The Electrical Breakdown of Thin Dielectric Elastomers: Thermal Effects

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INTRODUCTION

- Dielectric elastomers are being developed for use in actuators, sensors and generators to be used in various applications, such as artificial eye lids[1], stretch sensors[2] and human motion energy generators[3] **[see fig 1]**.
- For maximum efficiency, the devices are operated at high electrical fields which increases the likelihood for electrical breakdown significantly.
- Thermal effects that may lead to electrical breakdown in thin PDMS film will be modeled. We assume the effect of temperature on electrical breakdown of thin PDMS film is different from polypropylene film as investigated by Xiaoguang et al. (2003)[4].
- The main difference is that the PDMS elastomer is chemically crosslinked and thus the Young's modulus will not decrease with temperature as for the thermoplastic **[see fig 2]**.

MATERIALS AND METHODS

- Several different types of silicone elastomers with different loadings of reinforcing silica particles as well as a permittivity enhancing filler (titanium dioxide) were studied.
- Four of the elastomers are commercially available elastomers of either the type LSR (liquid silicone rubber) or RTV (room temperature vulcanizing).
- A TA Instruments ARES G2 Rheometer was used to characterize the rheological properties of the prepared films.
- Volume resistivity measurements were performed in a three-terminal cell by means of a Keithley 617 electrometer.
- The thermogravimetric analysis (TGA) was performed with a TA Q500 equipped with autosampler.

