THE PUBLISHING HOUSE
OF THE ROMANIAN ACADEMY

*PROCEEDINGS OF THE ROMANIAN ACADEMY, Series A,*
*Volume 22, Number 3/2021, pp. 247–256*

# EXPERIMENTAL STUDY ON THE VARIATION OF TEMPERATURE IN SOFT DIELECTRIC ELASTOMER ACTUATORS

İbrahim KARAMAN[*], Davut Erdem ŞAHİN[**]

[*] Institute of Science, Mechatronics Engineering Department, Yozgat Bozok Üniversitesi,66100,Yozgat,Turkey.
[**] Mechanical Engineering Departman, Yozgat Bozok Üniversitesi,66100,Yozgat,Turkey.
Corresponding author: İbrahim KARAMAN, E-mail: ibrahim.karaman@yobu.edu.tr

**Abstract**. Dielectric elastomers, regarded as the member of electroactive polymers, possess the ability of undergoing large deformations when an electric field is applied, making them very appealing for the design of artificial muscles that can be used by robots and human beings. Understanding their behaviors subjected to various electric fields still remains a very important field of study. Thus, this study deals with the investigation of temperature variations on the surface of soft dielectric elastomer actuators (DEA) generated by the applied various waveforms of electrical signals with different frequencies including square, sine and triangular. It was observed that the highest temperature on the surface of DEA is generated by the square waveform. Furthermore, the surface temperatures reach their maximum values with the frequencies ranging between 2 Hz and 10 Hz, regardless of the type of waveform. Moreover, an increase in the ambient temperature, pre-stretching and voltages leads to an increase the temperature on the surface of DEA.

***Key words***: soft robotic, dielectric elastomer actuators, artificial muscle, temperature characterization, frequencies.

## 1.INTRODUCTION

Dielectric Elastomer Actuators (DEA) are active materials with flexible structure that can adapt to the environment by being inspired by nature. Active materials can convert electrical or chemical energy into mechanical energy [2]. Dielectric Elastomers (DE) have advantages over conventional motors with their characteristics such as lightness, flexible structure, low cost, low noise, fast response and high energy density [3,4]. DEA's are deformed by changing shape and size under voltage. On the other hand, when deformable or electro-mechanical loading occurs, it works like capacitance and can be used as a sensor due to its displacement [7,10]. Such actuators are found in flexible robot holders and arms, surgical applications, and wings of micro air tools [1]. DEAs are also called artificial muscles because they resemble living muscles [1,5]. Pelrine et al. they reported that the DEA deforms more than 100% rapidly with the applied voltage and has a promising potential as an artificial muscle [1,8]. The physical operation of the dielectric elastomer actuator, as shown in Figure 1 when a voltage is applied to the dielectric elastomer membrane generally coated with two matched electrodes, it decreases in thickness direction and expands in-plane, creating a pressure. This pressure, which can be deformed when high voltages is applied, called Maxwell pressure, is shown by the following equation [1,5,6].

$$p = \varepsilon_r \varepsilon_0 E^2 = \varepsilon_r \varepsilon_0 (V/d)^2 \quad (1)$$

In this equation $\varepsilon_r$ is the dielectric constant, $\varepsilon_0$ is the free space permeability ($8.85 \times 10^{-12}$ F / m), $E$ is the electric field, $V$ is the voltage, $p$ is the maxwell stress, $d$ is the thickness DE.
The elastomer is under high voltages and causes electrical breakdown by thinning too much. Using the Mooney-Rivlin model of DE, thermo-electro-mechanical imbalance [13] proposed a model on the effect of temperature under the electric field of temperature increase [14]. There are many factors that affect the

temperature of DE. Electromechanical behavior of DE is one of the most important factors affecting temperature [15]. It is known that as the dielectric constant of DE decreases, its temperature increases linearly [16]. Temperature changes occurring on the DEA surface differ in electrical signals. Among electrical signals, it is seen that the square waveform is higher than the sine and triangle waveform [17]. As the operating frequency increases and at very low frequencies (0-1Hz), the DEA deformation decreases. [18,19]. On average, an order of magnitude improvement occurs between 5Hz and 10Hz frequencies, while beyond 10 frequencies there is less reaction [20].

Considering the different design aspects, geometries and materials, many different types of dielectric elastomer actuator (DEA) configurations have been proposed in the literature. The performance of devices is considerably influenced by all these parameters [23]. although there many outstanding combined mechanical and physical properties offered by the DEA, one of the most promising qualities is reliability resulting from its fully covered edge. Moreover, both ease of manufacturing and multilayer processing are the other properties coming into prominence [18, 24]. Some of the properties of dielectric elastomers, including power density, flexibility, stress and strain, are as similar as with the properties of natural muscles. Any actuator built with the VHB-4910 requires a material pre-stretched in order to increase the failure strength up to a significant level.

