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***A Study of the Effect of Temperature on Cavity Partial Discharges in
Polyethylene (PE) Insulation***

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Declaration

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Signature.....

Dedication

To my late parents, Mr and Mrs Khangale

To this day it always feels like yesterday. In losing you I lost the greatest blessing and comfort, for you were always that to me. Thanks for your love, guidance, support and most importantly, believing in me throughout my studies.

“The world changes from year to year, our lives from day to day, but your love and memory will live on forever. May your souls rest in eternal peace”

To my wife Seriti and Our Kids (Ronewa and Andani) without your support, this work would not have been possible.

Abstract

Synthetic Polymers such as polyethylene are prevalent for high-voltage insulation applications as they offer remarkable insulating and dielectric properties. Notwithstanding precautionary measures made during manufacturing and installation processes, insulation systems are always susceptible to defects for various reasons, which constitute a significant source of Partial Discharge (PD) activity. It is a precursor to insulation degradation leading to premature failure of high-voltage equipment. PD activity is complex due to its non-stationary behaviour and multi-variance dependence. Studies in partial discharge mechanisms have received significant attention over the years to improve phenomena understanding and, in some cases, to allow conclusions to be drawn on the parameters affecting PD mechanisms. These studies have shown that different mechanisms and parameters influence partial discharge activity. In this study, experimental and analytical modelling techniques are used to explore the behaviour of partial discharge mechanisms at varying temperatures. Experimental PD measurements were carried out in accordance with the IEC 60270 standard. A test voltage of 11 kV ac was used. The test temperatures studied were 15°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C. Test specimens with a cavity diameter of 2.5 mm were assembled using three 1.5 mm thick polyethylene sheets sandwiched between two flat brass electrodes. Partial discharge parameters such as the charge magnitude, inception voltage and PD phase resolved pattern (PDPRP) were measured and analysed at varying temperatures. For analytical modelling, the streamer-like discharge concept is adopted to model PDIV while the apparent charge magnitude is modelled based on the induced charge concept introduced by Pedersen in the 1980s. The curve fitting approach was adopted to replicate and explain the measured experimental data. Results showed that Partial Discharge Inception Voltage (PDIV) increased linearly with temperature for the entire test temperature range. PD charge magnitude initially decreased with temperature from 15°C to 60°C and then increased from 60°C to 90°C. The evolution of PD phase resolved pattern (PDPRP) with temperature was characterised by a turtle-like pattern at ambient temperature, which transitioned into a rabbit ear PDPRP as the temperature increased to 90°C. The findings are interpreted using the mean free path effect on ionisation probability as well as the residual charge dynamics in the cavity as a function of temperature. The overall conclusion is that in polyethylene, cavity discharge characteristics respond to temperature changes. The variations in PD characteristics

are monotonous for PDIV and non-monotonous for apparent charge magnitude as well as PDPRP. The implications of the findings are that in PD diagnosis, temperature of the equipment under test must be taken into account in interpretation of PD measurements results.

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List of Acronyms

AC	: Alternating Current
DC	: Direct Current
EGR	: Electron Generation Rate
FEA	: Finite Element Analysis
GND	: Ground
GFRP	: Glass Fibre Reinforced Polymer
Hz	: Hertz
HDPE	: High-Density Polyethylene
HV	: High Voltage
IEC	: International Electrotechnical Commission
IEEE	: Institute of Electrical and Electronics Engineers
kV	: Kilo Volts
MHz	: Mega Hertz
NRF	: National Research Fund
nS	: nano Second
Pa	: Pascal
PD	: Partial Discharge
pC	: Pico Coulomb
PDIV	: Partial Discharge Inception Voltage

PDEV : Partial Discharge Extinction Voltage

PDPRP: Partial Discharge Phase Resolved Patterns

PE : Polyethylene

XLPE : Cross-Linked Polyethylene

1 Introduction and Background

1.1 Research Background

Synthetic polymers are extensively used as an insulation medium in the electrical power industry, particularly polyethylene (PE), due to their remarkable chemical, electrical, mechanical and thermal properties [1], [2]. Montanari [3], argued that insulation medium is the weakest link in high voltage and medium voltage electrical equipment. Insulation is almost always susceptible to degradation and ageing mechanisms. These mechanisms are generally linked to the insulation medium's inability to handle operational stress due to contaminants and other imperfections in the insulation medium, leading to degradation and eventually complete equipment failure.

Notwithstanding precautionary measures made during manufacturing and installation processes, the insulation medium is susceptible to defects or imperfections such as conductive contaminants, gas cavities, and water bubbles [4]. Andres *et al.* [5] inferred that insulation defects might arise from service-related ageing. Gas-filled cavities, also commonly referred to as voids, are the most common contaminants for solid insulation mediums. During the manufacturing process, gas-filled cavities are generally introduced due to inadequate cooling rate after extrusion or loss of pressure during extrusion [6]. Additionally, these cavities also occur during equipment installation process or as cracks due to ageing related degradation.

Gas-filled cavities embedded in insulation medium are a significant source of partial discharge and concern both power utilities and high voltage equipment manufacturers. Under working conditions, cavities in an insulation medium are a source of partial discharge activity due to enhanced electric field within the cavity [7]. Electric field enhancement is due to the relative permittivity of atmospheric air being usually lower than that of the bulk insulation medium. The PD charge magnitude of a few coulombs is a precursor of insulation failure and can cause permanent damage to the insulation medium. For that reason, understanding the physical processes before, during and after a discharge phenomenon under operational conditions such as thermal stress is imperative in PD diagnosis.

1.2 Research Motivation

Under working conditions, the insulation material is subjected to variable thermal stress due to load current fluctuations. According to IEEE standard 400.3 of 2006 [8], Guidelines for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment, environmental conditions, including temperature or thermal stress, affect partial discharge activity. Studies by Illias *et al.* [9] on partial discharge within a spherical cavity in a dielectric material as a function of the cavity size and material temperature indicated that insulating material temperature affects partial discharge activity amongst other parameters such as the supply voltage magnitude, frequency. Despite significant research work on partial discharges as a function of temperature, researchers have mainly focused on limited conventional partial discharge parameters and temperatures above the material maximum operating temperature [10], [11].

Other PD parameters such as Partial Discharge Inception Voltage (PDIV), Partial Discharge Extinction Voltage (PDEV) and Partial Discharge-Phase-Resolved-Patterns (PDPRP) have received diminutive attention. These parameters are important to gain insights into the physical processes involved in the discharge activity. In particular, the physical processes before and after a discharge event. Although PD charge magnitude and repetition rate are well investigated, there are still contradictory opinions on these parameter trends with varying insulation material temperature. Furthermore, researchers have conducted their studies at temperatures lower than the insulation material prescribed limits to avoid entering into the regions where temperature alters the insulation material's electrical properties.

Notably, for solid dielectrics with an embedded cavity, PD behaviour under the influence of temperature is extensively researched using epoxy insulation material. As for the other widely used polymers, such as polyethylene in power cables, little consistent and credible information is available from the literature in this research area. The combined effect of thermal stress and partial discharge activity have relations with the physics and chemistry of the partial discharge phenomenon together with the properties of insulating material. In this context, the work of this dissertation is motivated to seek understanding of the effect of temperature on cavity partial discharge mechanisms in polyethylene insulation material.

1.3 Problem Statement

Despite precautionary measures made during manufacturing and installation processes, insulation medium is susceptible to defects such as conductive contaminants, gas cavities and water bubbles [4]. These contaminants are a significant source of partial discharge, leading to insulation degradation and complete equipment failure [7], [12]. Literature survey shows that insulation material temperature affects partial discharge activity, amongst other parameters [9] [13]. Under operating conditions, electrical apparatus are subjected to temperature stress owing to varying loads. Therefore, it is most likely that, in practice, PD measurements on an electrical apparatus such as power cables can be performed over a wide range of insulation temperatures.

The problem in this research area is inadequate knowledge of how temperature influences partial discharge activity, which has implications on the interpretation of PD diagnosis results. In addition, standards, such as the IEEE Standard *400.3 of 2006* [8], Guidelines for Partial Discharge Testing of Shielded Power Cable Systems in a Field Environment, do not explicitly prescribe temperature test conditions for PD measurements. Hence, this study aims to examine the influence of temperature on cavity partial discharge behaviour for Polyethylene (PE) insulation medium.

1.4 The Research Question

This study aims to answer the following critical question through a research enquiry methodology that comprises of laboratory based as well as simulation experiments.

How and why do cavity partial discharge characteristics respond to variations in the temperature of the polyethylene solid insulation?

1.5 Dissertation Structure

Chapter 2: This chapter deals with the work covered relating to partial discharge characteristics with varying dielectric material temperatures for solid dielectrics. A summary of relevant literature is presented and critically analyzed to identify research gaps.

Chapter 3: Details the tailored experimental method followed to realize cavity partial discharge activity as a function of temperature. In particular, the process followed to prepare the test

sample, experimental set-up and the procedure followed for partial discharge measurement at different test temperature points.

Chapter 4: This chapter outlines the theoretical model followed to realize cavity partial discharge activity as a function of temperature. In particular, the theoretical model for PDIV and the apparent PD charge magnitude. The chapter further provides details on how the theoretical models were implemented in MATLAB to obtain the PD characteristics of PD under varying dielectric temperatures.

Chapter 5: The experimental and theoretical modelling results are presented and discussed in detail. The response of conventional PD parameters, including PDIV, PDEV, PD charge magnitude and PDPRP, with varying temperatures, are reported, analysed and discussed. Furthermore, the experimental results are compared with those obtained from the theoretical model.

Chapter 6: This chapter summarizes and concludes the dissertation. In addition, future work relating to cavity PD as a function of temperature is proposed.

Appendix A: This appendix details the heat transfer model developed in COMSOLTM Multiphysics software to estimate the time taken for the cavity to reach the desired steady-state temperature before PD measurements were taken. The model parameters and the simulation results are presented and analysed.

Appendix B: The methodology for estimating the breakdown voltage in order to determine the appropriate test voltage is outlined.

Appendix C: The electric field simulation model is described in this appendix.

Appendix D: This appendix presents the MATLABTM code used to implement the theoretical PD inception voltage and PD charge magnitude models

Appendix E: This appendix comprises a conference paper presented at the International Symposium on High Voltage Engineering (ISH2023), Glasgow, UK, 27 August to 01 September 2023

2 Literature Review

Chapter Abstract: *In this chapter, the literature review on the effect of temperature on PD characteristics is presented in detail. Despite significant work in this research area, researchers are not in agreement on how PD responds to varying temperatures. For example, researchers reported four diverse PD charge magnitude trends as a function of temperature: increasing, decreasing, slightly increasing and slightly decreasing. Some researchers have closely correlated the simulation models with the experimental measurements. Notably, many free parameters, such as the material work function, surface conductivity, cavity gas pressure, relative permittivity, and the rate of de-trapping charges, are often used concurrently. Therefore, it can be deduced that the response of PD parameters, identifying critical parameters and physical processes that influence PD activity under varying temperatures, is still an area of research interest and is the basis of the present work.*

2.1 Introduction

Investigations into the effect of temperature on cavity partial discharge behaviour in solid insulation have been an ongoing area of research interest in the field of partial discharge (PD) diagnosis. Studies such as Illias *et al.* [9] on partial discharge within a spherical cavity in a dielectric material as a function of the cavity size and material temperature confirmed that temperature affects partial discharge activity amongst other parameters. Most studies have focused on modelling and physical experimental work with a particular interest in studying partial discharge parameters such as the inception and extension voltage, PD repetition rate, maximum PD charge (q_{max}), minimum PD charge (q_{min}). This chapter provides an insight into the research work conducted thus far on partial discharge as a function of temperature and highlighting important knowledge gaps especially with regards to temperature effects on PD. In the next sections the literature is reviewed on the effect of PD on each of the important parameters of PD.

2.2 Effect of Temperature on PD Magnitude

Illias *et al.* [9] studied PD activity as a function of the material temperature for epoxy insulation material with a cavity size of 1.7 mm in diameter subjected to a uniform electric field for the

following temperatures: 20 °C, 35 °C, 50 °C and 65 °C. Also, simulation studies were conducted using the finite element analysis (FEA) model to reproduce experimental results. The experimental studies reported an increase in the minimum PD magnitude (q_{min}) with the rise in temperature. Additionally, the maximum PD magnitude (q_{max}) decreased with an increase in temperature. It is worth noting that the studies never quantified the variations of PD parameters with temperature. However, simulations and measured results showed that at 65°C, minimum PD charge magnitude (q_{min}) increased by approximately 10% compared to ambient temperature results. Additionally, at 65°C, the maximum PD magnitude (q_{max}) reduced by 55%. Florkowska [11] studied the influence of temperature on partial discharges in epoxy/mica insulation with micro-sized gas cavities. In particular, PD magnitude and repetition rate were observed at ambient temperature and at 135°C, respectively. In agreement with Illias *et al.* [9], Florkowska reported an increase in PD magnitude at 135 °C and attributed this to the modification of electrical characteristics at a higher temperature. Although the studies in no instance quantified an increase in PD magnitude rate as a function of temperature, a closer analysis of the results show an increment of approximately 11% at 135 °C than the ambient temperature measurements.

Despite conducting experimental work at a temperature range of 20 °C to 80 °C different than that by Florkowska [11], other studies reported similar results on PD magnitude as a function of temperature [14]–[21]. In [20], the studies indicated that at a temperature of 60 °C, partial PD apparent charge is approximately 40 times higher than that at ambient temperature. Vibhakar and Kanitkar [21] postulated that the correlation between PD magnitude and the material temperature is attributed to rapid structural changes of the insulation medium at higher temperatures. In particular, the studies reported an increase in the void dimensions as the temperature is increased. Thus, in the present study, it is important to perform PD measurements at a temperature lower than the temperature at which the material starts to deform, that is, loses the mechanical properties.

Khouildi *et al.* [10] investigated the thermal effect on an XLPE power cable at a temperature of 120 °C for a micro-cavity using a needle plane electrode configuration. Similar to results obtained by other reserachers [9], [11], [14]–[19], [21], [22] , for epoxy insulation material, the studies show that at 120 °C, PD magnitude is approximately 12.5 times higher than at ambient temperature. The studies further reported that the PD activity significantly changes over time,

such that at some instances, PD magnitude was approximately 35 times higher than at ambient temperature. Moreover, Khouildi *et al.* [10] observed a diminishing PD activity with ageing. In contrast, Henningsen *et al.* [13] research work on the experience with an on-line monitoring system for 400 kV XLPE cables reported a decrease in PD magnitude with an increase in temperature. In agreement with [10], Henningsen *et al.* [13] also noted that the time evolution of on-line PD measurements exhibits a diminished PD magnitude at some stage. Nevertheless, Haghjoo *et al.* [23] reviews for a temperature range of ambient up to 90 °C reported similar results. Although the studies in no way revealed the cavity diameter measurements as a function of temperature, Haghjoo *et al.* [23] attributed this behaviour to the shrinkage of XLPE insulation medium at a temperature of 90 °C due to reduced cavity diameter.