RESULTS AND DISCUSSIONS

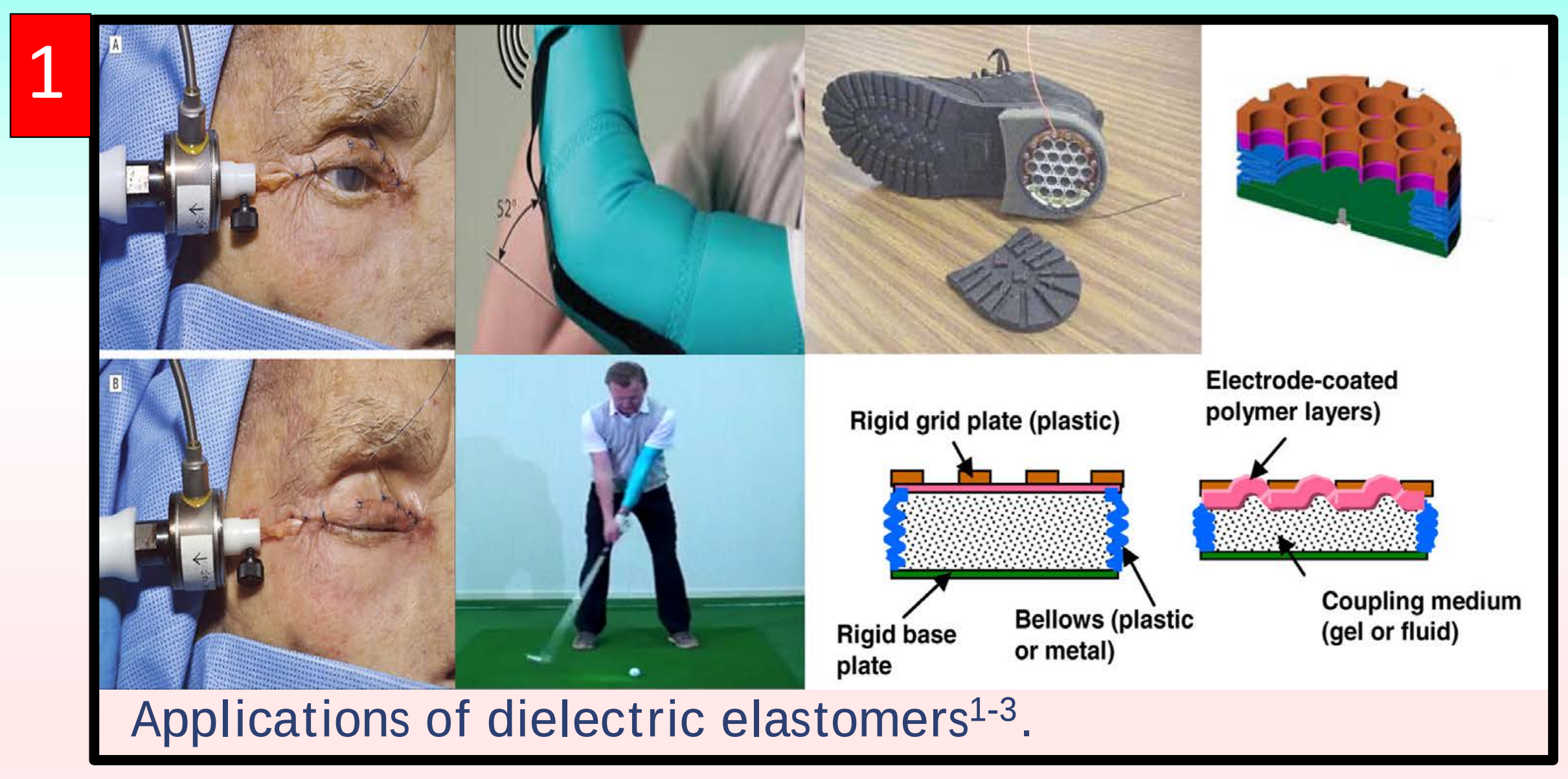
Experimental Data

- The increase of loss permittivity with increasing temperature is attributed to more dissipation of the electrical energy into heat[5] **[see fig 3]**.
- The increase of electrical conductivity **[see fig 4]** at elevated temperature causes more heat production since the joule heating is directly proportional to the electrical conductivity[6].
- The TGA data **[see fig 5]** show that RT625 and XLR630 with filler, possess relatively low 2% degradation temperatures (around 300°C) whereas the other two have to be heated above 400°C before significant degradation takes place.

Numerical Prediction of Electrothermal Breakdown

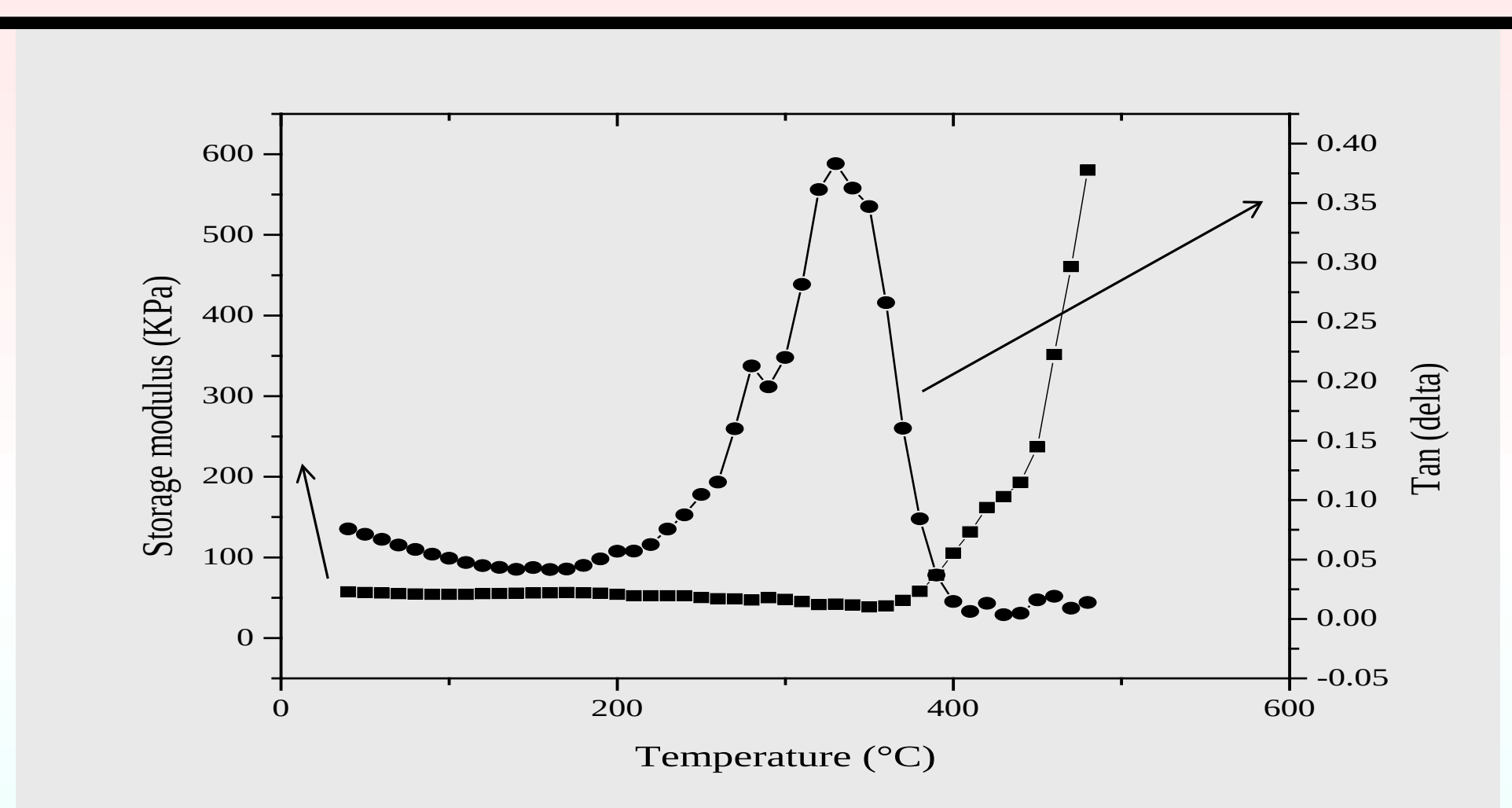
- The electrothermal breakdown was modeled based on numerical prediction as described in **[see fig 6]**.
- In solid dielectrics, electrical breakdown may be thermal which means it is caused by the fact that heat generated within the film cannot be dissipated sufficiently and thereby leads to thermal instability[6] **[see fig 7]**.
- The general behavior of temperature versus electric field for PDMS film for which the temperature at the center of the sample just before thermal runway is only a few degrees above the boundary temperature **[see fig 8]**. With only a few volts increase across the sample, thermal runaway occurs very rapidly.
- The breakdown field as function of electrical conductivity for 50 µm thick PDMS film **[see fig 9]**. The plot illustrates that higher electrical conductivity causes a lower breakdown field.
- The breakdown field exhibits a hyperbolic decrease as the position of x is closer to the film surface as the result of the heat generated inside the film can be removed rapidly to the surrounding **[see fig 10]**.