The VHB-4910 is an important material for the artificial muscle actuator due to its improved tensile performance and low power consumption. Ideally, a dielectric elastomer behaves like a capacitor and consumes only power when the input voltage changes.

Nonetheless, the residual current leads the elastomer to consume power at DC voltages, which results in a continuous high power usage. Breaking of a dielectric material causes damage to the actuator by short-circuiting the voltage applied to both sides due to both the high applied voltage and the very thin dielectric elastomer membrane. Such significant aspects, including a selection of suitable materials, developments in manufacturing techniques and possible pre-stress, play very considerable roles in improving the potential operating performance of actuators.

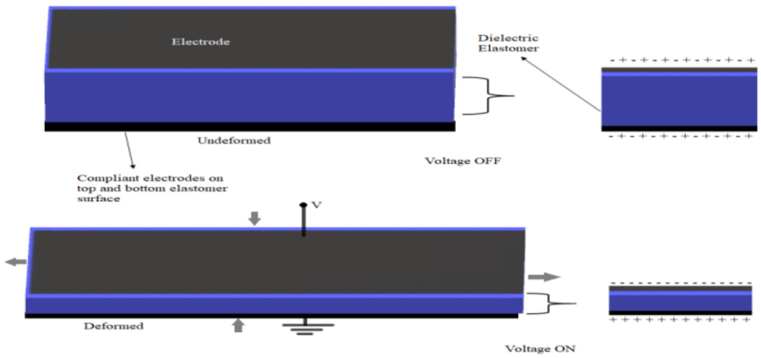


Fig. 1 Working principle of dielectric elastomer actuator.

In this experimental study, temperature changes occurring on the DEA surface were investigated depending on different ambient temperatures, frequencies of different electrical signals, voltage and pre-stretching. In the experiments, VHB4910 material was used because it produces high deformations with a temperature range (233 ~ 363 K) [18]. These changes are important for DEAs considered as artificial muscles. In order to use DEA in surgical and practical applications, it is necessary to know the conditions under which temperature change should be kept. One of the most difficult tasks encountered in this application is to impose the high voltage to DEA ranging from 1kV to 10 kV. Nonetheless, applying this high voltage to DEAs does not raise any safety concern because of their operation capabilities at low currents . Additionally, it allows it to be controlled by electronic circuits because it works with dc-dc converters.

## 2. MATERIAL AND METHODS

### 2.1. Design Principle

Dielectric elastomer materials generally consist of acrylic, silicone or polyurethane. The most widely used acrylic dielectric elastomer material is VHB4910 double-sided adhesive tapes produced by 3M, which has very high adhesion property and causes large deformation [9]. VHB adhesive tapes are soft and elastic and can be used with pre-stretching. Electrodes commonly used in the literature are carbon grease, carbon powder, graphite and thin metallic films [12]. In this study, conductive carbon grease (Premium Carbon Conductive Grease, MG Chemicals) was applied by brushing to both surfaces because of its good adhesion to the elastomer, providing excellent electrical conductivity, low resistance and affordable price. In order to obtain high dc voltage, copper tapes are used to connect the carbon grease applied to the elastomer with a dc-dc converter (Q-80, EMCO Inc.), which has an input voltage between (0 ~ 5) volts and can produce 8 kV. In the experiment, a signal generator (TT T-ECHNIC-C VC2002) with square, triangle and sine waveforms in the frequency range of 0.12Hz ~ 2MHz, an infrared thermal imager (HTI-04) with a sensitivity of 0.07 ºC that can measure between (-20 ~ 300 ºC)Temperature changes occurring at the surface temperature of DEA were measured with.

Experiments were carried out by preparing an adiabatic environment (Fig. 2). With the signal generator, using square, sine and triangle waveforms at different frequencies, 0 ~ 8 kV voltage is obtained by applying 0 to 5 volts with the help of dc-dc converter. The dielectric elastomer, which is pre-stretched with the help of the obtained voltage, is applied by brushing carbon oil on both surfaces and then attached to the converter using adhesive copper tapes. With the help of a thermal camera, temperature changes on the DEA surface are recorded instantly.

