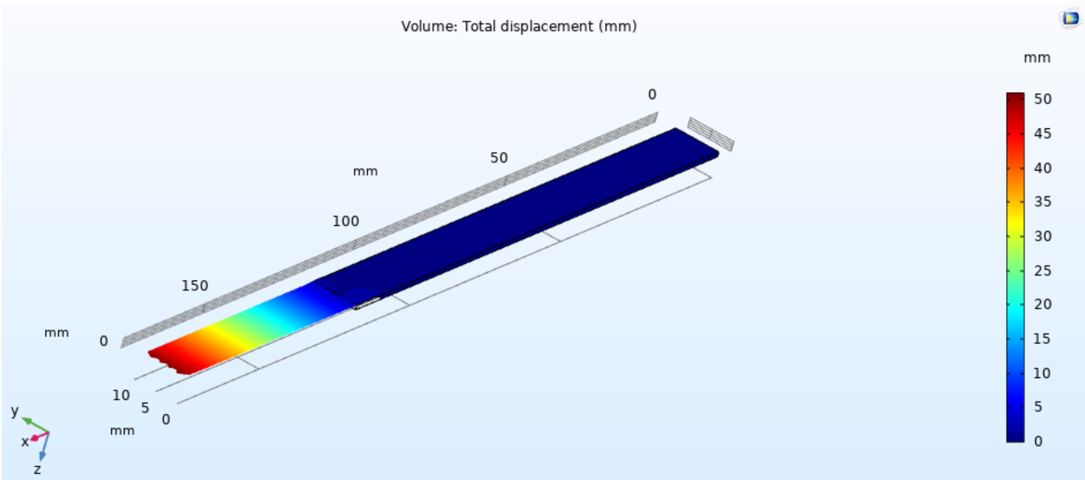
Upon the application of total force of 10000 N load on the surface mentioned in Fig. 4, following deformation and surface voltages shown in Fig. 8 are attained.

3.3 With Poly Vinyl Chloride (PVC)

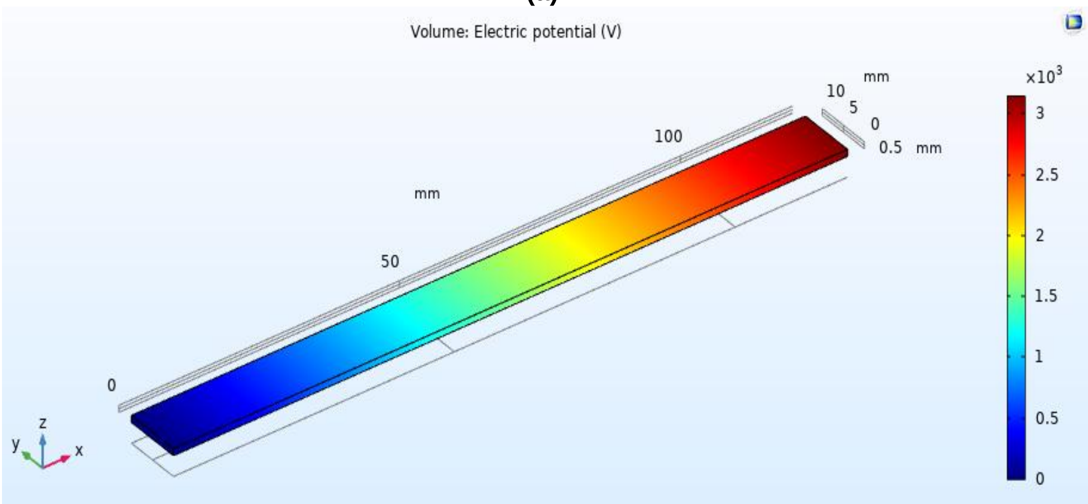
Upon the application of total force of 10000 N load per unit area on the surface mentioned in Fig. 4, following deformation and surface voltages shown in Fig. 9 are attained.

3.4 Combined Graphical Results

The combined graphical results of displacement and electric potential on the implemented 03x materials A, B and C are presented in Fig. 10.