1



Applications of dielectric elastomers[1-3].

2



Elastosil LR 3043/30 film with 25 mm diameter and 0.8 mm thickness was used for characterization of the thermal dependence of the rheological properties of PDMS. The storage modulus and the loss tangent are plotted for temperatures between 25°C and 480°C.

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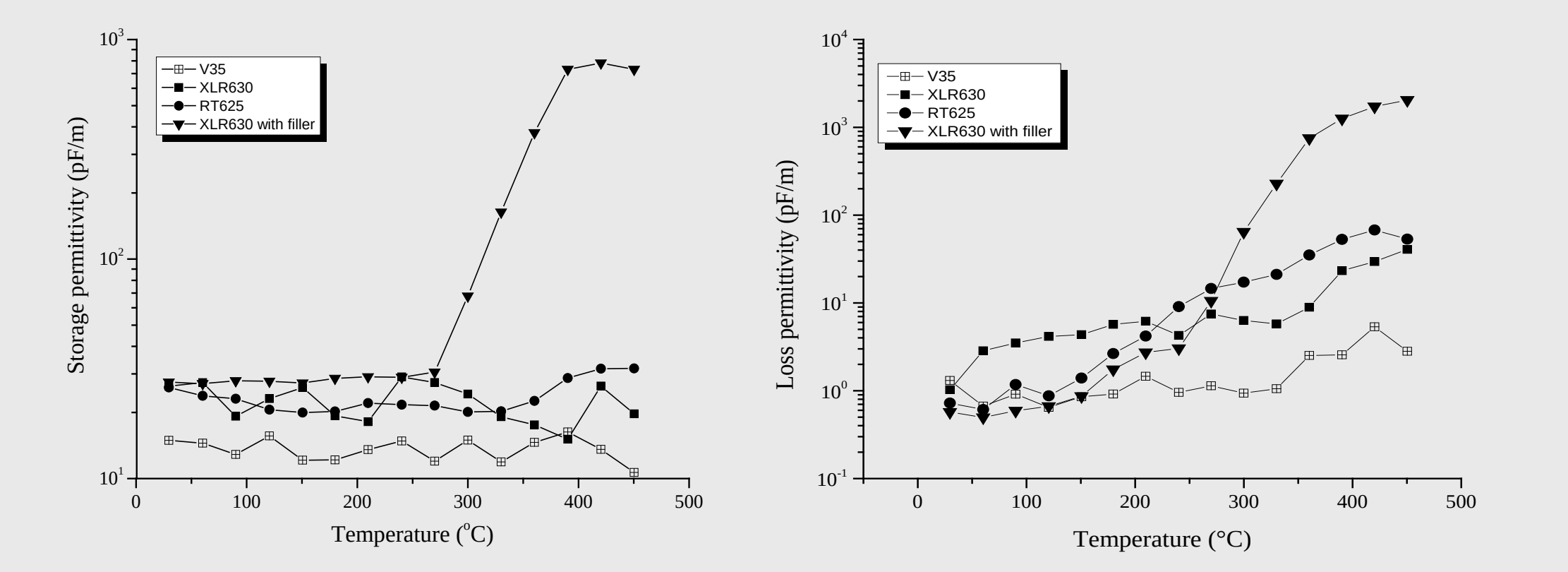

The dielectric properties as function of elevated temperatures for several PDMS films: (A) Storage permittivity (B) Loss permittivity.