Despite the consensus that temperature affects PD activity, other researchers reported that PD charge dependency on temperature is insignificant. Di Lorenzo *et al.* [24] studied a life model for epoxy resins subjected to PD activity for a 0.250 mm air gap using the test assembly described in Cigre Method 2. The cavity was subjected to a non-uniform electric field for a temperature range of 30 °C, 55 °C and 80 °C. The studies reported a slight growth of PD charge magnitude with increased insulation material temperature. Similar results were reported by Jineeth *et al.* [12] on numerical modelling, simulation and experimental validation of partial discharge in cross-linked polyethylene cables. The simulation studies considered an XLPE electric power cable with a cylindrical void of 0.75 mm radius using the Finite Element Method (FEM) at 35 °C, 50 °C and 65 °C.

Although the studies did not quantify the change in PD charge magnitude, results indicated an increment of approximately 4% from 35 °C to 50 °C. Additionally, the results show that the PD charge magnitude at 65 °C is 10% higher than that at 35 °C. Florkowska [11] reported the same increment at 135 °C and inferred that PD charge magnitude increases with temperature. Recent publications by Sakoda *et al.* [25] are in disagreement with the findings in [24] and [12]. Sakoda *et al.* [25] investigated PD activity as a function of temperature for an epoxy resin with a void diameter of 1.5mm under a uniform electric field at a temperature range of 30 °C to 50 °C. The studies reported a slight decrease in PD charge magnitude with increased temperature. Sakoda *et al.* [25] attributed the findings to an increase in relative permittivity of epoxy resin at 50 °C. Furthermore, the studies postulated that although partial discharge behaviour is related to thermal

stress, electric field stress dominates all other factors. In general, researchers have reported four different trends in PD charge magnitude as a function of temperature. The studies reported an increasing, decreasing, slight increase and slight decrease trend of PD charge magnitude as a function of temperature.

Thus, it can be deduced that researchers are not in agreement on the influence of temperature on PD charge magnitude. Additionally, other researchers studied PD charge magnitude as a function of temperature for only two test points and generalized PD behaviour as a function of temperature, which is misleading. It is important to consider a wide range of operational temperatures to gain more insight into PD charge magnitude as a function of temperature and this is the approach adopted in this research work.

2.3 Effect of Temperature on PD Repetition Rate

With regard to PD pulse repetition rate, most researchers are in consensus on the reduction of PD pulse repetition rate at higher temperatures. Studies by Schifani *et al.* [18] on PD mechanisms at high temperature in voids for an epoxy resin show that the PD repetition rate at 20 °C is ten times higher than the pulse repetition rate at 80 °C. Schifani *et al.* [18] deduced that this behaviour makes one postulate that the electron generation rate is lower at a higher temperature, i.e. 80 °C. Di Lorenzo *et al.* [14], [24] reported similar results to [18] for a 0.250 mm air gap using Cigre Method 2. Di Lorenzo *et al.* [16] also reported a reduction in PD pulse repetition rate by approximately 30% at 80 °C compared to pulse repetition rate at 30 °C. The studies deduced that this correlation is ascribed to the rapid increase of surface conductivity on the cavity walls.

Despite conducting studies using different insulation material than that in [4][6][8][14], recent publications by Haghjoo *et al.* [23] also reported a decrease of PD repetition rate with temperature attributed to a reduction in cavity size. Simulation studies by Haghjoo *et al.* [19] using a comprehensive three-capacitor model produced similar results. Although the studies considered XLPE insulation medium for their simulations, results showed a similar trend to the experimental studies for an epoxy resin with a 2 mm cavity at a temperature range of 20 °C and 80 °C [17]. Notably, Haghjoo *et al.* [23] reproduced the experimental results in [17] by varying the void's dimension, relative permittivity, gas pressure, surface conductivity, rate of charge de-

trapping and residual voltage in their model. Although most researchers have recorded a reduction in pulse repetition rate of PD at higher temperatures, other researchers [9]–[11], [26] reported the opposite trends. The studies observed an intensified PD repetition rate at higher temperatures. Illias *et al.* [9] attributed this behaviour to an enhanced electron generation rate with an increase in insulation material temperature. However, it is notable that from the literature, it is well documented that a higher electron generation rate reduces the statistical time lag. The research work further indicated that a higher electron generation rate is due to enhanced surface emission at high temperatures. Florkowska [11] deduced that an increase in temperature influences insulating material's electrical properties by polarization mechanisms, which increases the dielectric constant. In general, studies reported the reduction and intensified PD activity as a function of temperature, showing disagreements amongst researchers. However, it is important to note that researchers are in agreement that the observed behaviour is attributed to the variation of electron generation rate. Although elevated temperatures are assumed to influence electron generation rate, there are still disagreements on how temperature affects Electron Generation Rate (EGR) during PD activity. Next in the review is the effect of temperature on PDIV.

2.4 Effect of Temperature on PD Inception Voltage

Illias *et al.* [9], experimental results exhibit an increase in partial discharge inception (PDIV) voltage at higher temperatures. From the experimental data, a growth of approximately 13% was observed at 65 °C compared to the one at 20 °C. Although the studies did not explicitly show the results of cavity pressure as a function of temperature, Illias *et al.* [9] postulated that the inception electric field increases with temperature due to an increase in cavity pressure. Important to note that the studies made an assumption that the insulation erosion due to PD is insignificant. Similarly, Haghjoo *et al.* [23] and Mariut [27] observed the same trends despite conducting studies on XLPE insulation material different from that by Illias *et al.* [9]. Simulation studies conducted by Illias *et al.* [22] using Finite Element Analysis also produced similar results, although the studies considered cavity temperature changes due to PD activity and not due to load variations. It is notable that the studies assumed that the cavity volume is constant and used the ideal gas law equation in their model to compute pressure changes within the cavity for every temperature change. In contrast, studies by Saadati *et al.* [26] on the temperature dependence of

PD under AC and combined AC/DC field stress observed a decrease in PDIV with an increase in temperature. The authors postulated that at elevated temperatures, the probability of having a seed electron to start the avalanche process is high such that PDIV is reduced. Thus, the statistical time is reduced. Zerui *et al.* [28] reported similar trends. Although some researchers reported a decrease in PDIV with temperature, there is a general agreement on PDIV increasing with temperature.

2.5 Critical Analysis and Discussions

Remarkably, despite significant work in the research area of temperature on PD, the literature review reveals that there are still inconsistencies in the findings and conclusions thereof. Table 1 presents the summary of the research work on PD as a function of temperature. As an example, with a particular reference to the influence of temperature on PD charge magnitude, researchers reported four distinct trends, namely: increasing, decreasing, a slight increase and a slight decrease of PD magnitude as a function of temperature. Although some studies indicated that the variation of PD charge magnitude with temperature is attributed to modifications of cavity size (volume) at higher temperatures, it is essential to note that these studies investigated PD phenomena considering the combined effect of temperature and PD-induced aging, degradation and breakdown. PD-induced effect changes in the physical and chemical characteristics of the discharge site, which makes PD phenomena inherently nonstationary.

The nonstationary and stochastic behaviour complicates the interpretation of partial discharge signals. Moreover, literature has shown that PD-induced aging erodes insulation material due to ion bombardment such that the discharge area is modified. Khouildi *et al.* [10] only observed the effect of temperature on PD behaviour for XLPE insulation material at 120°C above the material maximum operating temperature of 90°C. Also, Florkowska [11] focused on ambient temperature and a temperature of 135°C, which is higher than the material glass transition temperature. Therefore, generalizing PD characteristics as a function of temperature considering only two test points can be misleading. Under working conditions, the insulation medium is susceptible to varying temperatures due to load changes. For that reason, it is imperative to consider the full range of the insulation medium operational temperature to gain valuable insight into PD characteristics under varying temperatures.

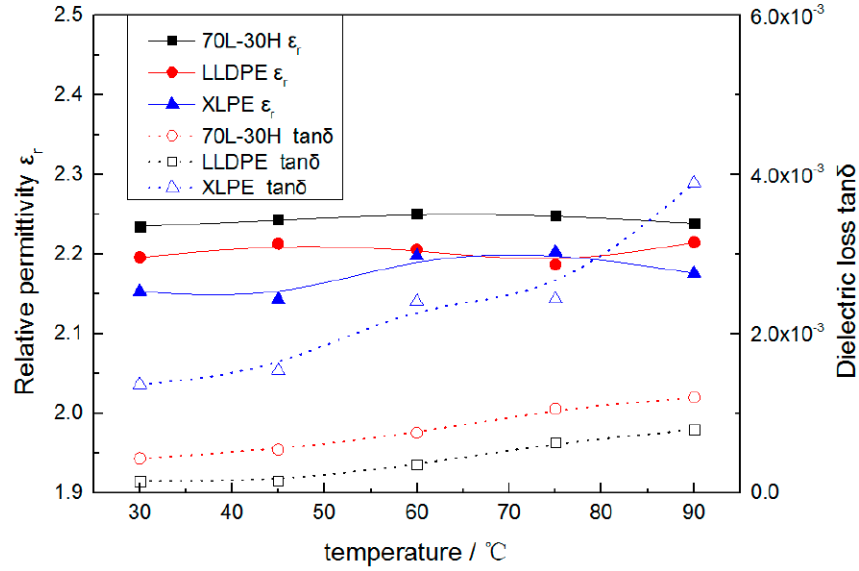


Figure 2.1: Relative Permittivity as a Function of Temperature [2]

Most researchers cited enhanced Electron Generation Rate and electrical properties, particularly the dielectric constant, as the main factors responsible for partial discharge behaviour under varying temperatures. Schifani *et al.* [18] investigated the latter from 400 Hz up to 1 MHz frequency range for epoxy insulation material. The studies inferred that the correlation of the dielectric constant with temperature is insignificant. Di Lorenzo and Schifani [16] studied the relative permittivity as a function of temperature from 25°C to 150°C and reported similar results with Schifani *et al.* [18] for temperatures below 120°C. However, from 120°C to 150°C, the studies reported an increasing trend with temperature.

Based on these discoveries, Di Lorenzo and Schifani observed partial discharge phenomena for temperatures up to 80°C to fix the dielectric constant. However, other studies reported insignificant variation of relative permittivity with the change in temperature in the polyethylene insulation medium, as depicted in Figure 2.1 [2]. The results show an increase of approximately 2% at 90°C. Although Illias *et al.* [9] indicated that the relative permittivity of epoxy increases with an increase in temperature, compared to the experimental results, the simulation results exhibit an overestimated total charge per cycle at 20°C and underestimate the same parameter at 65°C. One other factor attributed to PD changes with temperature is the Electron Generation Rate.

Table 2.1: Summary of Key Findings in the literature on cavity PD as a function of temperature

Researchers	Type of Defects	Temperature and Test Voltage	PD Characteristics Studied	Key Findings
Haghjoo <i>et al.</i> [19]; Candela <i>et al.</i> [17]	Void of 2mm diameter in XLPE insulation medium.	Temperature: 20°C and 80°C	PD Magnitude PD Repetition Rate	- PD apparent charge increased upon temperature rise. - The repetition rate of PD pulses decreases as the insulation temperature is raised.
Mariut [27]	0.4mm diameter cavity in XLPE insulation medium.		PD Inception Voltage	- The study found that PD inception voltage appears at higher temperatures.
Haghjoo <i>et al.</i> [23]	Sample 1: Number of small cavities in XLPE insulation medium. Sample 2: 5mm diameter cavity on the semiconductor layer (XLPE cable).	Temperature: 25°C, 45°C, 68°C and 90°C	PD Inception Voltage PD Magnitude PD Repetition Rate	- PD inception voltage is increased as the temperature increases. - High temperatures reduce PD magnitude attributed to the XLPE insulation medium's shrinkage at 90°C, which minimizes the cavity size. - As the temperature increases, the occurrence of PD pulses (repetition rate) decreases
Khouildi <i>et al.</i> [10]	A sharp needle was inserted into the XLPE insulation.	Temperature: 100°C and 120°C	PD Magnitude PD Repetition Rate	- PD magnitude is increased at high temperatures. - PD activity is intensified at a higher temperature (PD repetition rate increased with the temperature rise).
Illias <i>et al.</i> [9], [22]	Epoxy resin (2.5 mm in thickness) with a cavity of 1.7mm in diameter	Voltage: 20 kV AC at 50 Hz Temperature: 20°C, 35°C, 50°C and 65°C	PD Magnitude PD Repetition Rate	- PD magnitude increases at high temperatures. - The repetition rate of PD pulses increases as the insulation temperature is raised, attributed to enhanced electron generation rate, which reduces statistical time lag. The higher electron generation rate is due to enhanced surface emission at high temperatures.
Vibhakar& Kanitkar [21]	Test Cell: Epoxy resin (Sphere plane electrode) immersed in oil enclosed in a thermal chamber.	AC Voltage of 15 kV and 30 kV Temperature range From -20°C to 120°C	PD Magnitude	- PD magnitude increases with temperature due to modification in void geometry (void size is increased in diameter) attributed to a change in epoxy resin's internal structure. In addition, at temperatures higher than 60°C, the study found no significant PD change in magnitude.

Researchers	Type of Defects	Temperature Range and Test Voltage	PD Characteristics Studied	Key Findings
Di Lorenzo <i>et al.</i> [24]	Epoxy resin with a cavity of 0.25mm in diameter	Voltage: 20 kV, 24 kV & 30 kV AC at 50 Hz. Temperature: 20°C, 55°C and 80°C	PD Magnitude PD Repetition Rate	- PD magnitude slightly increases at high temperatures. - PD repetition rate is lower at high temperature such that higher times to breakdown were recorded.
Schifani <i>et al.</i> [18]	Epoxy resin: Diameters ranging from 1.3 to 2 mm and a thickness of 3.5mm.	Voltage: 10 kV & 32 kV AC at 50 Hz. Temperature: 20°C and 80°C	PD Magnitude PD Repetition Rate	- PD magnitude increases at high temperatures. - A lower repetition rate was observed at higher temperatures. In fact, the repetition rate at 20°C was ten times higher than at 80°C and the author argued that this makes one believe that the electron generation rate at 80°C is significantly low.
Florkowska [11]		Voltage: 10 kV & 32 kV AC at 50 Hz frequency. Temperature: up to 135°C	PD Magnitude PD Repetition Rate	- PD magnitude increases at high temperatures. - PD repetition rate increases at high temperatures
Di Lorenzo <i>et al.</i> [16]	Epoxy resin with cavity	Voltage: 30 kV AC at 50 Hz. Temperature: 30°C, 55°C and 80°C	PD Magnitude PD Repetition Rate	- PD pulse amplitude is higher at 80°C (high temperature) - PD repetition rate is reduced at higher temperatures (55°C and 80°C), approximately 30% lower than the one at 30°C, attributed to a rapid increase in polymer surface conductivity.
Di Lorenzo <i>et al.</i> [14]	Epoxy resin with a cavity of 0.25mm in diameter	Voltage: 20 kV, 24 kV & 30 kV AC at 50 Hz. Temperature: 30°C, 55°C and 80°C	PD Magnitude PD Repetition Rate	- PD magnitude increases at high temperatures. - PD repetition rate is lower at high temperature ascribed to an increase in material work function with temperature.
Joseph <i>et al.</i> [12]	11 kV XLPE Cable with cavity radius of 0.75 mm	Voltage: 6.35 kV AC at 50 Hz. Temperature: 35°C, 50°C and 65°C	PD Magnitude	- PD magnitude slightly increases with temperature.
Henningesen <i>et al.</i> [29]	400 kV XLPE Cable	On line measurements	PD Magnitude PD Repetition Rate	- PD magnitude decreases at high temperatures - PD repetition rate significantly decreases at high temperatures.