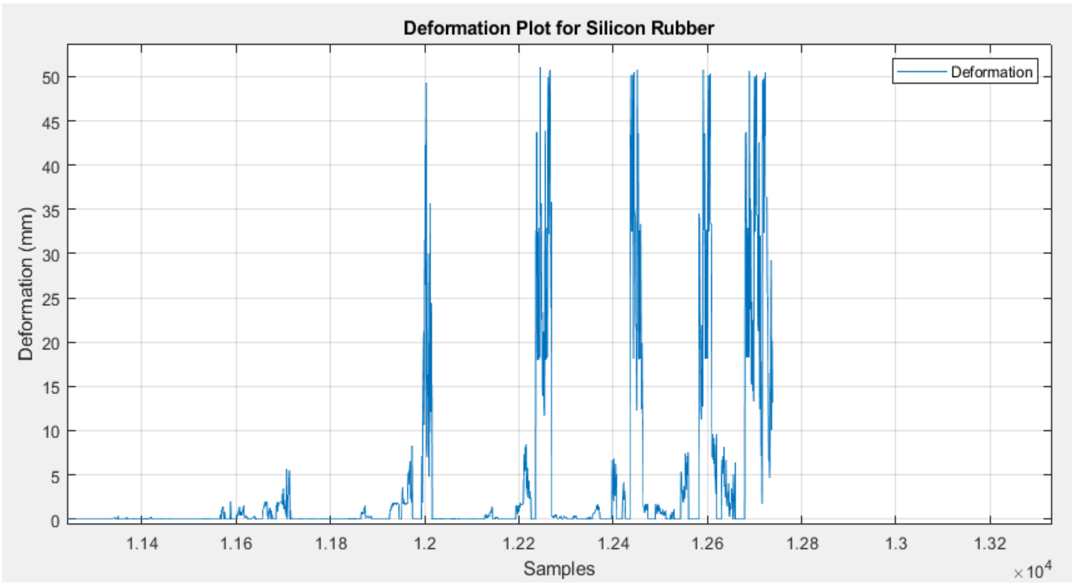


(a)



(b)

Fig. 6. FEM results of (a) Deformation and (b) Electric Potential on Silicon Rubber



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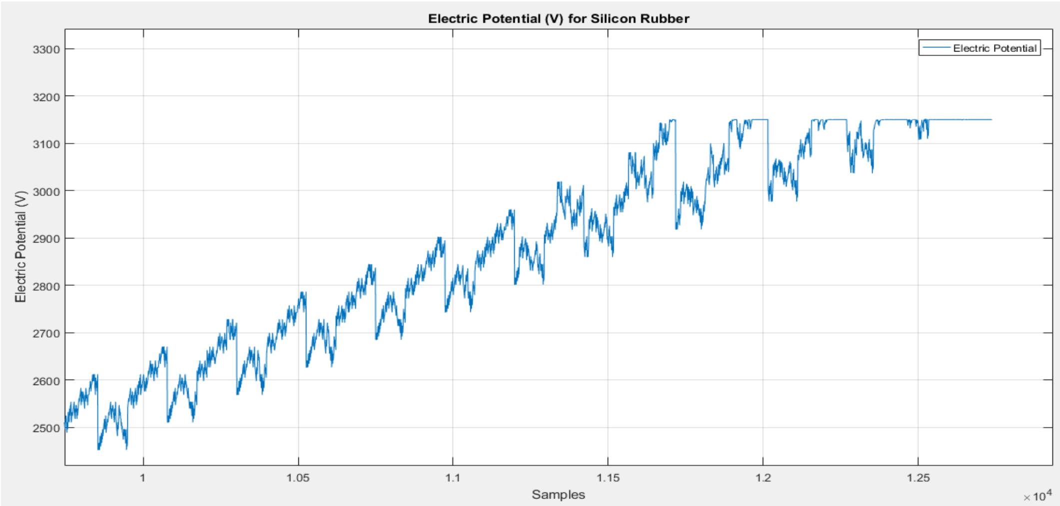
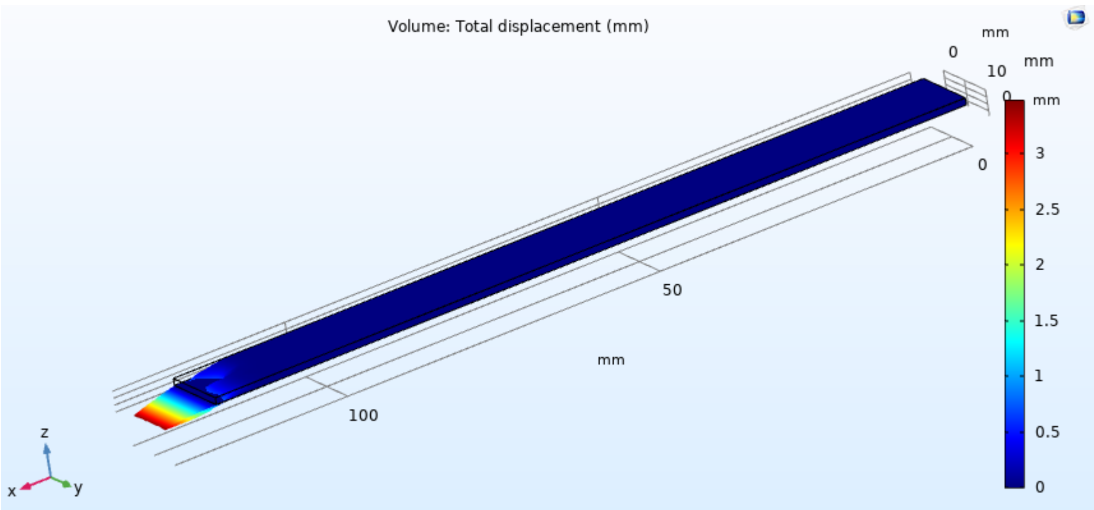