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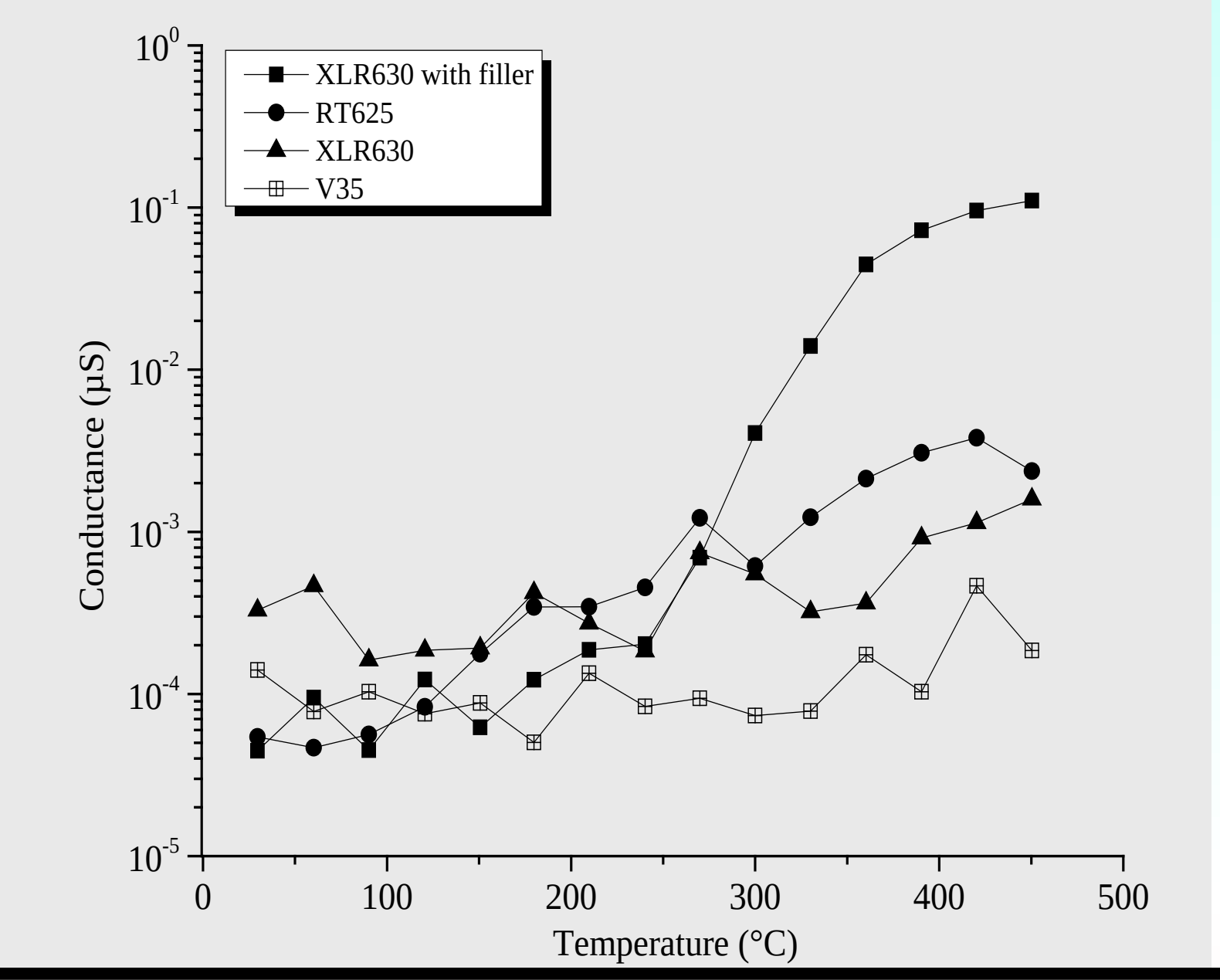

The electrical conductivity at 1 Hz as function of temperature for several PDMS films.