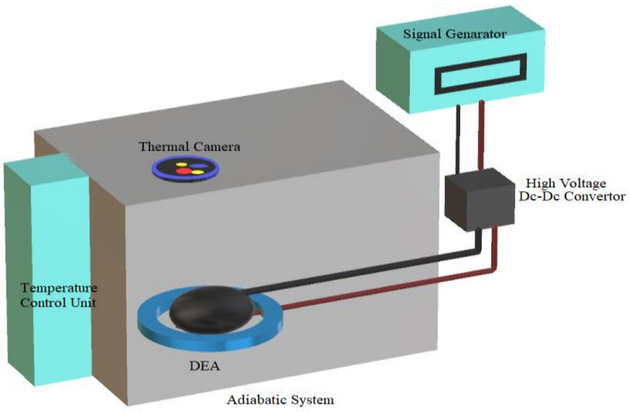


Fig. 2 DEA surface temperature experiment setup.

### 2.2. Preparation of the Test Samples

On the DEA surface in the experiments; temperature changes in different frequencies of electrical signals, temperature changes due to pre-stretching, temperature changes due to ambient temperature and temperature changes due to voltage were investigated with the help of signal generator.

#### 2.2.1. Pre-stretch

Pre-stretching is the thinning of DE. Thinning was achieved by applying stretching process of DE in both directions equally. Pre-stretch rate is one of the most important factors affecting both deformation and temperature. In the experiments, the pre-stretching processes were tested under different measurements of the elastomer as shown in Fig.3.

Pre-stretch achieves a stretch of more than 300% from elastomer membranes. Pre-stretching is the process of applying tension to the elastomer membrane. The pre-deformation process also keeps the elastomer membrane under pressure. In essence, both voltage characteristics of the dielectric elastomer actuator and the stress vary with the bias voltage [21, 22].

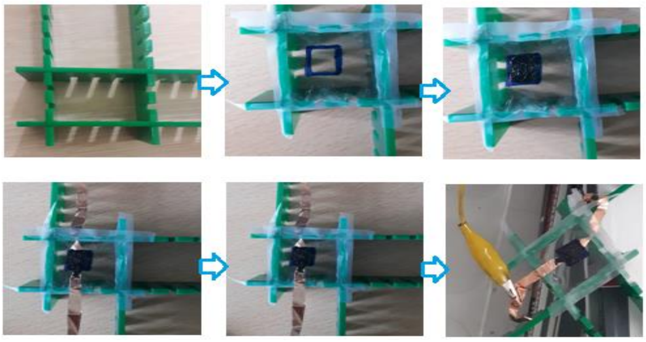

**Figure 3.** The fabrication layer of DE.

In these experiments, a DE 30mm x30mm pre-stretching process with diameters of 15mm x15mm has been performed. Electric field has been applied to the surface of 10mm x10mm in the center of DE. The variations of temperature with the imposed electric field on the surface of DEA have been examined.

## 3. RESULTS

### 3.1. DEA Determination of Surface Temperatures

By using a thermal camera in an adiabatic environment, the temperature changes on the surface of DEA resulting from the applied electric fields with various waveforms (square, triangle and sine) at different frequencies have been measured. The measured results are illustrated in Fig 4 and documented in Table 1.The obtained temperature values reported in Table 1 have been transferred to the computer environment. From the measurements, it has been deduced that many factors, including ambient temperatures, voltage, frequency size, electrical signal type and pre-stretching, influence the surface temperature of DEA. It is seen as (Δt) ~ ± 1 $^{o}$C between the temperature averages and temperature differences.

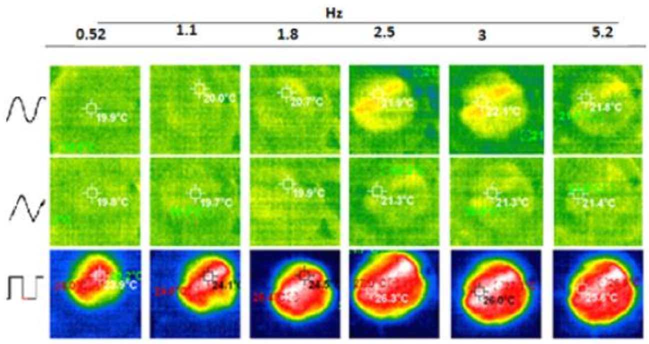


Fig. 4 DEA surface temperature measurements obtained for different electrical signal formats between 0.52 and 5.2 Hz at 16 $^{o}$C temperature and 20% moisture.