(b)

Fig. 7. Graphical Results of (a) Deformation and (b) Electric Potential w.r.t. No of Samples on Silicon Rubber



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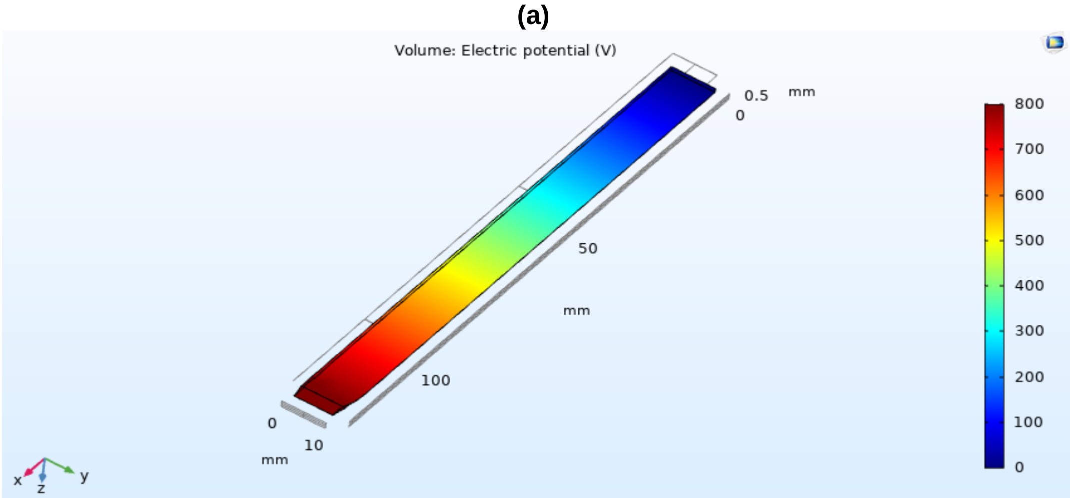