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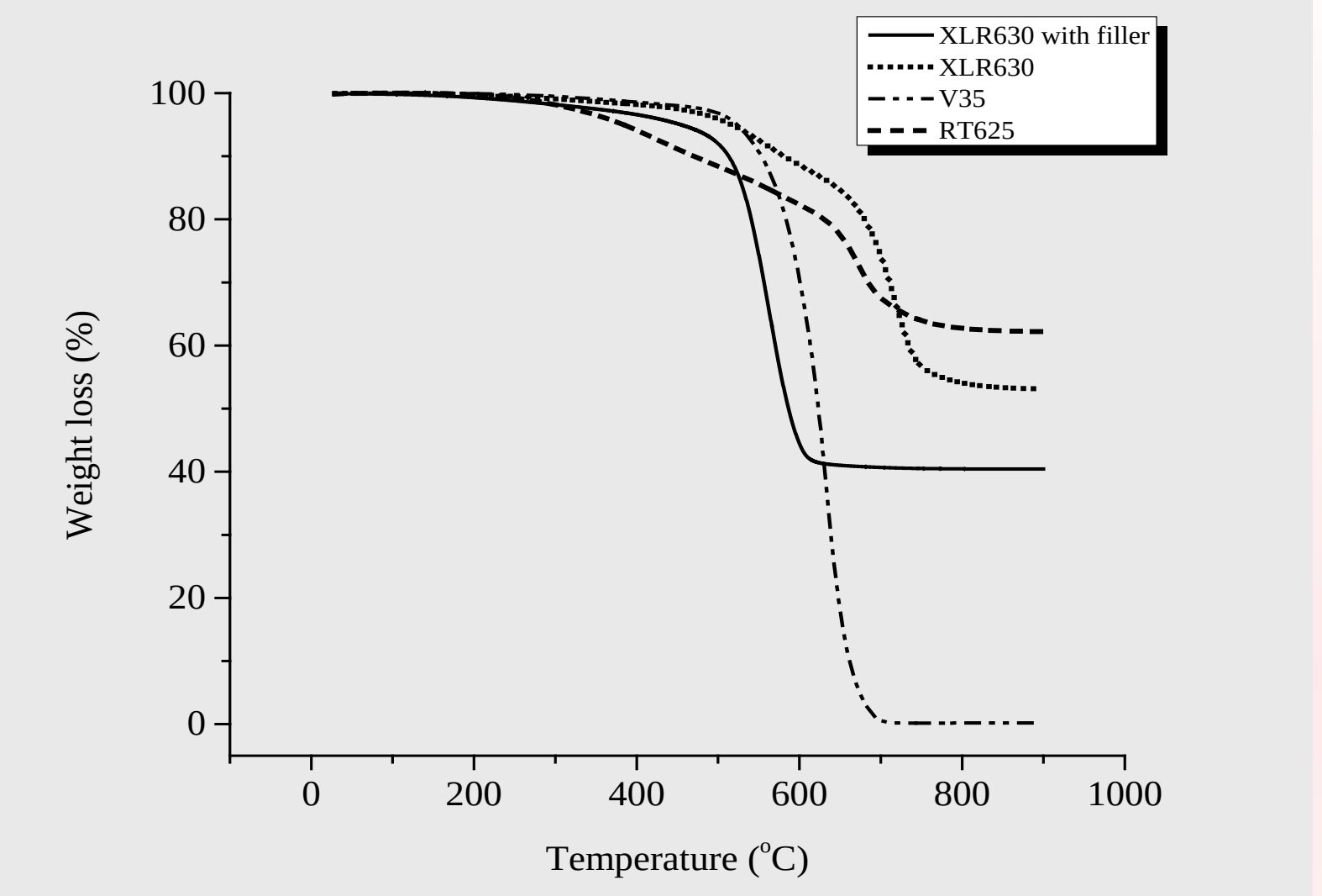
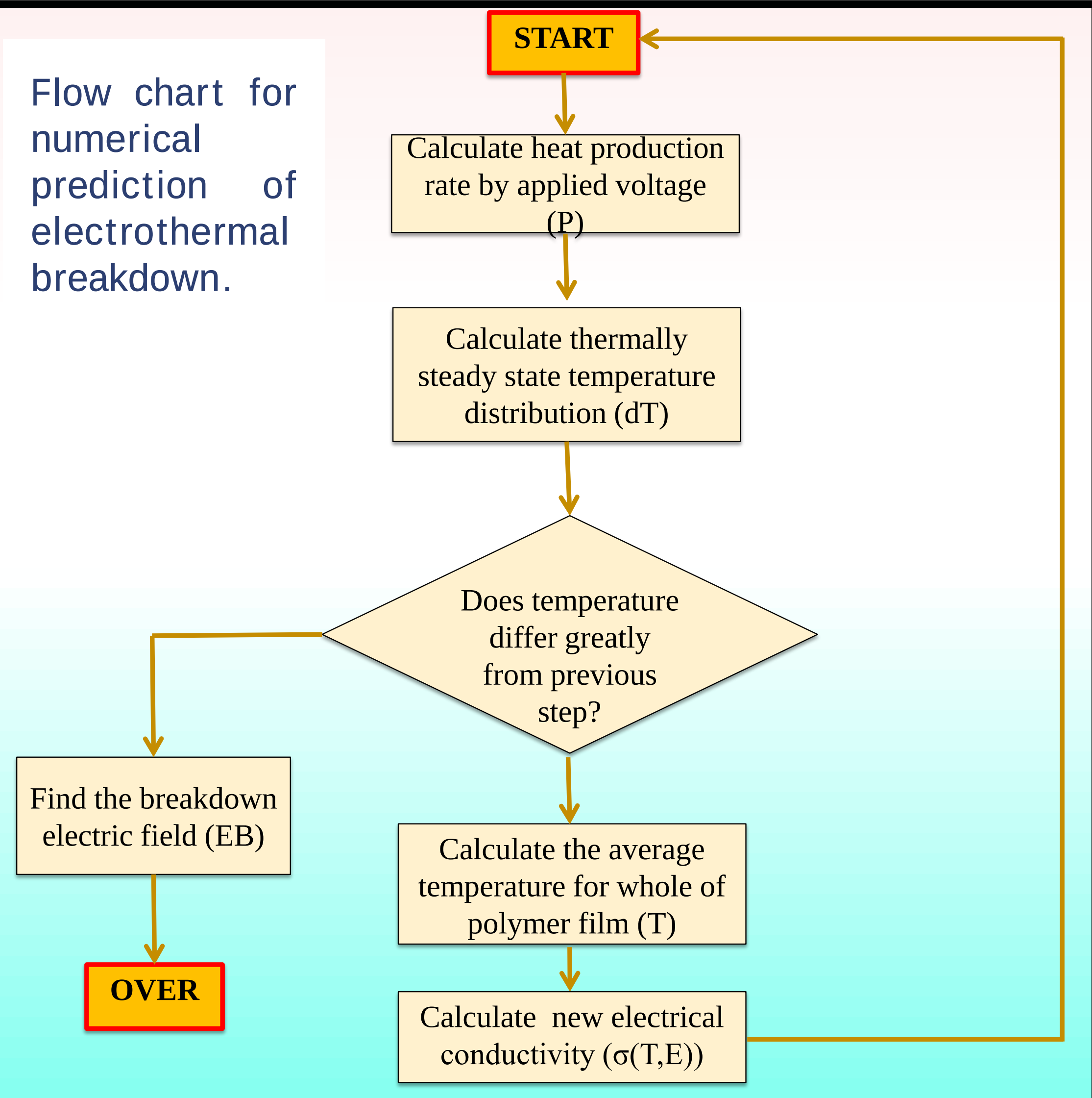