Table 1. Temperature variations ($^{o}$C) on the surface of DEAs for various electrical signals with different frequencies

| **Electrical Signals** | **Frequencies *f* (Hz)** | | | | | |
|---|---|---|---|---|---|---|
| | **0.52** | **1.1** | **1.8** | **2.5** | **3** | **5.2** |
| Sine | 19.9* | 20* | 20.7* | 21.9* | 22.1* | 21.8* |
| Triangle | 19.8* | 19.7* | 19.9* | 21.3* | 21.3* | 21.4* |
| Square | 24* | 24.6* | 26.4* | 27* | 27.1* | 26.9* |

* Temperature generated on DEA surface($^{o}$C)

In order to attain the reliable experimental data for the determination of temperature change on the surface of DEA, five tests were carried out for each electrical signal with each frequency. The experimental data was assessed with 95% confidence bounds in *MSTAT-C* package program.

When the difference between groups was significant, the difference between the average values was compared to Duncan test. Thus, the success rankings of the factors included in the experiment were determined by dividing them into homogeneity groups according to the least important difference (LSD) critical value. As seen in Table 2, the sine and triangle waveforms are in the same homogeneity group at high and low frequency levels.

Table 2. Temperature variations (oC) on the surface of DEA for various electrical signals with different frequencies.

| Frequences (Hz) | Square | | Sine | | Triangle | | LSD ± |
|---|---|---|---|---|---|---|---|
| | $\bar{X}$ | HG | $\bar{X}$ | HG | $\bar{X}$ | HG | |
| 0.12 | 27.50 | A | 22.02 | B | 22.16 | B | 0.3378 |
| 0.2 | 28.10 | A | 22.36 | B | 22.34 | B | 0.1966 |
| 1 | 32.52 | A | 23.30 | B | 22.58 | C | 0.2187 |
| 2 | 38.32 | A | 24.22 | B | 23.22 | C | 0.3665 |
| 3 | 38.08 | A | 25.36 | B | 23.98 | C | 0.3563 |
| 12 | 33.88 | A | 24.18 | B | 23.50 | C | 0.2941 |
| 16 | 31.26 | A | 23.64 | B | 23.32 | B | 0.4159 |

HG: Homogeneity Group $\bar{X}$ : Arithmetic Average (ºC)

### 3.2. Temperature Change on DEA Surface with Different Frequencies at Constant Voltage

In the temperature measurements on the DEA surface, the frequency and voltage have been taken as constant for the square, sine and triangular waveforms and their change with time has been examined. As a result of this examination, it was concluded that the temperatures generated on the surface of DEA first drastically increase up to their maximum values within one minute shortly after the electrical signals are applied, and then tend to be stable as shown in Fig 5.

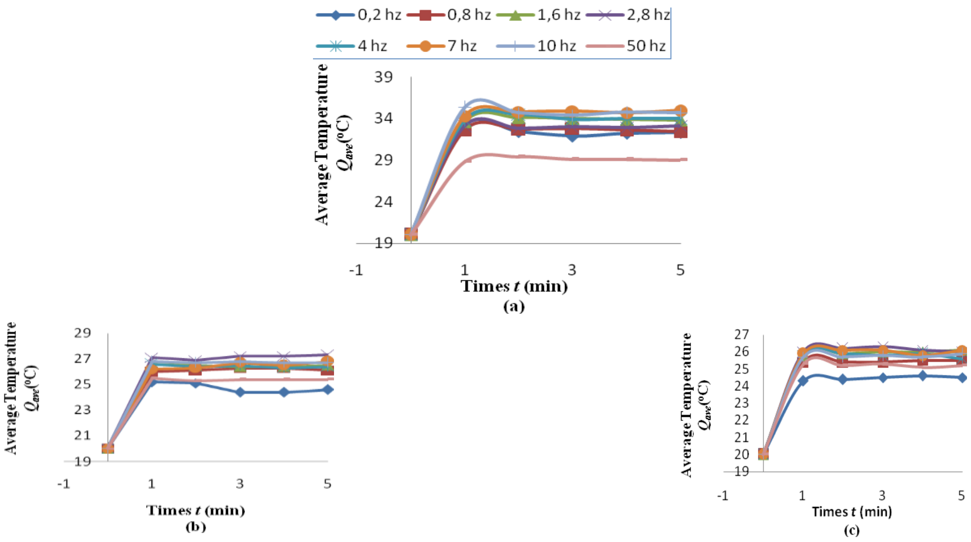


Fig. 5 Temperature changes with time at different frequencies on the DEA surface (a) square, (b) sin, (c) triangle waveforms.