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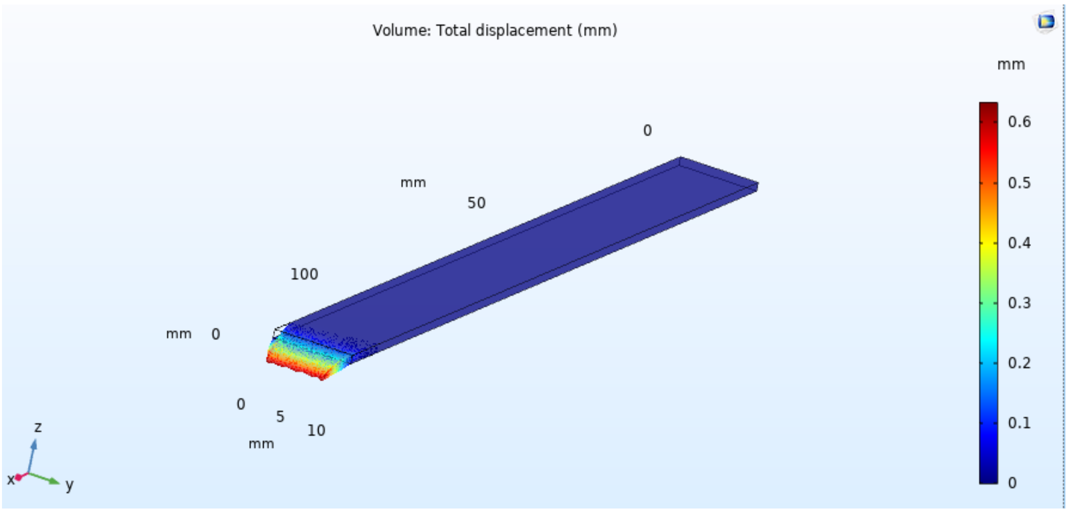
Fig. 8. FEM results of (a) Deformation and (b) Electric Potential on Nitrile (Acrylonitrile Butadiene (NBR))



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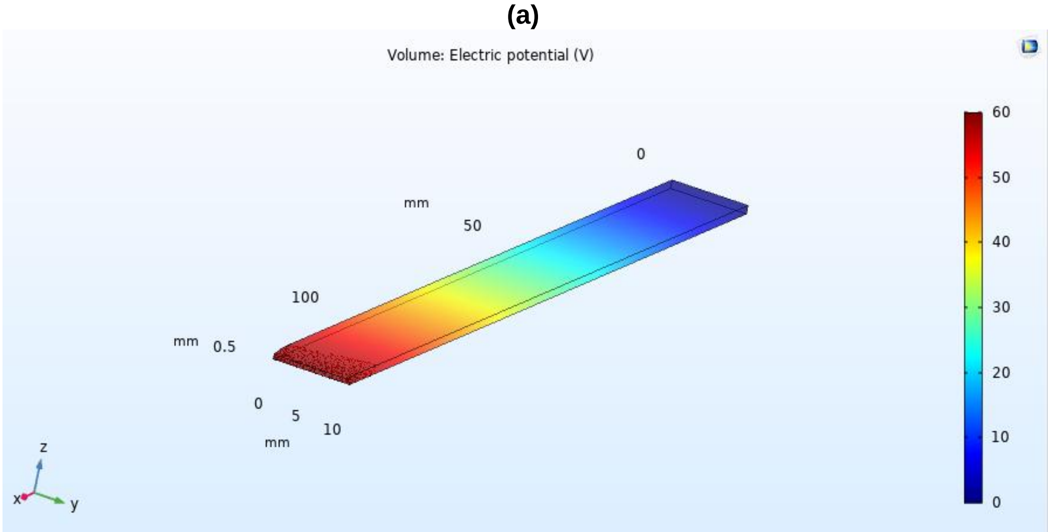