TGA thermograms of PDMS films with different percentages of silica and permittivity enhancing filler.

6

Flow chart for numerical prediction of electrothermal breakdown.



START

Calculate heat production rate by applied voltage (P)

Calculate thermally steady state temperature distribution (dT)

Does temperature differ greatly from previous step?

Find the breakdown electric field (EB)

OVER

Calculate the average temperature for whole of polymer film (T)

Calculate new electrical conductivity (σ(T,E))

7

$$C\frac{dT}{dt} = \sigma(\mathrm{E},T)E^2 + \nabla(\mathrm{K}(T)\nabla T)$$

The heat balance equation where C= volumetric heat capacity, T= temperature, t= time, E= electrical field, ∇= the Laplace operator, K(T)= the temperature dependent thermal conductivity, and σ(E,T)= field and temperature dependent electrical conductivity.

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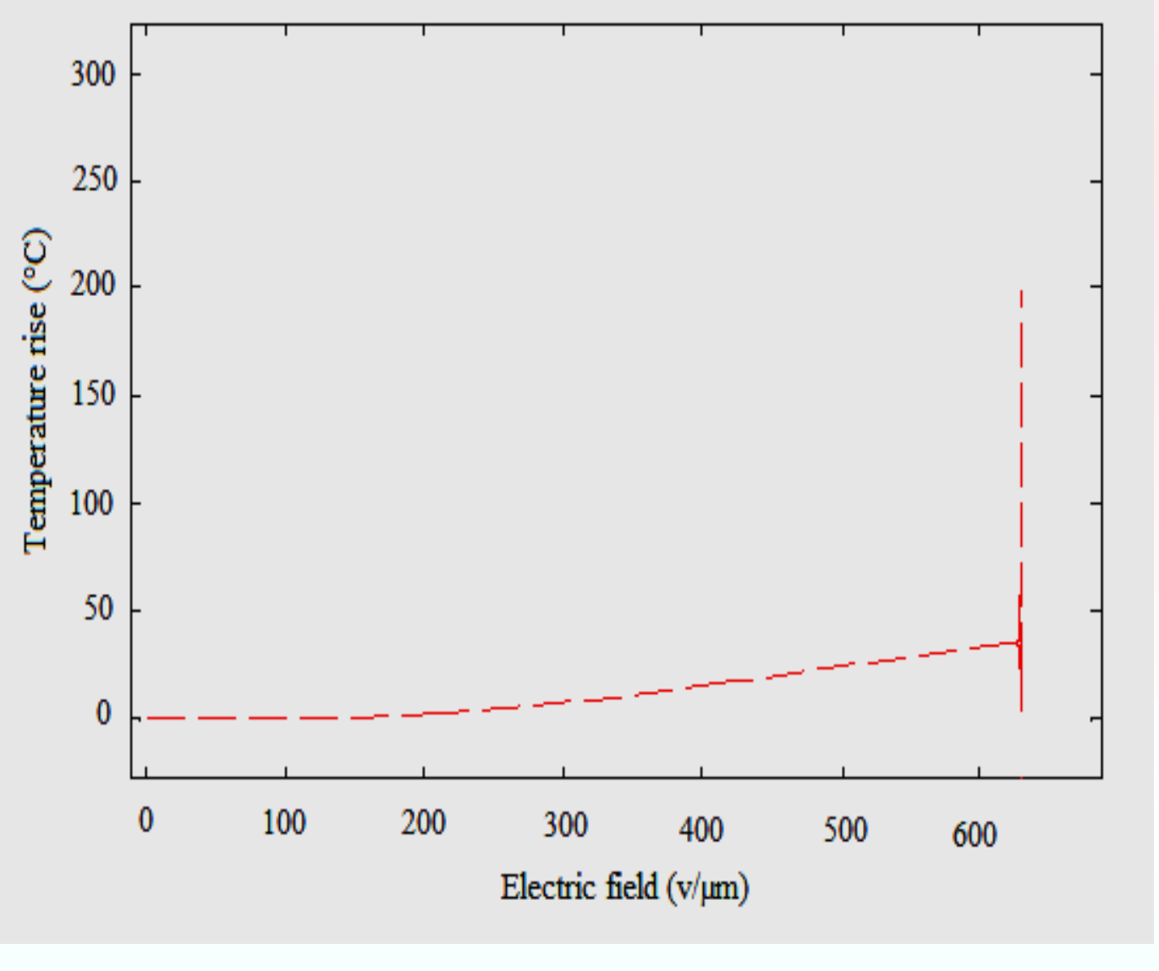