Temperature changes consisted of 5 different measurements at different frequency values of three different signal types by applying 25% humidity and 17ºC temperature value, 3.2 kV voltage and 10mmx10mm electric field. In the experiments, it was determined that (Δt)= ∓1 ºC temperature changes occurred in temperature measurements. As comprehended from the results in Fig 5, the square waveform induces the highest temperature that is mainly due to more deformation observed in DEA compared to other waveforms.

It has been observed that by applying 3.2 kV voltages and 10mmx10mm electric field to DEA, temperature values change in the frequency changes of different electrical signals. The temperature on the surface of DEA generated by the square waveform was found to be higher than other two waveforms under a condition where the ambient temperature as well as the environment humidity is equal to 17ºC and 20%, respectively. On the other hand, the temperatures resulting from both the applied sine and triangle waveforms were found to be close to each other. Furthermore, as independent of the type of electrical signal, the generated temperature attains its maximum value as the frequency varies between 2 Hz and 10 Hz as illustrated in Fig 6. Additionally, increasing the frequencies up to MHz and KHz levels causes a reduction in the temperature.

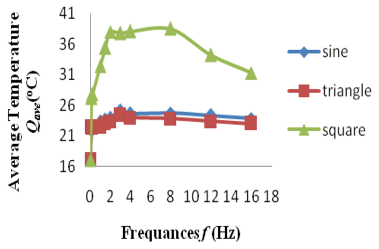


Fig 6. Temperature change at different frequencies of sine, triangle and square waveforms.

When operating frequencies are examined in the literature, the deformation of DEA decreases with an increased frequency and at very low frequencies [10, 19]. On average, there is an enhancement in the reaction taking place between 5 Hz and 10 Hz, while it is seen that the reaction occurs at frequencies less than 10 Hz [30]. Hence, it was observed that the temperatures on the surface of DEA generated by all the electrical signal types decreases while the frequencies increases as documented in Table 3.

Table 3. Temperature variations (ºC) on the DEA surface with different electrical signals at different high frequencies

| **Electrical Signals** | **Frequencies *f* (Hz)** | | | | | |
|---|---|---|---|---|---|---|
| | **1 kHz** | **2 kHz** | **5 kHz** | **10 kHz** | **1 MHZ** | **2 MHz** |
| Square | 30.8* | 30.7* | 30.3* | 29.9* | 28.6* | 28.4* |
| Sine | 19.2* | 19.2* | 18.8* | 18.7* | 18.4* | 18.2* |
| Triangle | 19.1* | 19.0* | 18.8* | 18.6* | 18.2* | 18.1* |

* Temperatures on DEA surface (ºC) generated by different types of signals at different frequencies.

### 3.3. Voltage-dependent DEA surface temperature measurements

One of the most important factors affecting the temperature of the DEA surface is the applied voltage. It has been observed that as the applied voltage increased, the temperature occurring on the DEA surface increased linearly and the temperature values increased suddenly after 5kV. VHB4910 material is a high temperature resistant material. For this reason, the breakdown of DEA also occurs by applying high voltage and at high temperatures. With the increase in temperature, the elastomer breakdowns and the short circuit of the electrodes causes the DEA to lose its feature. According to the results of the experiment, as seen in Figure 7 and Figure 8, the temperature value increased as the tension increased on the DEA surface. Breakdowns have occurred when the voltage level exceeds 5 kV.

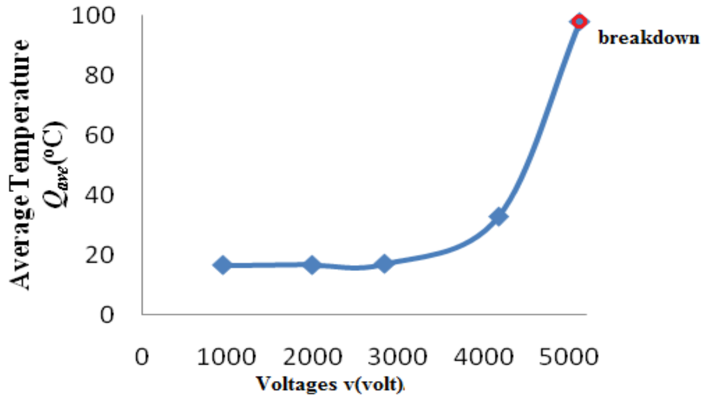


Fig. 7 Temperature change due to voltage on the DEA surface.