Researchers	Type of Defects	Temperature Range and Test Voltage	PD Characteristics Studied	Key Findings
Di Lorenzo [15]	Epoxy resin with a cavity of 0.25mm in diameter	Voltage: 30 kV AC at 50 Hz Temperature: 30°C and 80°C	PD Magnitude PD Repetition Rate	- PD magnitude increases at high temperatures. - PD repetition rate is lower at high temperatures.
Illias <i>et al.</i> [30]	1.4mm diameter cavity in Epoxy insulation medium.	Voltage: 18 kV AC at 50 Hz	PD Inception Voltage	- The study found that PD inception voltage appears at higher temperatures.
Sakoda <i>et al.</i> [25]	Epoxy resin with a cavity of 1.5mm in diameter	Voltage: 6.9 kV AC and 12 kV AC at 50 Hz Temperature: 30°C to 50°C	PD Magnitude PD Repetition Rate	- PD charge magnitude slightly increases with an increase in temperature owing to an increase in epoxy dielectric constant at higher temperatures. - As the temperature increases, the occurrence of PD pulses (repetition rate) is increased.
Saadati <i>et al.</i> [26]	GFRP embedded in epoxy with a cavity of 1.5mm in diameter	Temperature: 20°C, 40°C, 60°C and 80°C	PDIV PD Repetition Rate	- PDIV is reduced owing to the high electron generation rate at higher temperatures. - A higher repetition rate was observed at higher temperatures. In fact, the repetition rate at 80°C was 100 times higher than at 20°C.
Saadati <i>et al.</i> [20]	Cavity embedded in epoxy resin	Temperature: 18°C and 60°C	PDIV PD Magnitude	- PDIV decreases with temperature. - Higher PD charge magnitude is observed at 60°C. At 60°C, the measured charge magnitude is 40 times higher than that at ambient temperature.
Illias <i>et al.</i> [31]	Epoxy resin with a cavity of 2.5mm in diameter	AC Voltage: 20 kV at 50 Hz Temperature: 20°C, 35°C, 50°C and 65°C	Statistical time lag	- The studies found that when the material temperature is increased, the statistical time lag reduces.

Notably, researchers who observed an enhanced PD repetition rate at higher temperatures postulated this trend to an enhanced EGR. Thus, reducing the time taken from the instant the electric field is higher than the critical value until a discharge appears. This duration is usually known as the statistical time lag. Temperature is assumed to reduce the statistical time lag by reducing the material work function. The material work function is a property defined as the minimum energy necessary to extract an electron from a solid material surface. However, these are tentative explanations without experimental proof or simulation studies. From the literature review, the following key points are deduced:

PD Physical Mechanisms:

The influence of temperature on the physical processes before, during and after a discharge activity is still not fully understood. Although other researchers managed to fit the simulation models with the experimental data, they considered many free parameters (material work function, surface conductivity, gas pressure, relative permittivity, rate of de-trapping charges, charge time decay constant) to reproduce the experimental results. The drawback is that the critical parameters influencing PD activity as a function of temperature may not be revealed. Researchers mainly considered material work function, dielectric constant, and cavity volume variations to identify properties responsible for PD trends under varying temperatures. Other significant elements such as the residual charge decay concept and surface conductivity have received minimum attention.

Insulation Material Electrical Properties:

Researchers mainly focused on the material dielectric constant as a function of temperature. For an insulation medium with an embedded cavity, the dielectric constant of the bulk insulation medium affects the electric field profile inside the cavity. It is important to note that researchers conducted their studies at temperatures lower than the insulation material prescribed operational limits to avoid entering into the regions where temperature alters the insulation material's dielectric constant. Although the dielectric constant is an important property, it is important to consider other material properties such as conductivity.

Type of Insulation Material:

Notably, for solid insulation dielectrics, the PD behaviour under the influence of temperature is widely researched using epoxy insulation material. As for the other widely used polymer, such as polyethylene used in power cables, little consistent and credible information is available from the literature on this research area.

2.6 Conclusions on the Literature Review

Despite significant work in this research area, results from different researchers are contradictory. As an example, researchers reported four different results for PD charge magnitude as a function of temperature, namely: increasing, decreasing, a slight increase and a slight decrease with varying temperatures. Additionally, some research work reported an aggressive PD repetition rate, while other researchers reported a diminutive repetition rate with changing temperatures. Using experimental techniques that allow the mechanism of the discharge itself to be investigated could offer valuable insight into PD activity under working conditions. In conclusion, there is still significant scope for research work where the ultimate purpose is to provide an additional physical interpretation of PD activity under varying temperatures and this is the intension of the present work.

3 Experimental Procedure

Chapter Abstract: This chapter presents the detailed experimental design to study cavity partial discharge characteristics as a function of temperature in a polyethylene insulation medium. PD measurements were carried out using the conventional PD detection circuit in accordance with the IEC 60270 standard. A test voltage of 11 kV ac at 50 Hz was used. The test temperatures considered were 15 °C, 40 °C, 50 °C, 60 °C, 70 °C, 80 °C and 90 °C. Three test specimens with identical cavity of diameter 2.5 mm were assembled using three 1.5 mm thick polyethylene sheets sandwiched between two flat brass electrodes. The cavity temperature was raised using a thermostatically controlled heat source. Before carrying out PD measurements, the test specimen was heated for 30 minutes in an oil bath for each test temperature point to enable the cavity to reach the desired steady-state temperature. The charge magnitude, inception voltage, and partial discharge phase resolved pattern (PDPRP) were then measured at various temperatures and measurement data recorded for further analysis.

3.1 Experimental Overview

The experimental design entailed three processes: the test specimen design, the heating cycle experiment and partial discharge measurement arrangement. Figure 3.1 illustrates the detailed experimental design process. The first part of the experimental design details the processes involved in the preparation and construction of the test specimen. In particular, the void diameter, test object geometry and the test cell arrangement. The second part of the design describes the heating cycle's experimental setup and the testing procedure. The last section covers the PD measurement circuit, testing methodology and data acquisition.

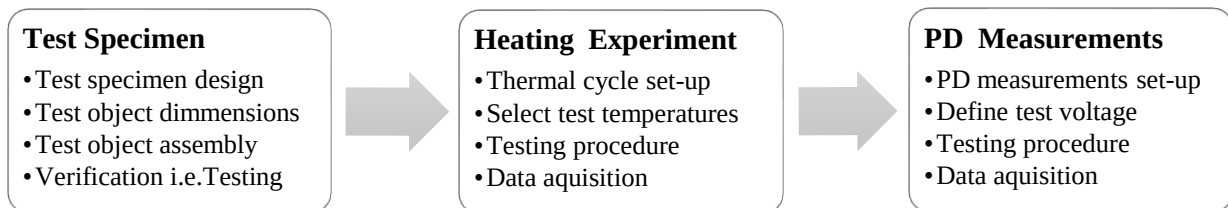


Figure 3.1: The Experimental Design Process Flow

3.2 Test Specimen

3.2.1 Test Sample Preparation

The insulation material considered in this research work is a synthetic polyethylene polymer. Polyethylene is a thermoplastic polymer and is usually used in the engineering industry for various applications. In high-voltage engineering, these polymers are used as insulation medium for high-voltage equipment due to their unique electrical, mechanical, chemical, thermal properties and low production cost [32], [33]. High-Density Polyethylene (HDPE) sheets with a thickness of 1.5 mm and a diameter similar to the electrodes were prepared. Figure 3.2 (b) shows the polyethylene sheets prepared for this research work. The electrodes considered are made of brass and are cylindrical, as presented in Figure 3.2 (a).

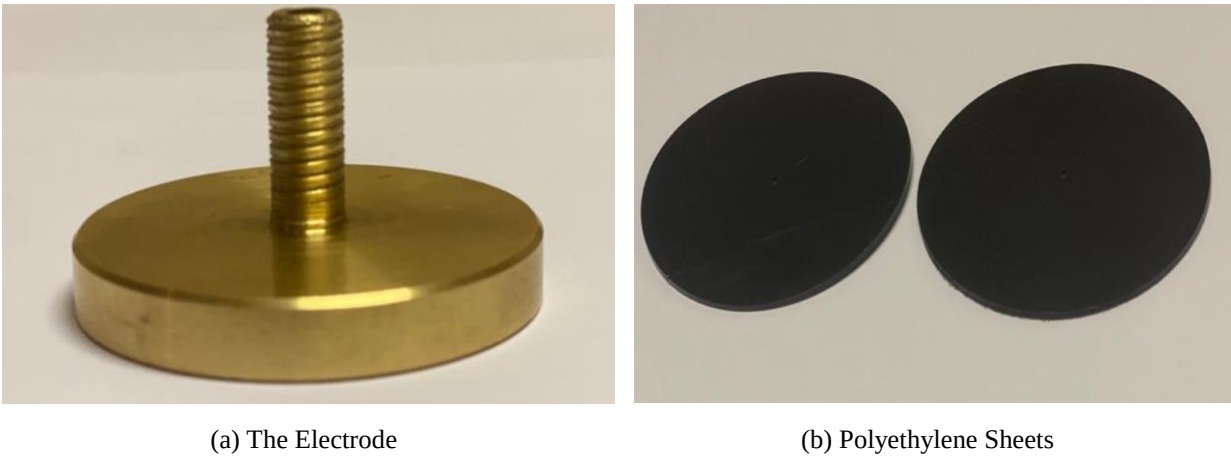


Figure 3.2: Brass Electrode and Polyethylene Sheet components of the test cell

The electrode is connected to either the high voltage or ground conductor in the PD measuring circuit. The defect or PD source is created by producing an artificial void in the middle of the polyethylene sheet using a drilling bit of the size equivalent to the required void diameter. It is important to ensure that the electrodes are sufficiently smooth to limit the likelihood of generating other PD sources during the test sample's assembling phase. Further details of test cell construction are in the next section.

3.2.2 Test Sample Arrangement

Among other parameters, the void geometry influences partial discharge characteristics; thus, it is important that the test objects considered in this research work have the exact dimensions. The test sample consists of a parallel cylindrical electrode configuration with polyethylene (PE) insulation sheets in between. Polyethylene sheets are sandwiched between brass electrodes and comprise three layers. The middle layer is sandwiched between the layers adjacent the electrodes and it consists of a cylindrical artificial air cavity with a diameter of 2.5 mm. The test object's arrangement is such that the PD is only initiated in the artificial cavity.

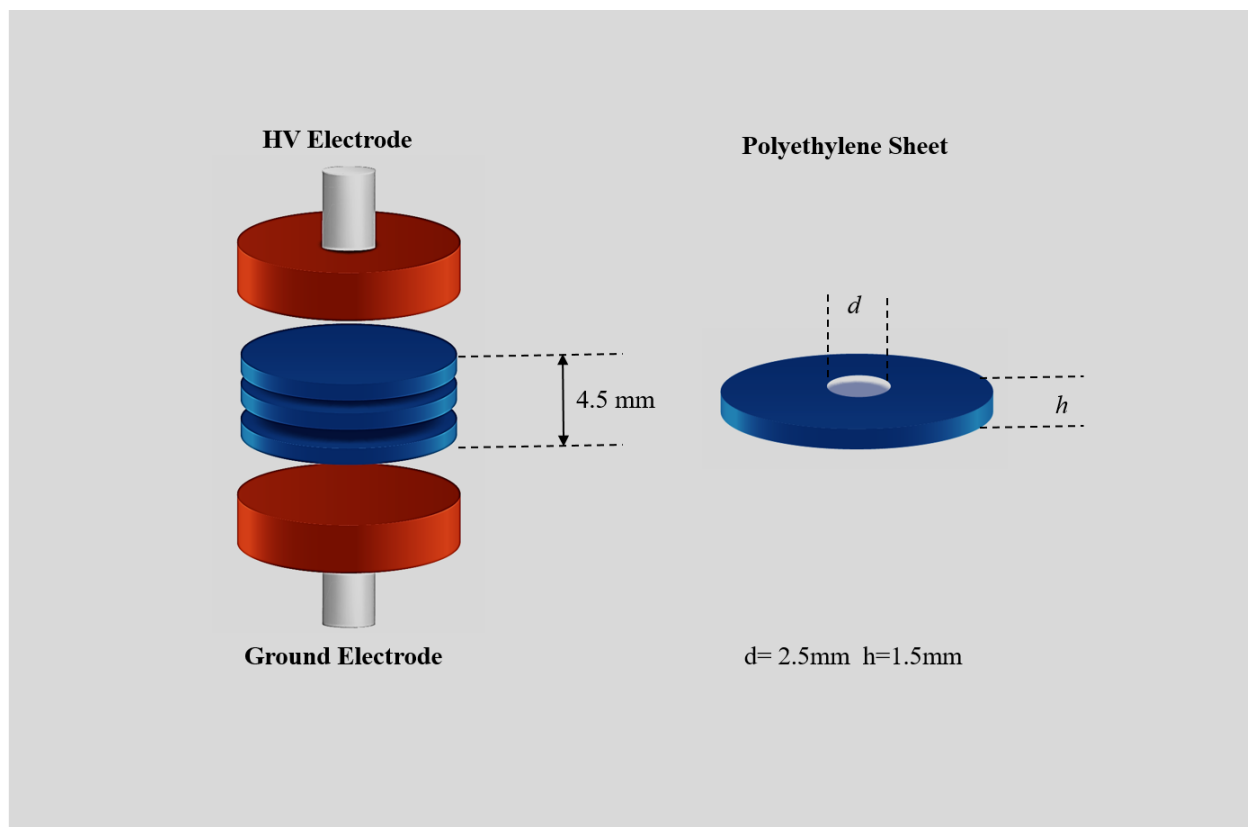


Figure 3.3: Test Specimen Construction Arrangements

The entire test cell is immersed in an insulating oil to avoid surface discharges during voltage application [21], [27]. The test specimen is tightly clamped using clamps made from Perspex material, nylon rods and bolts to prevent the oil from penetrating the air cavity and therefore ensure unvented cavities. Additionally, the clamps are used to ensure that the test sample is mechanically robust and the air cavity is unvented. The high voltage and ground electrodes are bare brass plate

conductors with a thickness and diameter of 10 mm and 65 mm, respectively. The dimensions and arrangements of the test specimen are shown in Figure 3.3. The cavity diameter is chosen such that the measured PD parameters in this study can be compared with findings from previous research work. For example, in [25], a similar cavity diameter is used. Other researchers conducted their studies with a cavity diameter range of 0.25 mm to 5 mm [9], [11], [14], [17], [21], [23], [34]. Even though the diameters are different, which would affect partial discharge characteristics such as repetition rate, the cavity location is similar. Thus, the trend of PD as a function of temperature can be compared with the results obtained from the previous studies.