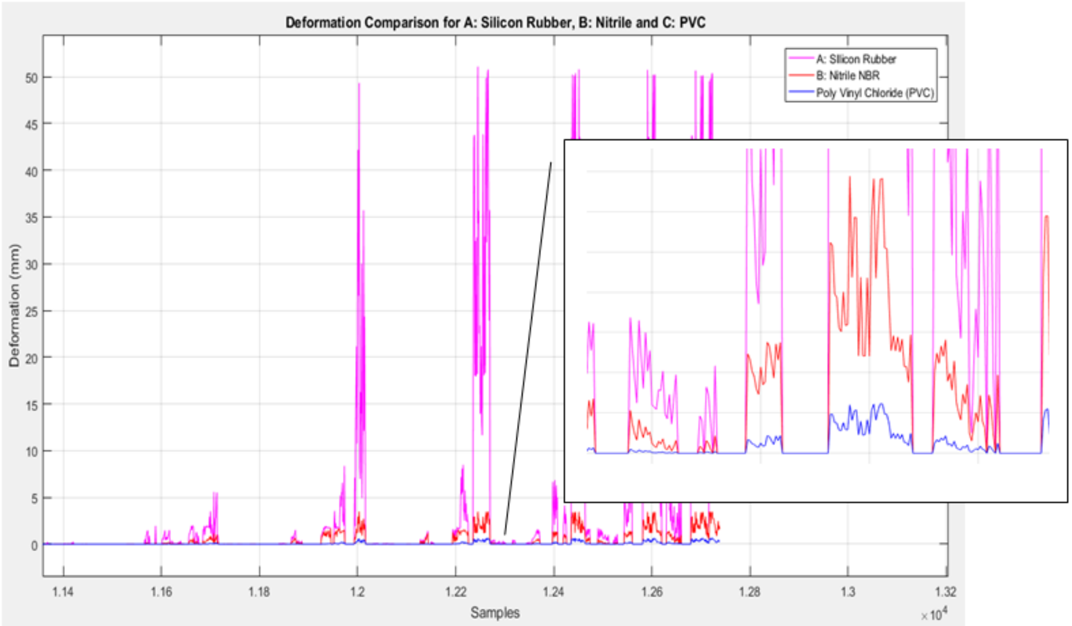
(b)

Fig. 9. FEM results of (a) Deformation and (b) Electric Potential on Poly Vinyl Chloride (PVC)

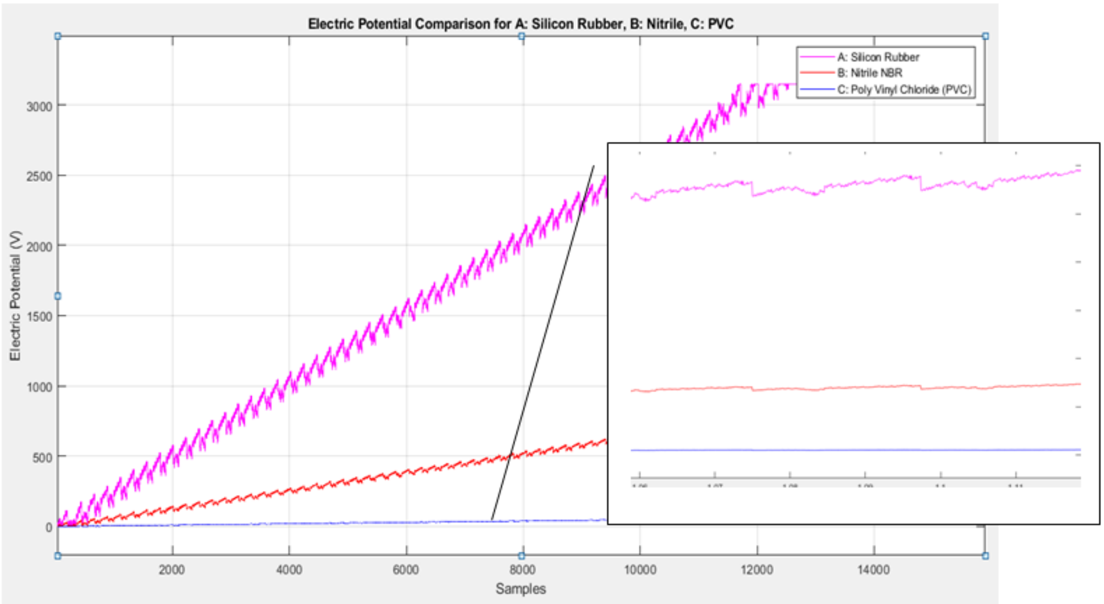
4. DISCUSSION

From the results presented in Section IV and summarized in Table 1, it can be clearly observed that deformation of the material is dependent upon the Young's Modulus and Poisson Ratio. Furthermore, the results also show that the more the deflection, the higher will be the electric potential, In case of Silicon Rubber, from Fig. 6 and Fig. 7, it can be seen that the maximum deformation is about 50mm, whereas the maximum electric potential developed is 3100V. The results are within 2% of the results obtained in [27] and this similarity in the results proves the validity of the mechanism used for FEM analysis used in this research (Slight variation of deformation in the results from [27] is due to unavailability of width and height data of Silicon Rubber specimen). However, in the case of PVC, minimum deformation i.e. 0.6mm, from Fig. 9 and Fig. 10 is observed because the deformation is dependent upon the Young's Modulus and Poisson Ration. Furthermore, the Electric Potential on the surface is dependent upon the deformation. Therefore, there is the potential of 50V in case of PVC for the same loading force.