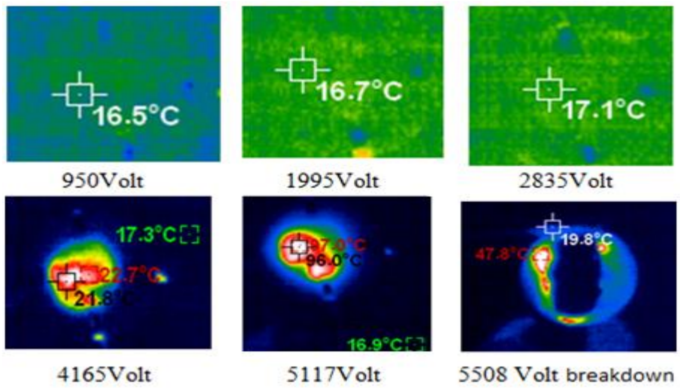


Fig. 8 Temperature change thermal camera images due to voltage on DEA surface.

In particular, actuators that transform an applied electric field into mechanical motion are used in many robotic applications, including biomimetic robots, prostheses, and artificial muscles [3]. The dc-dc convertor used in our experiments possesses the input and output voltages as equal to (0~5V) and (kV), respectively. In reality, these input and output voltages are considered as low and high, respectively. Due to low current (mA level) operation offered by DEAs, they are safe to use in any living thing and mechanism. While an applied voltage exceeding 5 kV causes an imperfection in the dielectric elastomer, an applied voltage less than 3kV results in an undesirable low mechanical reaction in the DEA. Therefore, the voltages varying between 3 kV and 5kV were applied to the DEAs in our experiments. In light of the experimental results, it was reached a conclusion that the ideal voltage providing the best mechanical reaction without any damage is the voltage between 3kV and 5kV. As observed, the applied voltage higher than 5.5 kV leads to a rapid increase in temperatures that eventually causes an imperfection in DEA as depicted in Fig 8.

### 3.4. Surface temperature change with the ambient temperature

It has been observed that applying the 3.2 kV voltage to DEA and ambient temperature (18°C to 32°C) is one of the most important factors influencing the temperature of DEA. It has been observed that it is directly proportional to the ambient temperature. In environments where the ambient temperature is different, the temperature values of different electrical signals were measured as shown in Fig. 9. In the experiments performed, the DEA surface temperature has been also high in square wave form and when the ambient temperature has been high. When the frequency changes of the sine and triangle waveforms have been examined, it has been observed that the temperature values have been close to each other.

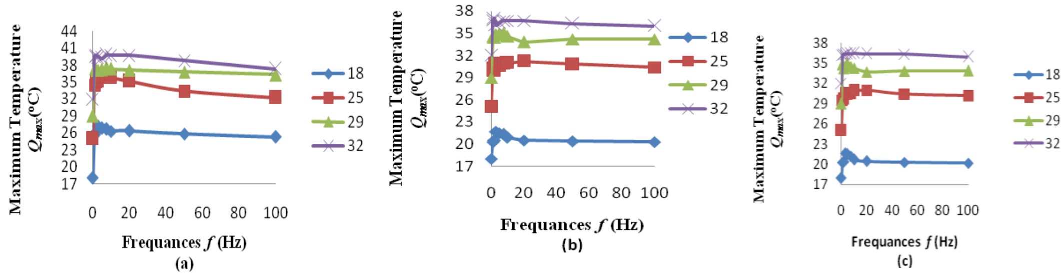


Fig. 9 (a) Square waveform graphs of temperature change in different frequency levels and different temperature environments on the DEA surface; (b) Sine waveform graphs of temperature change in different frequency levels and different temperature environments on the DEA surface; (c) Triangle waveform graphs of temperature change in different frequency levels and different temperature environments on the DEA surface.

### 3.5. Pre-stretching DEA's surface temperature measurements

Pre-stretching is one of the most important factors affecting the temperature of DEA. It has been observed that as the pre-stretching ratio increased, the temperature values also increased significantly. DEA surface temperatures measured at ambient temperature 22ºC and 20% moisture occur as shown in Fig. 10. Temperature measurements at different frequencies have been carried out for 3 different pre-stretched elastomers. According to the results of the experiments, the highest deformation and temperature increase have been occurred in square wave form due to elastomer thinning as the pre-stretching increases. There is a drop observed in the voltage that is caused by the pre-stretching. On account of this, the mechanical motion with lower voltage can be achieved by increasing the pre-stretch. In this experimental study, the effects of three different pre-stretching processes at different wavelengths were evaluated. By means of the pre-tensioned process, the dimensions of the dielectric elastomers for three various cases were increased from 15X15 mm to 21X21 mm, and from 20X20 mm to 31X31 mm, and finally from 12X12 mm to 27X27 mm. From the results shown in Fig 10, it was deduced that an increase in pre-stretching leads to an increase in both mechanical reaction and the surface temperature of DEA. The electric field applied in this experiment has been realized as equal to 3.2kV / 10mm x10mm.