3.3 Experimental Methodology

Two integrated experiments were employed to study the characteristics of cavity partial discharge in response to temperature. The experimental design included the heating cycle and the partial discharge measuring arrangement for detecting partial discharge signals. The initial stage of the experiment involved carefully applying a heat source to the heating chamber to vary the temperature of the insulation material to the desired value. The second part of the experimental design entailed the measurements and acquisition of partial discharge signals at different temperatures. The sections that follow describe how these experiments were conducted.

3.3.1 Heating Cycle Experimental Method

The heating experimental setup was necessary to vary the cavity temperature to a desired test temperature. Figure 3.4 illustrates the details of the heating cycle experimental setup arrangements. The temperature was increased using a thermostatically controlled heat source. The test temperatures were chosen as : 15°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C. The setup consisted of a metallic oil bath chamber, heat source, temperature control device and a temperature-measuring sensor. The temperature-measuring sensor was placed in close proximity to the bulk insulation medium. The cavity temperature was raised by heating the oil bath to the desired value and through heat convection, the oil was forced to circulate, transferring heat to the test specimen.

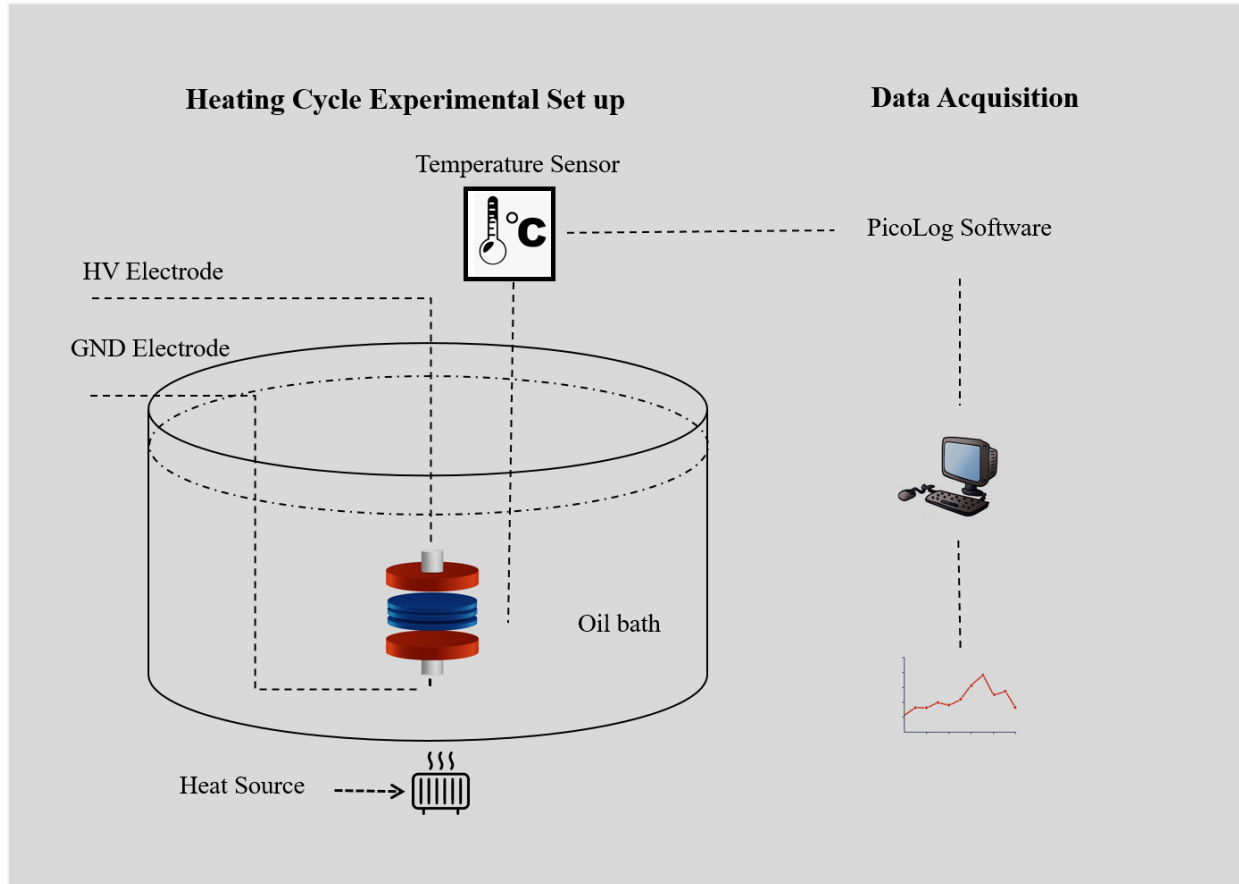


Figure 3.4: The Heating Cycle Experimental Set-up

The test specimen was heated for 30 minutes in the oil bath for each test temperature point to allow the cavity to reach the desired steady-state temperature before PD measurements were taken. The 30 minutes settling time was determined using heat transfer model simulated in COMSOLTM Multiphysics Software. The details of the heat transfer model implemented in COMSOLTM Software are illustrated in Appendix A. The simulation results of the temperature distribution profile on the specimen during two heating scenarios are presented in Figures 3.5 and 3.6. The first scenario involved heating the test specimen from 15°C to 40°C, while the second scenario involved heating it from 80°C to 90°C. The results show that the cavity took approximately 30 minutes to reach the desired steady state test temperature. The temperature was constantly monitored using a sensor immersed in the oil bath and positioned close to the polyethylene insulation. A computer-controlled software, PicoLogTM, was used to measure and monitor the oil bath temperature. At the desired steady state test temperature voltage was applied and PD measurements conducted as explained in the next section.

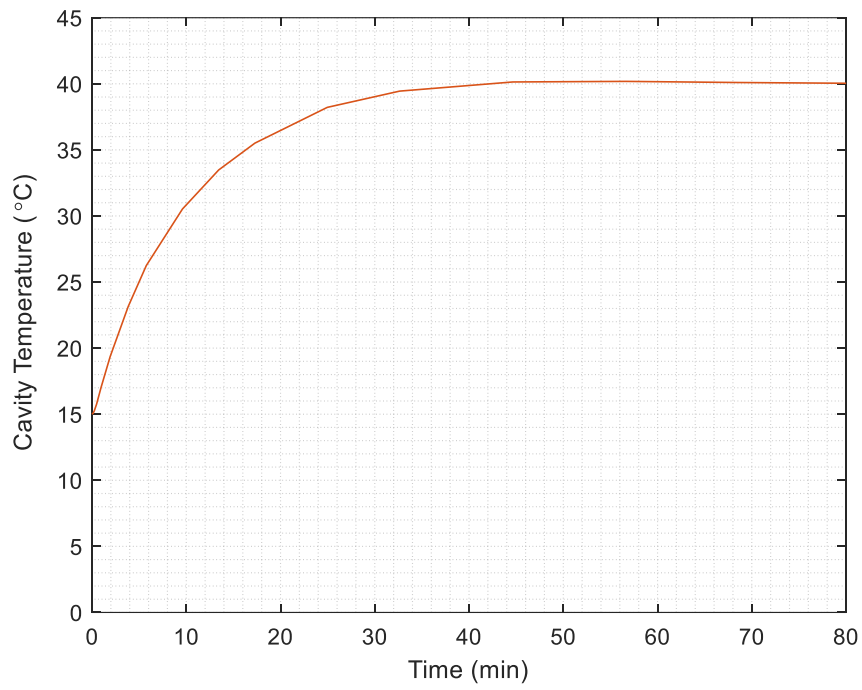


Figure 3.5: Cavity temperature settling time (15°C to 40°C)

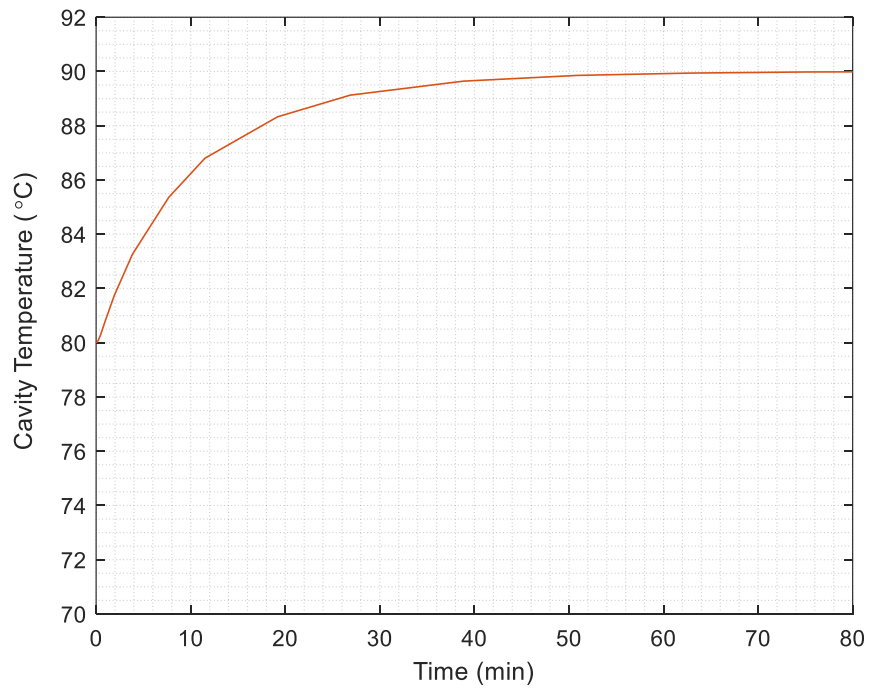


Figure 3.6: Cavity temperature settling time (80°C to 90°C)

Remarks on Measured Temperature Profile

Figure 3.7 illustrates the measured temperature data on one of the samples. Due to difficulties in controlling the temperature, an error of $\pm 3^{\circ}\text{C}$ on the test temperature point is observed. It is notable that there is a 2% increase in temperature between successive PD activities. Although the observed temperature increment seems insignificant, it is worth noting that the temperature sensor was positioned adjacent to the bulk insulation material. Thus, it can be postulated that the cavity temperature might have been higher than the observed increment of 1°C between the subsequent PD activities. The simulation studies in [35] also reported an increase in cavity temperature after a PD activity. Moreover, the research work reported a 15% increase in cavity temperature.

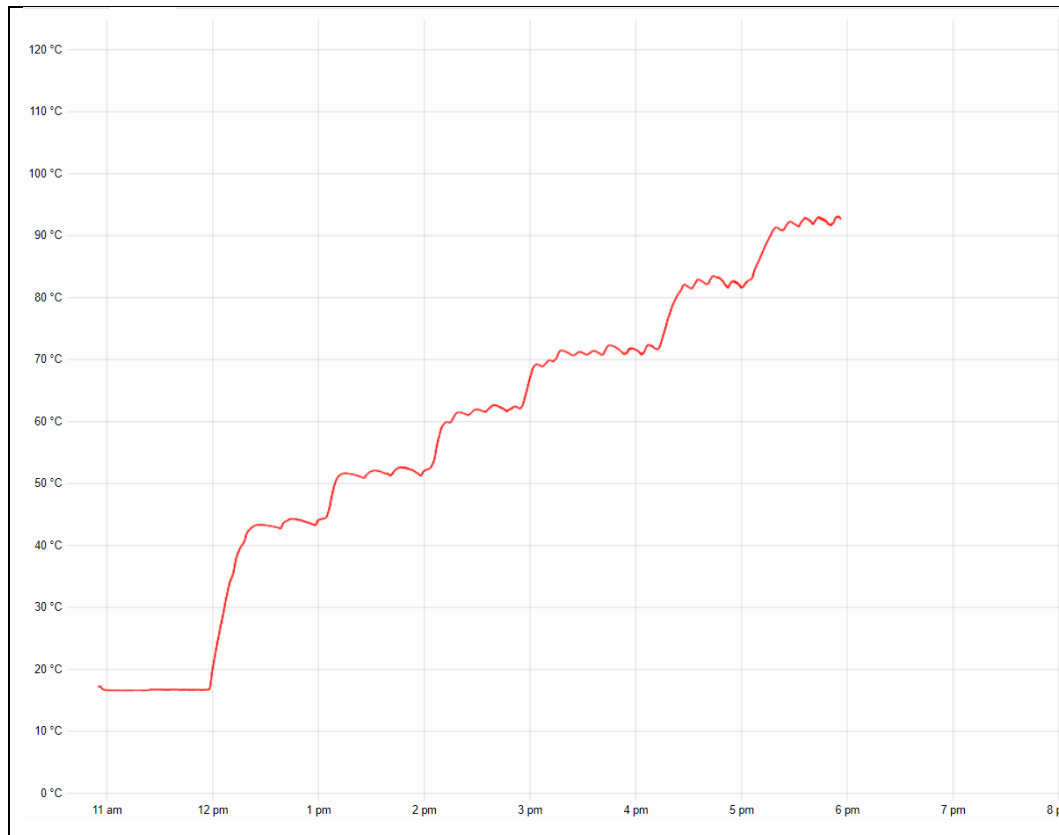


Figure 3.7: Measured temperature profile

3.3.2 Partial Discharge Measurement Circuit

Figure 3.7 shows the circuit arrangement used to measure the partial discharges and the picture of the set-up is shown in figure 3.8. The measuring circuit is in accordance with the IEC60270 standard. It comprises a 50 kV, 50 Hz ac PD free transformer, current limiting resistor, coupling capacitor, detection impedance, PD measurement device and the test specimen. The PD detector device and the coupling impedance detect partial discharge signals from the test specimen and log the PD signals on a personal computer using the Power Diagnostix ICM Compact™ software tool. As part of pre-measurements, a defect-free sample was tested to identify the voltage at which it starts to generate PD-like noise. It was found that the defect-free sample exhibited partial discharge noise at 18 kV ac and the extinction voltage of the noise was found to be 14 kV ac. Thus, the test specimens were stressed at 11 kV, 50 Hz ac voltage throughout the entire test temperature range. The estimation of the breakdown voltage is detailed in Appendix B. All the PD measurements were recorded for one minute to avoid PD-induced ageing.