The temperature rise (dT) versus electric field for 50 µm thick PDMS film as computed by the quasi-steady state numerical method. The temperature increases slowly prior to the critical field (629V/µm), at which thermal runaway occurs.

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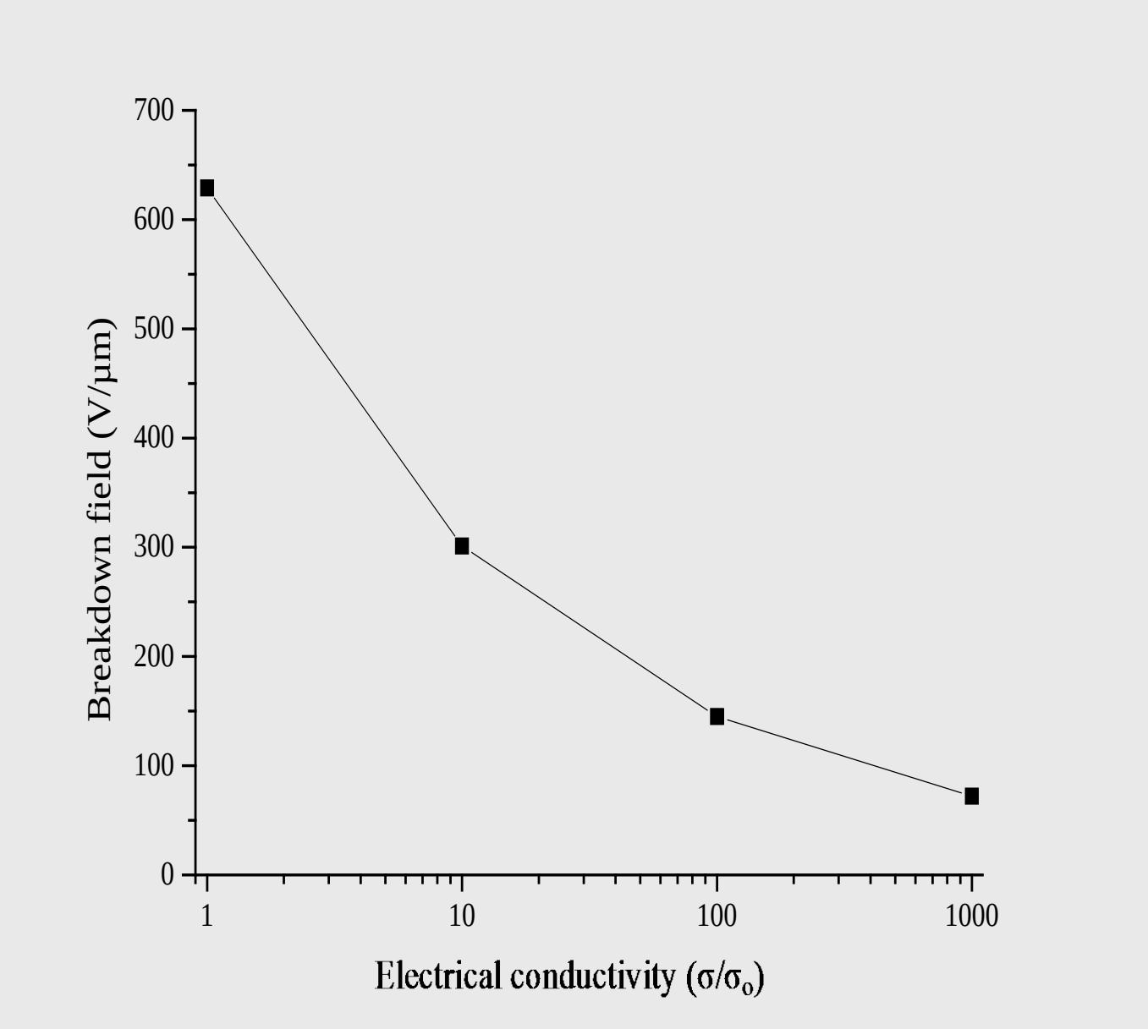

Breakdown fields as function of normalized conductivity at room temperature for the 50 µm thick PDMS film as computed by the quasi-steady state numerical method. The initial electrical conductivity, σ_0, of the PDMS film is 2.45×10^{-16} S/m at room temperature.