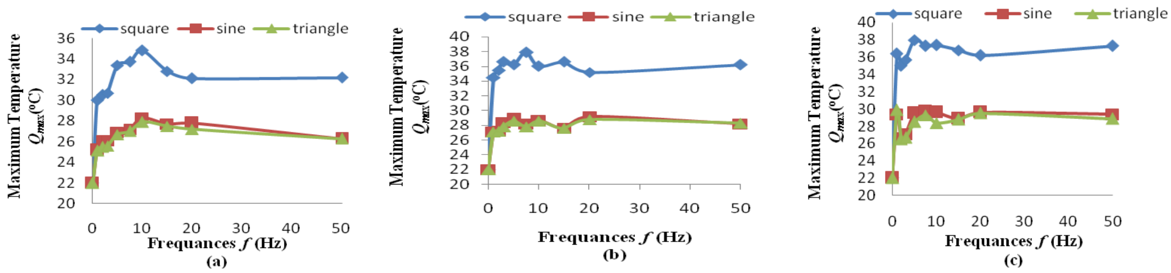


Fig. 10 Temperature variation caused by different electrical signals due to 15mm x15mm ➔ 21mm x21mm(a), 20mm x 20mm ➔ 31mm x 31mm (b) and 12mm x 12mm ➔ 27mm x 27mm (c) pre-stretching on the DEA surface.

## 4. CONCLUSION

The following conclusions can be drawn from the experimental results obtained in this study.

- The frequencies in the range of 2-10Hz generate the highest temperatures on the surface of DEA.
- Both high (kHZ) and low (0~1Hz) frequencies lead to a decrease in temperature on the surface of DEA.
- The highest temperature on the surface of DEA is generated by the square waveform.
- Both sine and triangle waveforms lead to similar temperatures on the surface of DEA.
- The temperature on the surface of DEA as well as the deformation increases with an increased voltage.

- As the pre-stretching and ambient temperature increased, the DEA surface temperature has been increased at the frequency levels of square sine and triangular waveforms.
- By means of this study, temperature changes on the surface of DEA generated by different waveforms have been phenomenologically explained. Applying a high voltage (> 5kV) to the DEA causes a rapid increase in temperature. Since DEAs are extensively utilized in a broad range of application fields including robotics, surgical and artificial muscles, obtaining in-depth information regarding their response to such different electrical signals with different frequencies at various temperatures causing a temperature change on their surfaces is highly crucial for robust design. As acknowledged, an excessive increase in temperature on the surface of DEA induces an imperfection and eventually a catastrophic failure. Therefore, the evaluated parameters in this study, including frequency type, its amplitude, ambient temperature, voltage and pre-stretching, need to be taken into consideration for the temperature-based design of DEA.

## ACKNOWLEDGEMENTS

We are grateful for this study being funded by Yozgat Bozok University BAP unit with project number 6602a-FBE / 19-244.