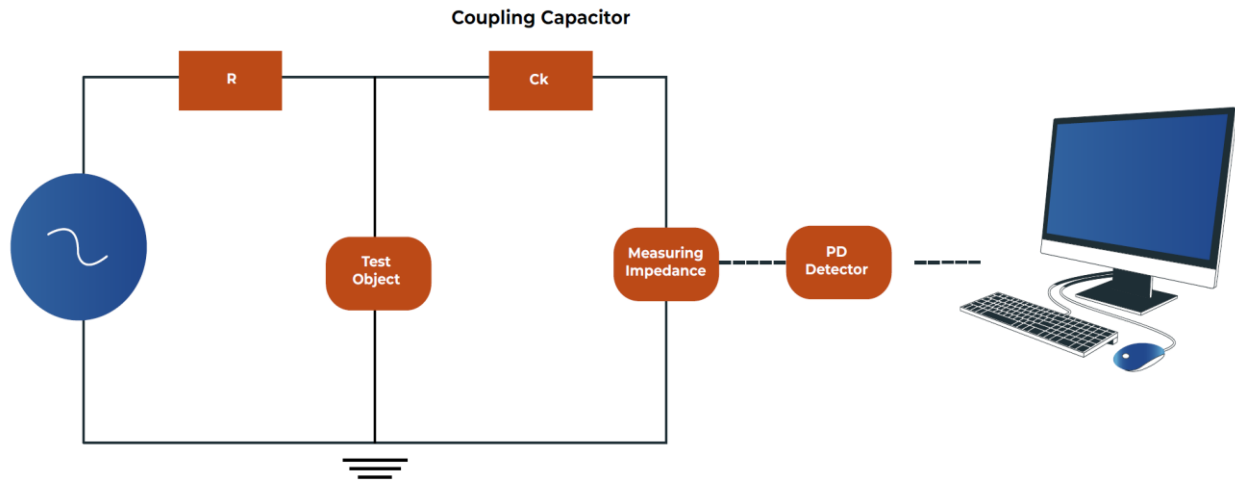


Figure 3.8: PD Measurements Experimental Set-up

All tests were conducted in a screened high-voltage laboratory with a background noise of 0.5 pC. The initial test temperature and pressure were 15 °C and 83.5 kPa, respectively.

System Calibration: The calibration process is fundamental to conventional PD diagnosis methods. The calibration of the PD test setup involves the introduction of a pulse with a known charge magnitude into the system. The calibration is accomplished by adhering to the guidelines outlined in IEC 60270 standards. The calibrator employed in this study is the CAL-1A model

manufactured by Power Diagnostix Systems GmbH. This calibrator possesses the capacity to introduce a predetermined charge ranging from 1 pC to 100 pC. The calibration was achieved by connecting the calibrator across the test object and applying a charge of 10 pC.

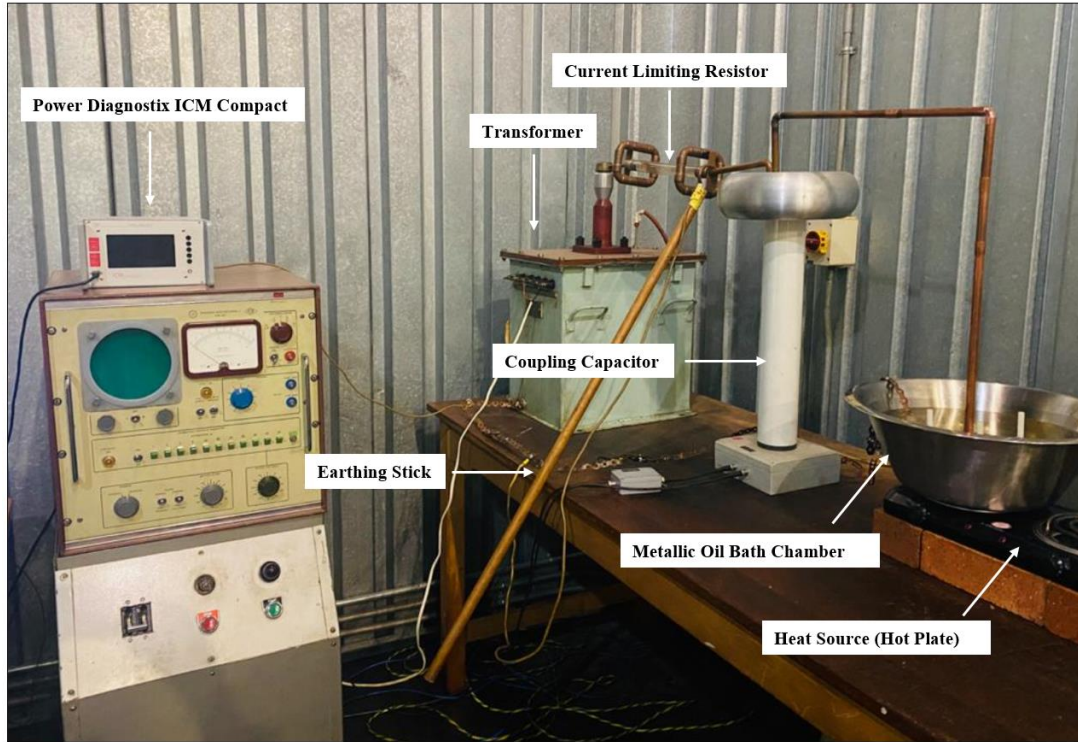


Figure 3.9: Experimental set-up of measuring cavity PD at variable temperature.

3.4 PD Measurements Procedure

The investigation into the effect of temperature on partial discharge characteristics was conducted for 15°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C test temperature ranges. The test samples were stressed at 11 kV AC voltage at 50 Hz for one minute to avoid PD-induced ageing while taking PD measurements. Three identical test specimens were prepared, and each test sample was tested individually for the abovementioned test temperature range. The test sample was first tested at 15°C. Then the temperature was raised to the next test temperature. The test sample was heated at the desired test temperature for 30 minutes before PD measurements were taken. This process was repeated until PD measurement data were recorded at all test temperature points. The PD data was stored for further analysis. The testing procedure is described in detail using the flow chart depicted in Figure 3.9.

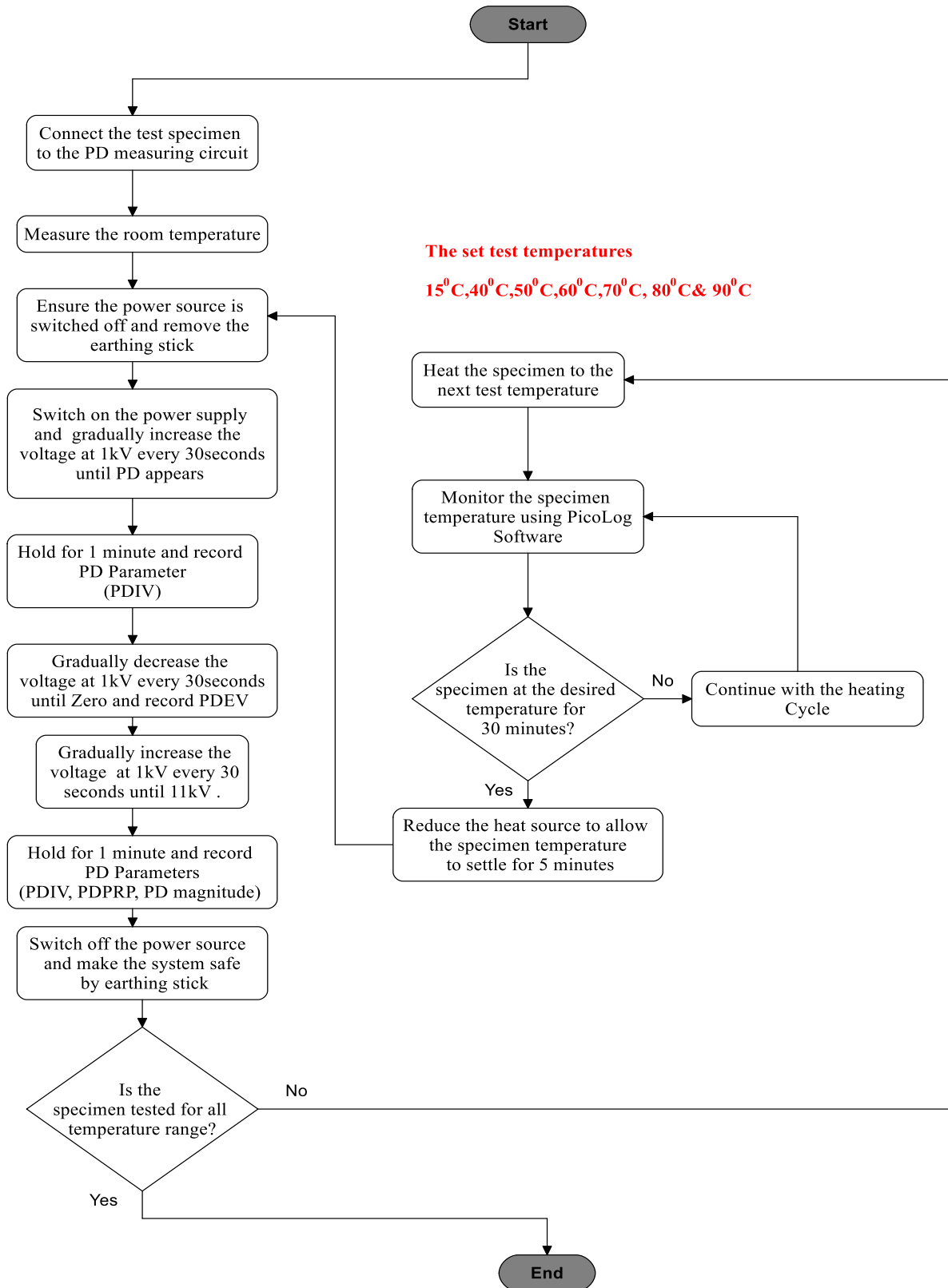
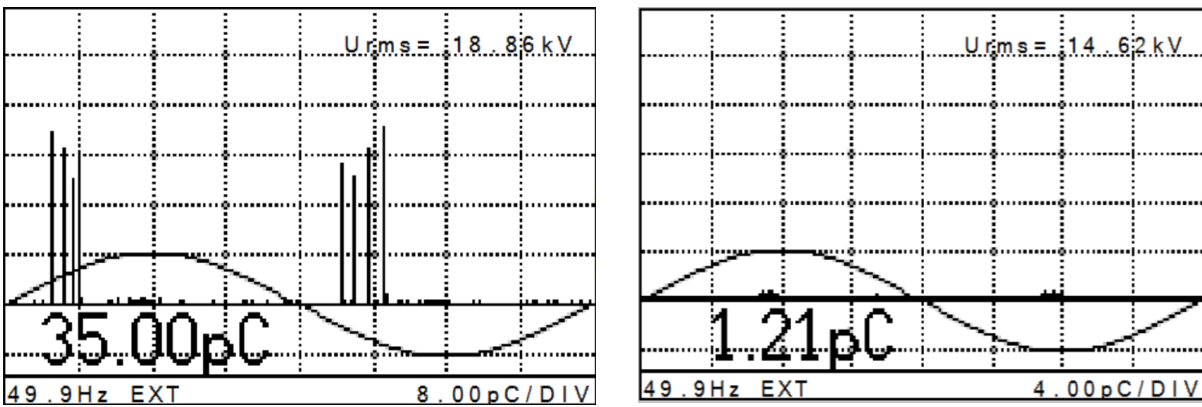


Figure 3.10: Thermal conditioning & PD measurement protocol flow chart

3.5 Background Noise Benchmarking Measurement Results

Noise level results of a defect-free test specimen with a thickness of 4.5 mm are shown in Figure 3.10. The results show that the test sample is partial discharge free for voltages up to 18 kVrms and the extinction voltage was found to be 14.62 kVrms, as shown in Figures 4.1 (a) and (b), respectively. The results show that for all defined test conditions, the voltage stress imposed on the test object should be kept below the threshold of 14.62 kVrms. Although the results are dependent on other parameters, such as the degree of smoothness of electrodes, uniformity of polyethylene sheets and the robustness of the test object clamping system, these results provide the upper boundary of the voltage stress for the testing system.



(a) Defect Free PDIV @ 18kV

(b) Defect Free PDEV @ 14.62kV

Figure 3.11: PD noise benchmarking measurements for defect-free sample

Noise level results are essential for the testing procedure to avoid measurement errors. From the phase-resolved pattern in Figure 3.10 (a), it can be seen that these patterns appear on both the negative and positive half-cycle of the supply voltage. Moreover, the observed patterns are symmetrical and are of similar charge magnitude. The observations made from the above patterns indicate a void defect located at the centre of the test sample. The measured PDs could be originating from the unevenness of polyethylene sheet surfaces. Although the results show the noise threshold of 18 kVrms, it is important to note that this threshold is 1.6 times higher than the chosen test voltage of 11 kV defined in section 3.3. Therefore, these results provide assurance that the measured PD's for each test sample are indeed due to the artificial defect created for this study.

3.6 Conclusions on Experimental Procedure

In this chapter, the design and development of the test specimen, the heating cycle experiment and PD measurements set up to study the influence of temperature on different PD parameters have been presented. Furthermore, the procedure followed to vary the cavity temperature to the desired test temperature and the process followed to carry out physical measurements are described in detail. The next chapter details the design and development of the theoretical model adopted to study the influence of temperature on different PD parameters. The theoretical models are used to explain the behaviour of PDIV, PD apparent charge magnitude and Phase-Resolved Patterns with varying temperatures.

4 Theoretical Prediction of PDIV and Magnitude as a Function of Temperature

Chapter Abstract: *This chapter presents a generalised theoretical modelling approach to estimate partial discharge inception voltage (PDIV) and PD charge magnitude. The streamer-like discharge concept is adopted to model the former, while the latter is modelled based on the induced charge concept introduced by Pedersen in the 1980s. The effect of variation in cavity temperature on PD critical parameters, particularly the cavity pressure, is illustrated through Dunbar's temperature correction factor. This temperature correction factor is based on the ideal gas equations and demonstrates that the cavity pressure increases linearly with temperature. Therefore, the temperature correction factor is included in these models to evaluate the influence of temperature on PD parameters.*

4.1 PD Modelling Overview

Partial discharge is inherently complex and usually exhibits a non-stationary behaviour during a discharge process. Additionally, it encompasses multi-physics phenomena, including the inception field, statistical time lag, surface charge dynamics and electron generation rate. It is, therefore, necessary to understand the physics before and after a discharge process to interpret PD measurements correctly. Moreover, it is essential to model the PD mechanism to gain more insights into the physical processes involved in the discharge and, most importantly, to identify the critical parameters affecting the PD process. The model developed in this study is based on analytical equations extracted from the available PD models in the literature. These equations are implemented in MATLABTM to estimate PDIV and PD charge magnitude with varying temperatures. The cavity pressure changes with temperature are modelled using ideal gas law equations. In the next chapter, comparisons are made between the modelled results and the measured experimental values and conclusions are drawn.