It is quite evident from the data that the Electrostatic Effect is related with the periodic deformation of the material. However, the deformation is also dependent on the material properties and thus is of non-linear nature. The same non-linearity is observed in case of the electric potential which also depends upon the electric potential. The results of all three materials are compared graphically in Fig. 10 and are summarized with material properties in Table 1.



(a)



(b)

Fig. 10. Comparison of Results for (a) Deformation and (b) Electric Potential on A, B and C type polymers

Table 1. Summary / Comparison of Deformation and Electric Potential Results with Material Properties

Sr.	Material Properties			Observed Parameters	
	Material Type	Poisson Ratio	Young's Modulus (MPa)	Max. Deflection (mm)	Max. Electric Potential (V)
1	Silicon Rubber	0.02	4.15	50	3150
2	Nitrile Acrylonitrile Butadiene (NBR))	0.48	6.79	3.5	800
3	Poly Vinyl Chloride (PVC)	0.4	2900	0.6	50

Based on the conducted analysis, Silicon Rubber is widely recommended for its utilization in Pharmaceutical applications requiring electrostatics. The generated Electrostatics due to elasto-electric effect will cause the Silicon Rubber more prone to levitation and is therefore recommended for its use in Pharmaceutical products requiring sterilization. Based on this study Sterilization methods is to be carried out through levitation in order to avoid the potential contamination as a future prospective. Afterwards adaptive control strategy will be worked on to complete the levitation process for the sterilization of Silicon Rubber based applications for Pharmaceutical industry.

5. CONCLUSION AND FUTURE WORK

In the research presented here, a detailed analysis on the elasto-electric behavior of three types of elastomers, commonly used for medical / surgical gloves, have been carried out using FEM (finite element method) based technique. A model has been developed keeping in view an early research on the elasto-electric study and surface deformation and surface potential distribution developed on the application of external forces have been carried out on the said 03x types of elastomers i.e. Silicon Rubber, Nitrile (NBR) and Poly Vinyl Chloride (PVC). The whole study has been carried out in COMSOL multi-physics software.

After analysis of the results, it can be concluded that Electric Field generated on the surface of the elastomer is dependent on the deformation, however the deformation is non-linear and depends upon the material properties i.e. Young's Modulus and Poisson Ratio. The electric potential on the surface of the object also shows increasing behavior with the deformation but in a non-linear manner. Furthermore, Silicon Rubber out of the three materials chosen for this study, have shown very good elasto-electric properties and from results it can be seen that Silicon Rubber can produce electric potential of 3150V and can develop high deformation of up to 50mm with the application of repeated force.

Keeping in view the prime objective of levitating the elastomer and the results of this research, Silicon Rubber can be assumed to be a good choice of material due to its ability to develop electric potential. Furthermore, in future mechanism for generation of static electric field on Silicon Rubber will be studied. Subsequently, a mechanism for generating and controlling the electric field through an adaptive control technique will be developed to levitate a specimen of Silicon Rubber which will have a variety of application such as sterilization process for pharmaceutical gloves based application. Furthermore, FEM analysis of complete pharmaceutical gloves to evaluate the elasto-electric effect and electrostatic discharge generation during various lab operations will also be carried out as future prospective. Based on this study Sterilization methods is to be carried out through levitation in order to avoid the potential contamination as a future prospective. Afterwards adaptive control strategy will be worked on to complete the levitation process for the sterilization of Silicon Rubber based applications for Pharmaceutical industry.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

CONSENT

It is not applicable.

ETHICAL APPROVAL

We conducted our research after obtaining proper IEC approval.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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