## 6.REFERENCES

1. R. Pelrine, R. Kornbluh,, J. Joseph, R. Heydt, Q. Pei and S. Chiba, "High-field deformation of elastomeric dielectrics for actuators," Materials Science and Engineering: C, 11(2), 89-100, 2000.
2. L. Liu, Y. Liu, K. Yu and J. Leng, "Thermoelectromechanical stability of dielectric elastomers undergoing temperature variation," Mechanics of Materials, 72, 33-45, 2014.
3. P. Brochu, and Q. Pei, "Dielectric elastomers for actuators and artificial muscles," Electroactivity in polymeric materials, 1-56, 2012.
4. Z. Suo, "Theory of dielectric elastomers," Acta Mechanica Solida Sinica, 23(6), 549-578, 2010.
5. R. Pelrine, R. D. Kornbluh, J. Eckerle, P. Jeuck, S. Oh, Q. Pei and S. Stanford, "Dielectric elastomers: generator mode fundamentals and applications," In Smart Structures and Materials Electroactive Polymer Actuators and Devices, International Society for Optics and Photonics, Vol. 4329, pp. 148-156, 2001.
6. J. Zhu, H. Stoyanov, G. Kofod, and Z. Suo, "Large deformation and electromechanical instability of a dielectric elastomer tube actuator," Journal of Applied Physics, 108(7), 074113, 2010.
7. C. Keplinger, M. Kaltenbrunner, N. Arnold and S. Bauer, "Capacitive extensometry for transient strain analysis of dielectric elastomer actuators," Applied Physics Letters, 92(19), 192903, 2008.
8. R. E. Pelrine, R. D. Kornbluh and J. P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," Sensors and Actuators A: Physical, 64(1), 77-85, 1998.
9. R. D. Kornbluh, R. Pelrine, Q. Pei, R. Heydt, S. Stanford, S. Oh and J. Eckerle, "Electroelastomers: applications of dielectric elastomer transducers for actuation, generation, and smart structures," In Smart Structures and Materials 2002, Industrial and Commercial Applications of Smart Structures Technologies, International Society for Optics and Photonics, Vol. 4698, pp. 254-270, 2002.
10. E. L. White, , M. C. Yuen and R. K. Kramer, "Distributed sensing in capacitive conductive composites," IEEE SENSORS (pp. 1-3). IEEE, 2017.
11. A. O'Halloran,, F. O'malley and P. McHugh, "A review on dielectric elastomer actuators, technology, applications, and challenges," Journal of Applied Physics, 104(7), 9, 2008.
12. S. Rosset and H. R. Shea, "Flexible and stretchable electrodes for dielectric elastomer actuators," Applied Physics A, 110(2), 281-307, 2013.
13. Y. Liu, L. Liu, Z. Zhang and J. Leng, "Dielectric elastomer film actuators: characterization, experiment and analysis," Smart Materials and Structures, 18(9), 095024, 2009.
14. C. Jean-Mistral, S. Basrour, J. J. Chaillout and A. Bonvilain, "A complete study of electroactive polymers for energy scavenging: modelling and experiments," arXiv preprint arXiv:0802.3046, 2008.
15. J. Sheng, H. Chen, B. Li, Y. Wang and J. Qiang, "Effect of temperature on electromechanical instability of dielectric elastomers," In Electroactive Polymer Actuators and Devices (EAPAD) 2012 International Society for Optics and Photonics, Vol. 8340, p. 83402B, 2012.
16. İ. KARAMAN and D. E. ŞAHİN, "Elektromekanik Yükle Tahrik Edilen Yumuşak Dielektrik Elastomerin Sıcaklık Karakterizasyonu," Uluslararası Doğu Anadolu Fen Mühendislik ve Tasarım Dergisi, 2(2), 190-204, 2020.
17. C. Jean-Mistral, A. Sylvestre, S. Basrour and J. J. Chaillout, "Dielectric properties of polyacrylate thick films used in sensors and actuators," Smart materials and structures, 19(7), 075019, 2010.
18. F. A. M. Ghazali, C. K. Mah, A. AbuZaiter, P. S. Chee and M. S. M. Ali, "Soft dielectric elastomer actuator micropump," Sensors and Actuators A: Physical, 263, 276-284, 2017.
19. J. Zou and G. Gu, "Modeling the viscoelastic hysteresis of dielectric elastomer actuators with a modified rate-dependent prandtl–ishlinskii model," Polymers, 10(5), 525, 2018.

20. T. L. Buckner, E. L. White, M. C. Yuen, R. A. Bilodeau and R. K. Kramer, "A move-and-hold pneumatic actuator enabled by self-softening variable stiffness materials," IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pp. 3728-3733, 2017.
21. F. Carpi, P. Chiarelli, A. Mazzoldi, and D. De Rossi, "Electromechanical characterisation of dielectric elastomer planar actuators: comparative evaluation of different electrode materials and different counterloads," Sensors and Actuators a-Physical, vol. 107, pp. 85-95, 2003.
22. K. J. Kim and S. Tadokoro, "Electroactive Polymers for Robotic Applications," Artificial Muscles and Sensors, Springer, pp. 23,291, 2007.
23. O.A. Araromi, I. Gavrilovich, J. Shintake, S. Rosset, M. Richard, V. Gass and H.R. Shea, "Rollable multisegment dielectric elastomer minimum energy structures for a deployable microsatellite gripper," IEEE/ASME Trans. Mechatron. 20 pp. 438–446, 2015.
24. V. T. V. Khanh, A. T. Mathew, J. S. Short, Z. F. Quek, M. H. Ang, and S. J. A. Koh, (2018, July). "Displacement improvement from variable pre-stretch diaphragm type Dielectric Elastomer Actuator," In 2018 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) IEEE. pp. 545-550, 2018.


*Received March 3, 2021*