4.2 The Test Cell Model Geometry

The geometry of the model considered in this study is illustrated in Figure 4.1. The model encompasses the cylindrical air cavity embedded in polyethylene dielectric. The air cavity in the model has a diameter of 2.5 mm and a height of 1.5 mm. The model's overall height is 1.5 mm.

A multi-layered dielectric structure is produced when the air cavity is enclosed within the polyethylene bulk solid insulating medium. The relative permittivity of the bulk insulation is 2.3, and the thickness of the insulation is 4.5 millimetres.

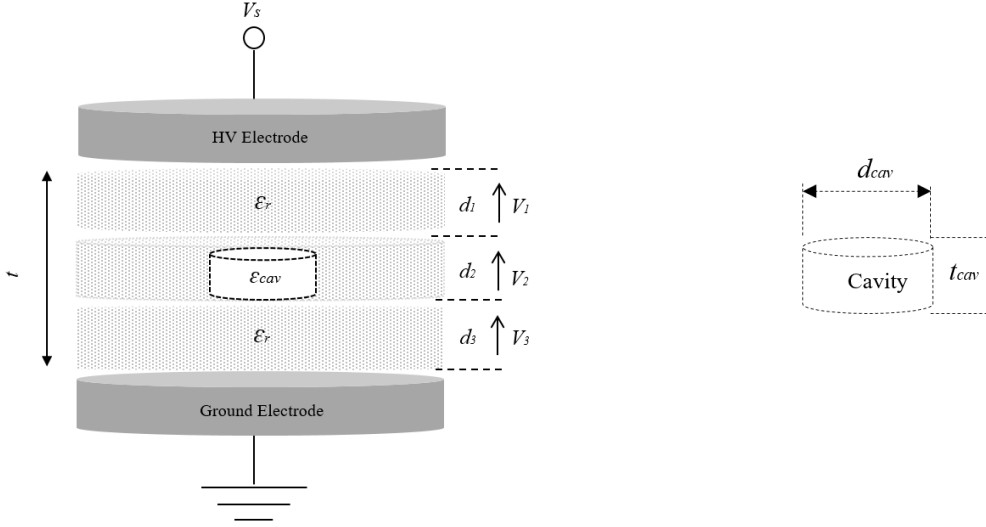


Figure 4.1: Cavity source test specimen

The values of the model parameters used in this study are presented in Table 4.1.

Table 4.1: PD Model Geometry Parameters with reference to Figure 4.1

Parameter	Symbol	Value	Unit
First Polyethylene sheet thickness	d_1	1.5	mm
Second Polyethylene sheet thickness	d_2	1.5	mm
Third Polyethylene sheet thickness	d_3	1.5	mm
Cavity diameter	d_{cav}	2.5	mm
Cavity thickness	t_{cav}	1.5	mm
Sample thickness	t	4.5	mm

4.3 PD Inception Voltage Theoretical Model

Partial discharge mechanisms in air cavities embedded in bulk insulation are generally modelled as streamer-like discharges [16]. Streamer-like discharges are characterized by a short pulse duration of approximately 100 ns and a relatively sizeable apparent charge magnitude, typically

of magnitudes ranging from 10 pC and higher. For partial discharge activity to initiate, the following two conditions are necessary: The first one is an electric field higher than the critical field at a defect location. The supplementary condition and yet significant, is the availability of an initial seed electron to initiate the avalanche process [36], [37]. The former is usually denoted as E_{inc} , and it is generally defined as the minimum electric field required to initiate partial discharge process. The inception electric field E_{inc} can be modelled using the mathematical expression in equation 4.1 [38][39] [40].

$$E_{inc} = Ap \left[1 + \frac{B}{\sqrt{(a+b)p}} \right] \quad (4.1)$$

Where:

- A = is a constant representing the pressure reduced field
- p = gas pressure between the electrodes [Pa]
- B = gas-dependent constant
- a and b = cavity radius and height [m]

The constant A denotes the pressure-reduced field, with a value of 24.2 V/Pa.m, B is the gas-dependant constant; for atmospheric air, it equals 8.6 Pa^{1/2} m^{1/2} [41]. From the above mathematical expression in equation (4.1), it is notable that regardless of the cavity dimensions, the electric field within the cavity needs to exceed the product of pressure reduced field $(E/P)_{cr}$ and the pressure (P) for partial discharge to occur [42]. To estimate the minimum voltage required across the electrode in relation to E_{inc} , it is necessary to understand the correlation between the electric field in the insulation medium and that in the cavity.

Defects embedded in insulation medium represent a multilayered dielectric system. Figure 4.1 shows the physical model of the multilayered dielectrics system between parallel electrodes. Let V_1 , V_2 and V_3 be the voltages across each dielectric thickness d_1 , d_2 and d_3 , respectively. For parallel plate electrode set-up, the electric field is given as $E=V/d$, then $V_1=E_1 d_1$, $V_2=E_2 d_2$, and $V_3=E_3 d_3$. Thus, the voltage across the electrode is given as $V_s = E_1 d_1 + E_2 d_2 + E_3 d_3$. From the relationship that if there is no charge in the dielectric, then the product of the electric field

and its relative permittivity will remain constant, then the inception field inside the air cavity is given by equation 4.2.

$$E_{inc} = V_s \left[\frac{\epsilon_{cav}}{\epsilon_r} d_1 + d_2 + \frac{\epsilon_{cav}}{\epsilon_r} d_3 \right]^{-1} \quad (4.2)$$

Where:

- V_s = voltage across the electrodes [V]
- ϵ_{cav} = relative permittivity of air
- ϵ_r = relative permittivity of polyethylene
- $d_{1,2,3}$ = the thickness of polyethylene layers [mm]

By combining equations (4.1) and (4.2), the voltage across the electrodes can be expressed as in equation (4.3). The predicted breakdown voltage using equation 4.3 below is known as the PD inception voltage. The present work is interested in exploring the temperature dependence of partial discharge inception voltage V_{inc} .

$$V_{inc} = Ap \left[1 + \frac{B}{\sqrt{(a+b)p}} \right] \left[\frac{\epsilon_{cav}}{\epsilon_r} d_1 + d_2 + \frac{\epsilon_{cav}}{\epsilon_r} d_3 \right] \quad (4.3)$$

By inspecting equation 4.3, the parameters that respond to temperature variations are identified and can be expressed as a function of temperature. In this case, the parameter which responds to temperature is the cavity pressure, p . One other parameter evaluated from equation 4.3 is the relative permittivity ϵ_r of polyethylene. For polyethylene insulation, literature has shown that the response of relative permittivity ϵ_r to varying insulation temperature is insignificant. Although the studies by Nedjar [43] reported that the relative permittivity ϵ_r of polyethylene decreases with an increase in temperature, the experimental results show that from 30°C to 90°C, the relative permittivity decreased from 2.3 to approximately 2.1. Similarly, Linzhi *et al.* [2] and Ishimoto *et al.* [44] observed the same trends of relative permittivity with varying temperatures with those in

[43]. Further observations show that the relative permittivity decreased by approximately 9% from ambient temperature to 90°C. It was, therefore, necessary to observe how a decrease in relative permittivity affects the electric field. The electric field distribution was evaluated using the COMSOLTM Multiphysics software. The relative permittivity values at ambient and at 90°C used in the simulation model were obtained from the literature [2] [43] [44]. The COMSOLTM electrostatic model considered in this study is described in detail in Appendix C.

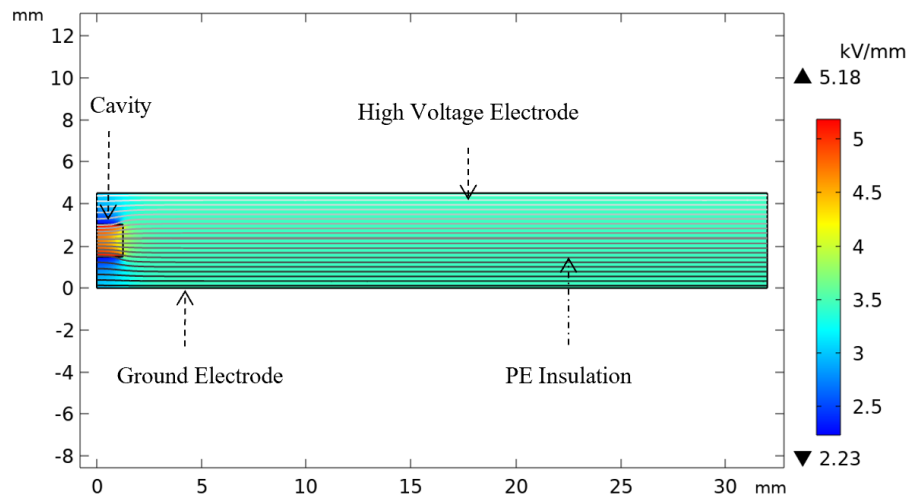


Figure 4.2: Electric field density plot at relative permittivity of 2.3 that corresponds to temperature conditions of 20°C

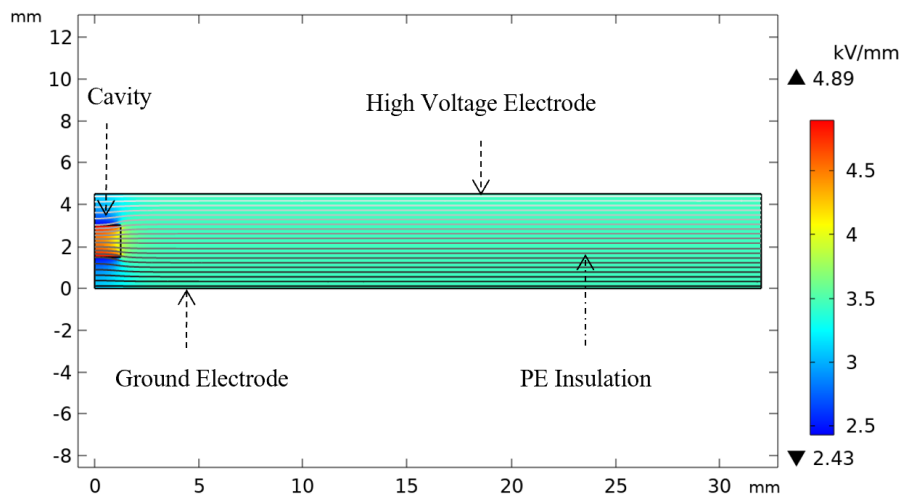


Figure 4.3: Electric field density plot at relative permittivity of 2.1 that corresponds to temperature conditions of 90°C

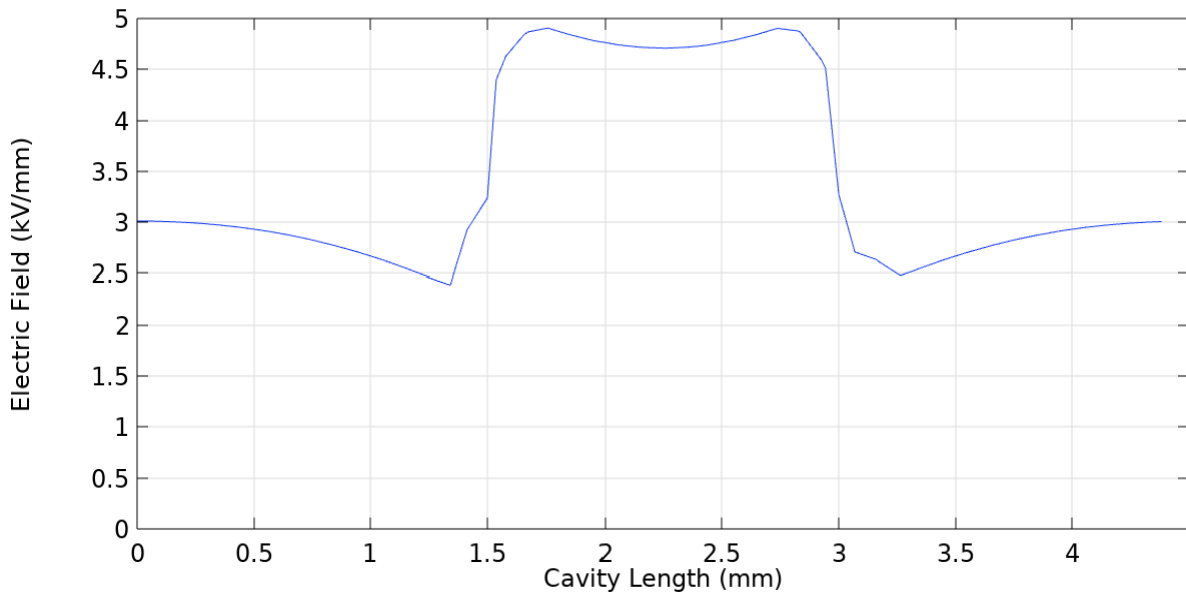


Figure 4.4: Electric field profile at relative permittivity of 2.3 at 20°C

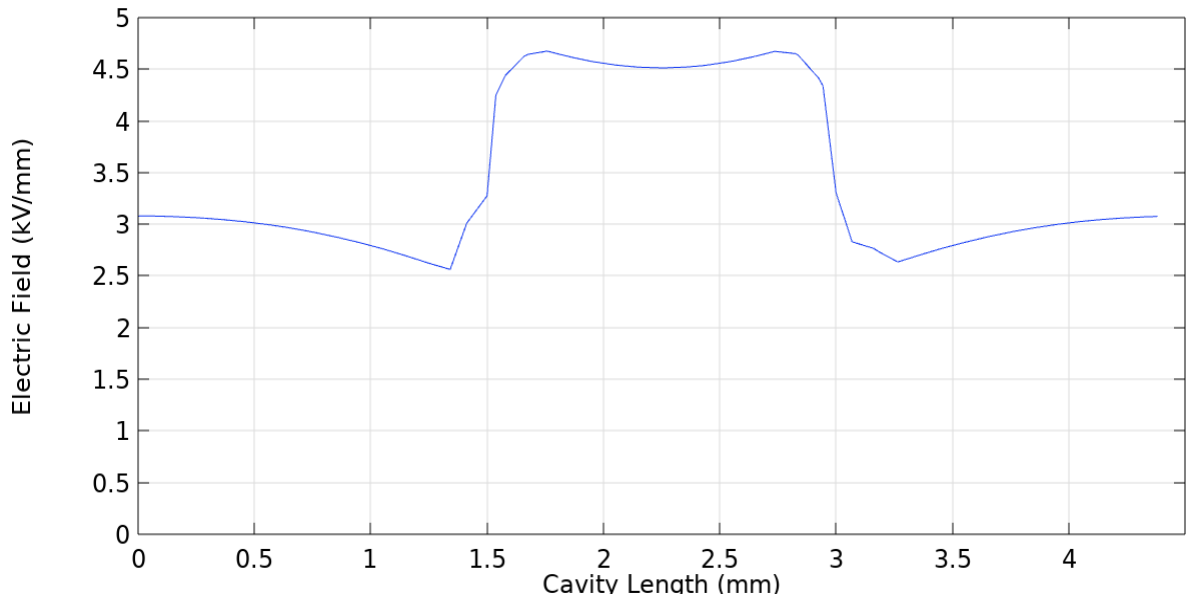


Figure 4.5: Electric field profile at relative permittivity of 2.1 at 90°C

Figures 4.2 and 4.3 show the electric field density profile at the relative permittivity of 2.3 (corresponding to 20°) and 2.1 (corresponding to 90°), respectively. The results show that at the relative permittivity of 2.3, the maximum electric field within the cavity is approximately 5.2 kV/mm. In contrast, at the relative permittivity of 2.1, the maximum electric field was found to

be approximately 4.89 kV/mm. Figures 4.4 and 4.5 further show the electric field profiles at ambient and 90°C, respectively. Comparing the electric field profile at ambient temperature and 90°C, the results show that the electric field decreased by 3.8% from ambient temperature to 90°C. The interpretation is that the decrease of the electric field from ambient temperature to 90°C is insignificant. Therefore, the response of relative permittivity to temperature is negligible and as a result, this parameter was kept constant at 2.3

The previous section demonstrated that the response of relative permittivity to variations in temperature is insignificant. This section focuses on how cavity pressure responds to an increase in temperature. Interpreting the relevant literature, the temperature correction factors from Peek and Dunbar have been predominant in the studies of the gas breakdown mechanisms [18][45]. The temperature correction factors are used to incorporate the temperature changes to predict PD inception voltage between two conducting electrodes. The following section details the modelling of temperature changes on the cavity pressure.