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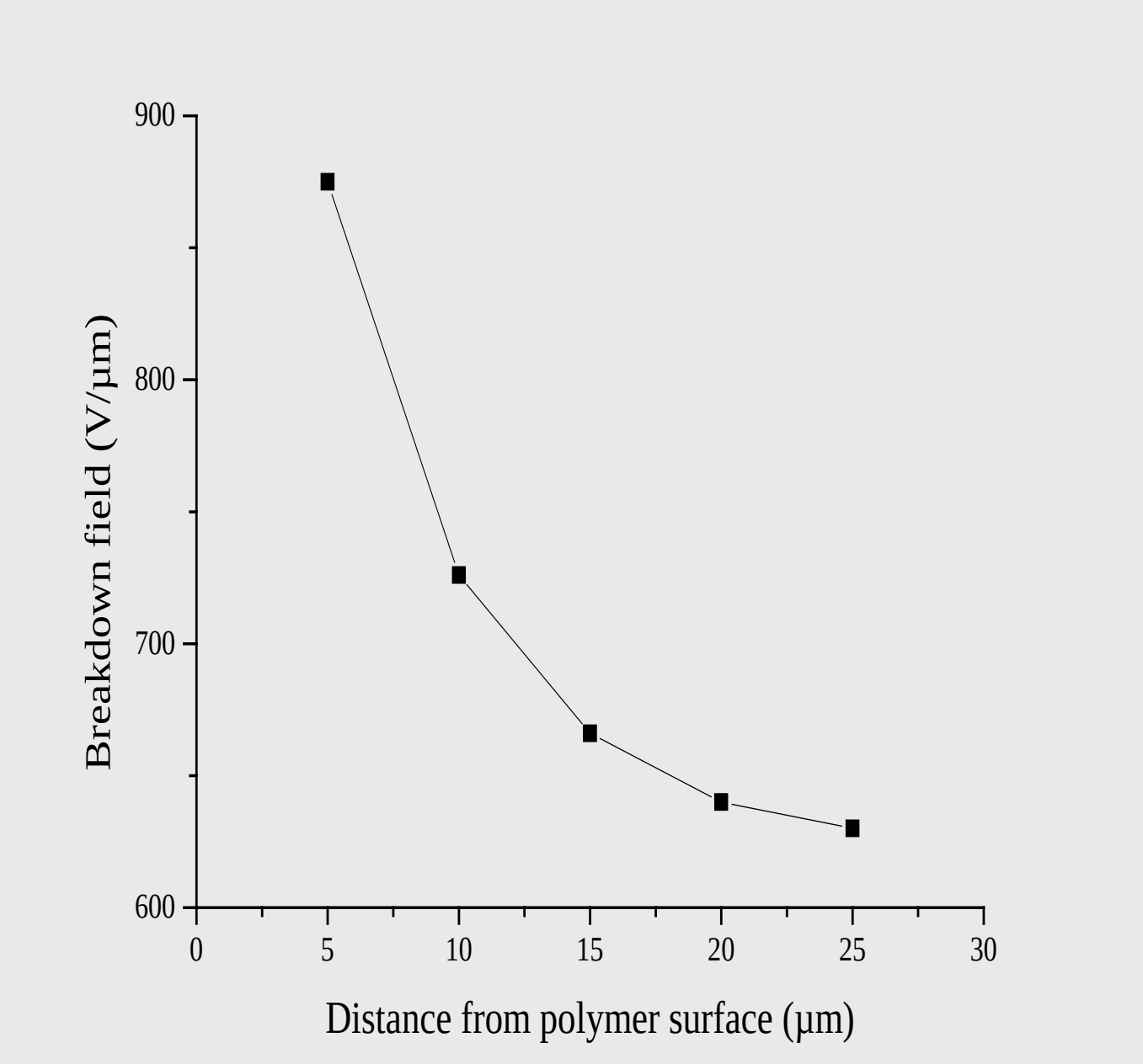

Breakdown strengths at given distances (*x*) from the polymer surface for 50 µm thick PDMS film.

CONCLUSION

- The effect of temperature on dielectric properties of different systems of PDMS dielectric elastomers has been studied experimentally and a model of electrothermal breakdown in thin PDMS based dielectric elastomers has been applied.
- From both methods, it can be concluded that electrothermal breakdown of the materials is strongly influenced by the increase in both dielectric permittivity and conductivity.
- The electrothermal breakdown may not be a major factor to cause electrical breakdown in thin PDMS based dielectric elastomers since the required electrical field required for thermal runaway is about 5 times larger than the reported breakdown fields of silicones.

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