Modelling Cavity Pressure Dependence on Temperature:

To evaluate the effect of temperature on PD activity, it is necessary to understand how temperature influences the gas cavity's initial conditions. One of the most critical initial conditions for the PD mechanism is the gas pressure in the cavity. Several studies have shown that, amongst other parameters, the gas pressure greatly influences the PD parameters, such as the inception and extension of electric stress. It is in this context that the influence of temperature on the cavity pressure is incorporated into the PD theoretical model. The cavity pressure changes with temperature are modelled using the ideal gas law equations, which relate the gas pressure, cavity volume and gas temperature.

Although this law describes the behaviour of a perfect or an ideal gas, studies have shown that the ideal gas law equations closely approximate the behaviour of natural gas. The application of an ideal gas law equation is based on the assumption that the cavity volume remains constant throughout the entire test temperature range and during the discharge process. Also assumes an unvented cavity in an insulation. It is worth mentioning that the model in this study did not consider the cavity temperature changes due to the discharge process itself, as this is considered

minimal as PD activity was limited to just one minute. The relationship between temperature and pressure is given by equation 4.4.

$$\delta = \left[(t_{n+1} + t_0) / (t_n + t_0) \right] p_n \quad (4.4)$$

Where:

t_{n+1}	= cavity test temperature
t_n	= initial cavity temperature
p_n	= initial cavity pressure
t_0	= temperature constant [K]

The parameter t_0 is the temperature constant and its value is 273 K. Equation (4.4) demonstrates that an increase in temperature increases the cavity pressure linearly by a factor (t_n/t_{n-1}) . Figure 4.2 illustrates the linear relationship between the cavity temperature and pressure obtained from equation (4.4). Substituting the pressure p with the correction factor δ in equation (4.3) gives equation (4.5). Equation 4.5 is an analytical expression used to estimate PD inception voltage at temperature t_{n+1} in the cavity.

$$V_{inc(t_{n+1})} = A\delta \left[1 + \frac{B}{\sqrt{(a+b)\delta}} \right] \left[\frac{\varepsilon_{cav}}{\varepsilon_r} d_1 + d_2 + \frac{\varepsilon_{cav}}{\varepsilon_r} d_3 \right] \quad (4.5)$$

Equations 4.4 and 4.5 are implemented on MATLABTM to obtain the relationship between the cavity temperature and PD inception voltage. Figure 4.2 illustrates the steps and the sequence followed in developing the MATLABTM source code for determining the PD inception voltage. The MATLABTM source code used to realise equation 4.5 is presented in Appendix D.

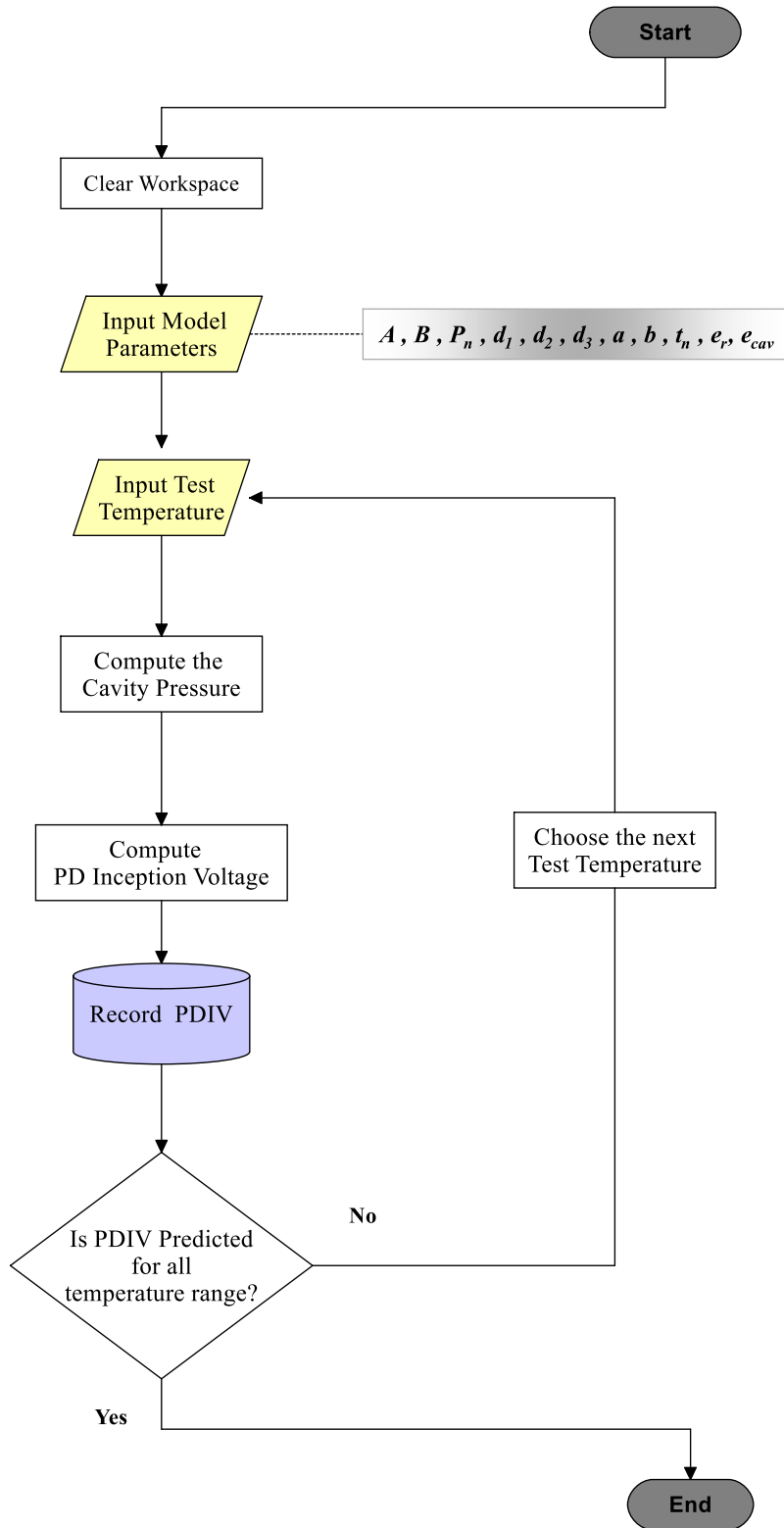


Figure 4.6: Flow Chart Process for Determining PDIV

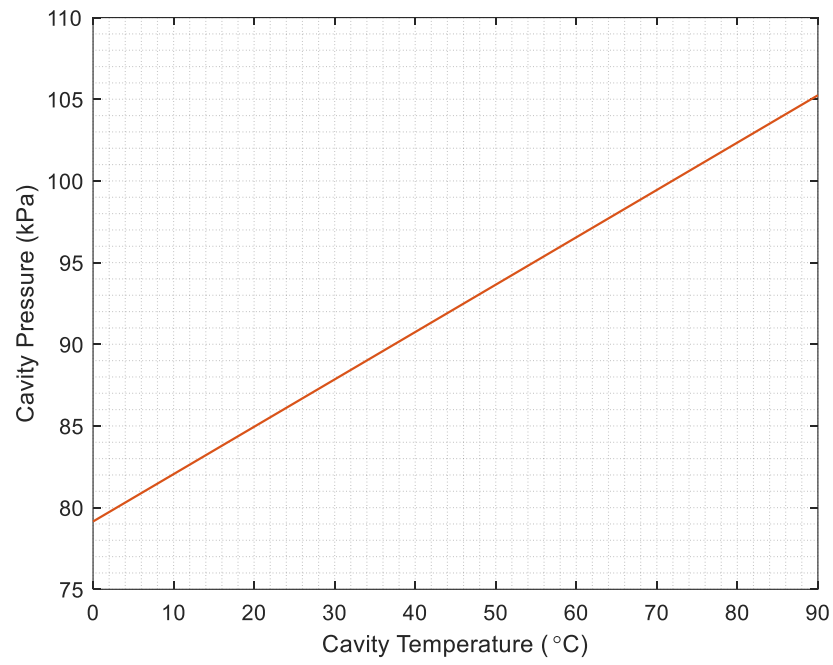


Figure 4.7: Simulated Variations of Cavity Pressure with Temperature

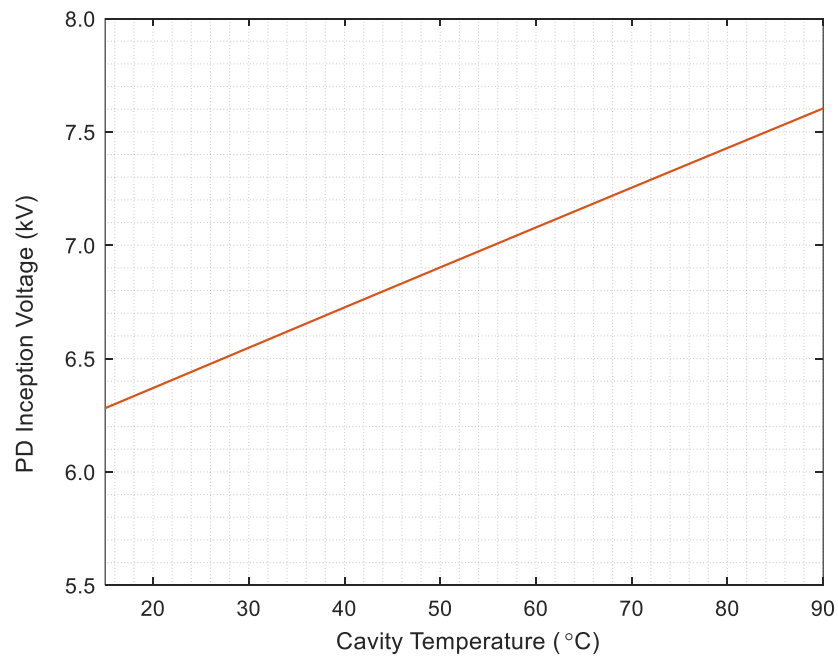


Figure 4.8: Simulated PDIV Variations with Temperature

Figure 4.3 illustrates the relationship between the cavity pressure and the cavity temperature, while Figure 4.4 shows the variation of PD Inception Voltage with the cavity temperature. Equation 4.4 demonstrates that the cavity pressure increases linearly with temperature. The simulation results further show that the cavity pressure increases by approximately 26 % from ambient temperature of 15°C to 90°C. Assuming an insignificant delay in the availability of seed electrons and considering that the dimensions and parameters in Figure 4.1 do not vary with temperature, the simulated results show that PDIV increases monotonously with temperature.

4.4 PD Charge Magnitude Theoretical Model

PD charge magnitude is generally categorized into the real and the apparent charge, also called the induced charge. The former is the actual charge deposited within the discharge area and is impossible to measure using the laboratory apparatus. The apparent PD charge magnitude is modelled by adopting an analytical model called the induced charge or the dipole model. It is a charge measured through external connections (electrodes) to the object that contains the PD source. It is a function of the signal transfer properties of the PD signal path from the source point to the measurement. Pedersen introduced this model in the 1980s and reasoned that the transients measured at the electrodes result from the dipole moment established in the cavity owing to a discharge event. The PD charge magnitude can be estimated using the following mathematical expression [46]:

$$q_{app} = -\Omega K \varepsilon_r \varepsilon_0 [E_{inc} - E_{res}] \nabla \lambda_0 \quad (4.6)$$

Where:

Ω	= cavity volume parameter
K	= dimensionless factor
ε_r	= relative permittivity of polyethylene
ε_0	= permittivity of free space
E_{inc}	= the inception electric field [V/mm]

E_{res} = the residual electric field [V/mm]

$\nabla\lambda_o$ = the proportionality factor

Notably, this model assumes that the entire void is involved in the discharge process and that the electric field inside the cavity is uniform. The inception and residual fields are denoted by E_{inc} and E_{res} , respectively. The residual electric field is a function of pressure and is given by: $E_{res}=\gamma Ap$, where γ is a constant and will be used as a free parameter in the present study [45]. The constant A was previously defined in section 4.3 and p is the cavity pressure. Lastly, $\nabla\lambda_o$ is the proportionality factor relating the actual charge in the cavity and the measured apparent charge magnitude. Implementing the temperature correction factor from equation (4.4) into equation (4.6), the PD apparent charge magnitude is estimated using equation (4.7) :

$$q_{app} = -\Omega K \varepsilon_r \varepsilon_0 \left[A\delta \left[1 + \frac{B}{\sqrt{(a+b)\delta}} \right] - \gamma A\delta \right] \nabla\lambda_o \quad (4.7)$$

The methodology employed in this study involved using the curve fitting strategy to accurately fit equation 4.7 to the experimentally obtained data. The parameters used in Equation 4.7 were sourced from the existing literature and are presented in Table 4.2.

Table 4.2: Parameters used for simulations

Parameter	Value	Reference
Ω	7.4 mm ³	The cavity volume
K	1	[16]
$\nabla\lambda_o$	1/d	[19]

Equations 4.1, 4.4, and 4.5 were implemented in MATLABTM software in order to establish the correlation between the temperature of the cavity and the PD apparent charge magnitude. The MATLABTM source code is detailed in Appendix D. Figure 4.5 depicts the procedural stages and sequential order employed in the development of the MATLABTM code used for the determination of the PD apparent charge magnitude. The curve fitting process was conducted by adjusting the free parameter γ in order to closely fit the calculated values with the experimentally obtained magnitudes of PD as the temperature was varied from 15°C to 90°C.

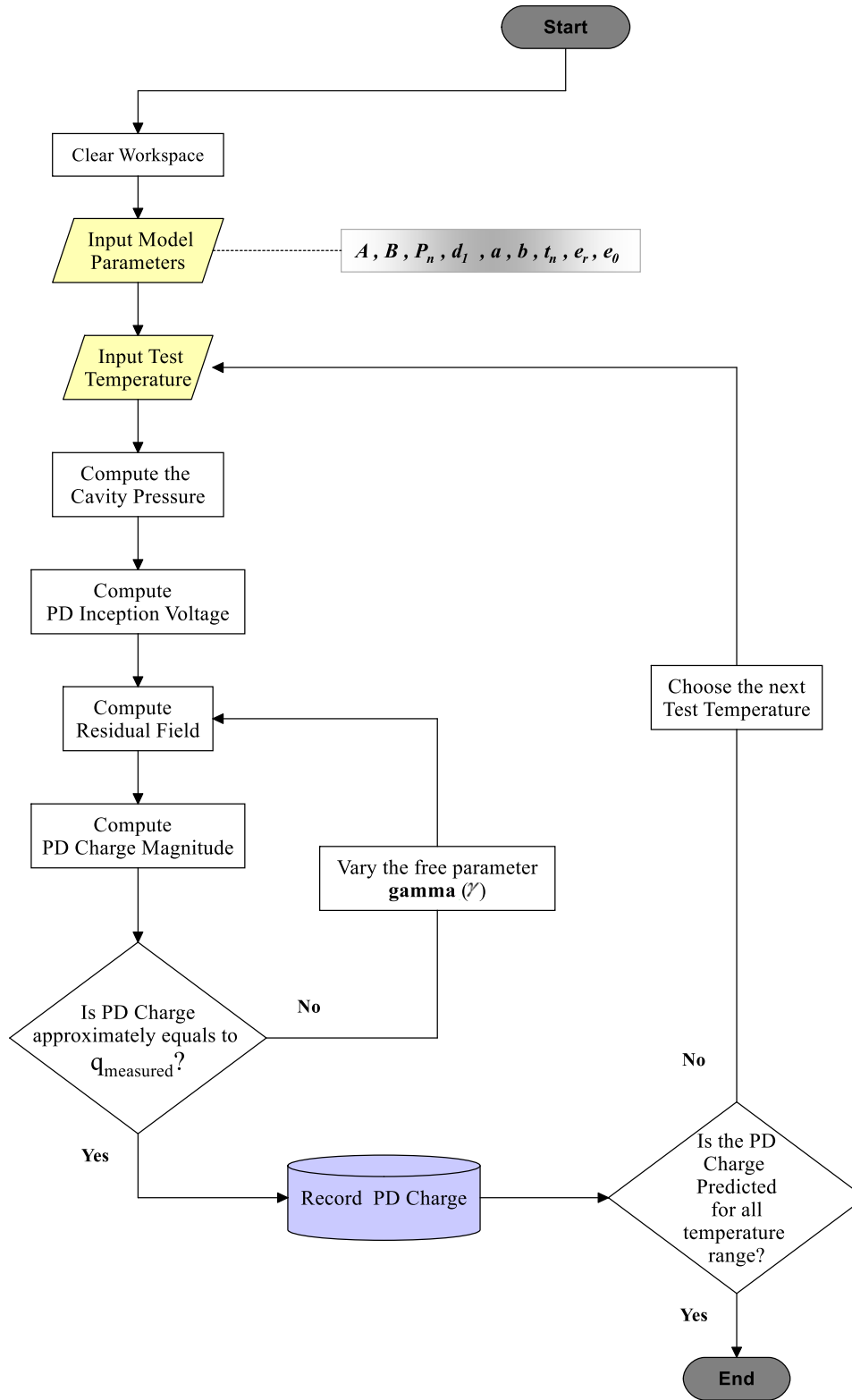


Figure 4.9: Flow Chart Process for Determining PD Charge Magnitude

4.5 Conclusion on Theoretical Prediction

In this chapter, the design and development of the theoretical model adopted to study the influence of temperature on different PD parameters has been presented. Furthermore, the process followed to implement the theoretical models in MATLABTM has also been presented. The implemented theoretical models are used to explain the behaviour of PDIV and PD apparent charge magnitude with varying temperatures. In the present work, physical measurements were conducted, as presented in Chapter 3. The next chapter compares the simulated results obtained using the theoretical model to the physical measurements. The comparison of the physical measured results and the theoretical simulations serves to explain the PD mechanisms responsible for co-relating temperature variations with corresponding variations in the PD parameter of interest, PDIV, PDEV, Apparent charge magnitude and Phase-Resolved Parttens.

5 Results, Analysis and Discussions on the Influence of Temperature on Cavity PD Characteristics

Chapter Abstract: In this chapter, experimental results are presented and analyzed. The partial discharge measurements obtained at different test temperatures are analyzed. In particular, conventional PD parameters such as PDIV, PDEV, PD magnitude and Phase Resolved Partial Discharge Patterns (PRPDP) are reported as a function of temperature. Results showed that PDIV increased linearly with temperature for the entire test range, while no particular trend was observed for PDEV. Notably, PD charge magnitude initially decreased with temperature from 15°C to 60°C and then increased from 60°C to 90°C. The evolution of PDPRP with temperature was characterised by turtle-like patterns at ambient temperature, which then transitioned into rabbit ear PDPRP as the temperature increased to 90°C.

5.1 The Influence of Temperature on PDIV and PDEV

5.1.1 Measurements and Observations

Table 5.1 provides information on the PDIV and PDEV measurements data that were taken as a function of the temperature. The plots of the measured PDIV and PDEV for variations of insulation temperatures are presented in Figures 5.1 and 5.2, respectively. The PDIV voltage is defined as the voltage that is measured when the PD charge magnitude exceeds the value of 10 pC. Subsequently, PDEV is recorded as the voltage after the PD charge magnitude falls below the threshold of 10 pC. According to the findings shown in Table 5.1 and plots in Figure 5.3, PDIV generally increased linearly with an increase in temperature.

Table 5.1: PDIV and PDEV Experimental Results

Test Temperature	15°C	40°C	50°C	60°C	70°C	80°C	90°C
Sample 1 Measured PDIV (kV)	6,31	6,76	6,98	7,02	7,16	7,50	7,79
Sample 1 Measured PDEV (kV)	5,56	5,53	5,58	5,68	6,66	6,41	6,19
Sample 2 Measured PDIV (kV)	6,42	6,72	7,00	7,10	7,21	7,38	7,53
Sample 2 Measured PDEV (kV)	5,70	5,74	6,52	6,30	6,37	5,95	6,21
Sample 3 Measured PDIV (kV)	6,23	6,85	6,93	7,17	7,47	7,68	7,71
Sample 3 Measured PDEV (kV)	6,11	5,98	6,01	6,05	6,08	6,19	6,11

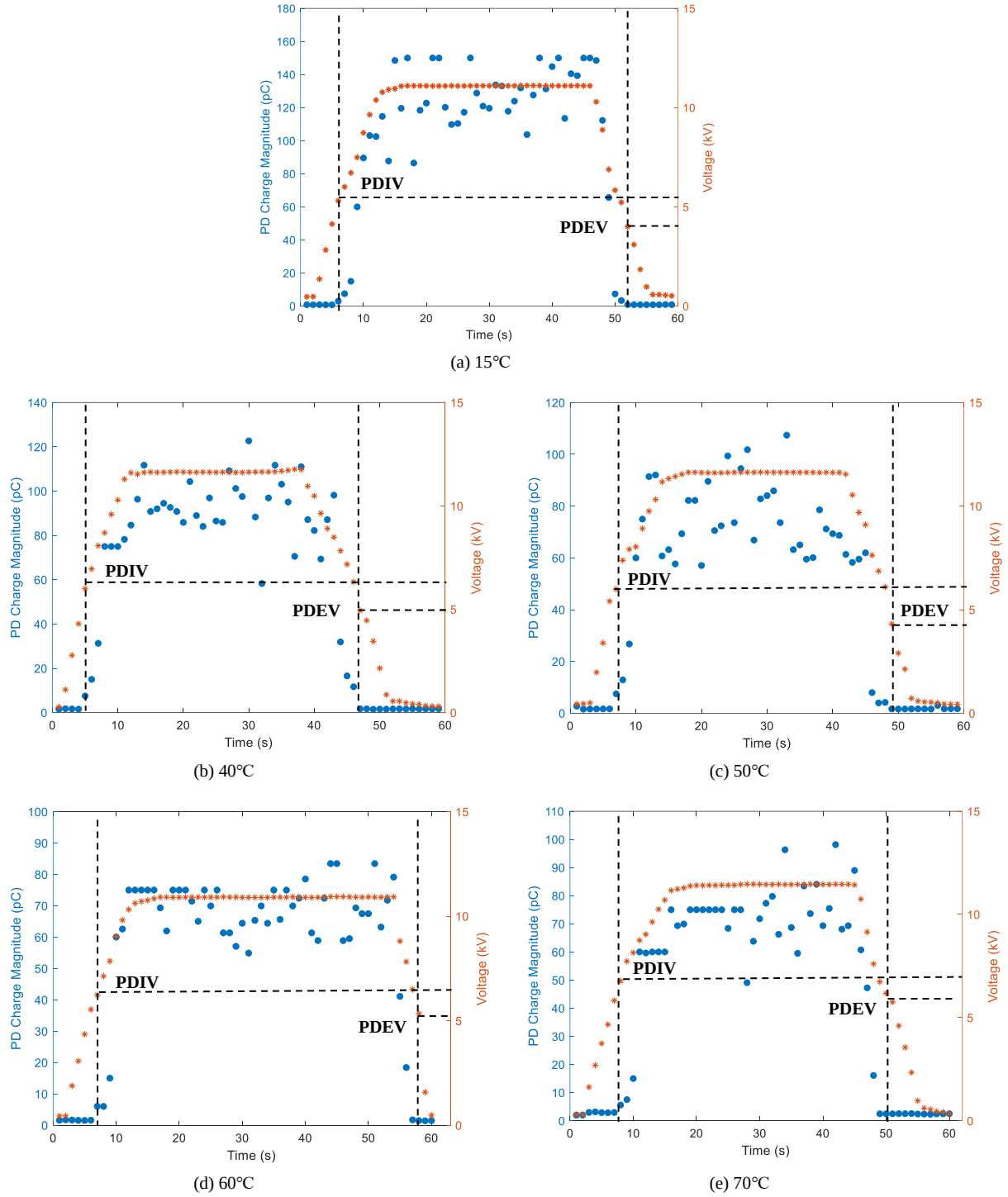


Figure 5.1: PDIV and PDEV Measurements at temperatures 15°C to 70°C

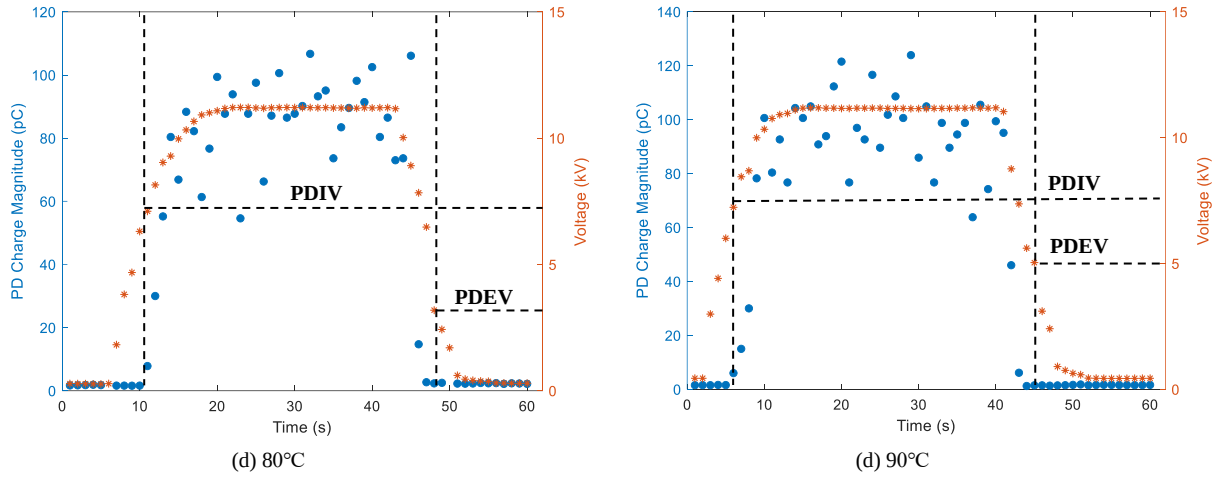
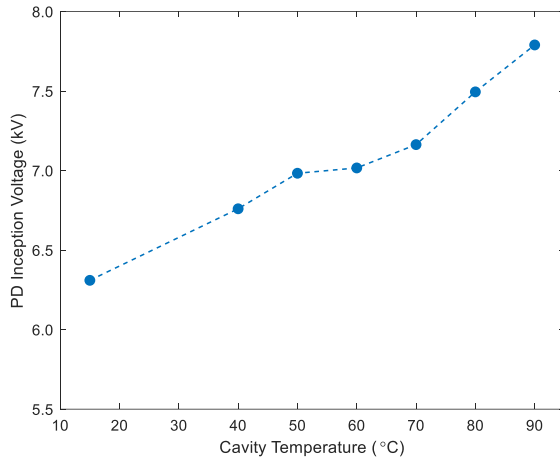


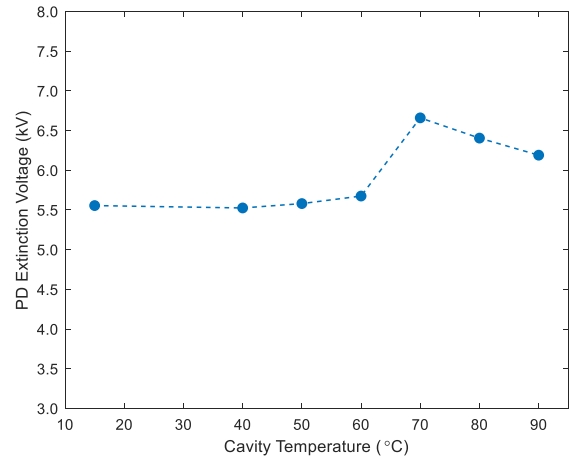
Figure 5.2: PDIV and PDEV Measurements at temperatures 80°C to 90°C

These observations are further supported by the plots presented in Figure 5.3. Notably, similar results were obtained with two other identical test specimens. A closer observation of the experimental results reveals that an increase in PDIV that occurs when the temperature is raised from 15°C to 90°C is higher than 15%. Despite conducting practical and simulation studies employing epoxy insulation material, the studies in [9] reported similar findings regarding PDIV as a function of temperature. In fact, from the experimental data, the studies show that PDIV increased by approximately 13% as the temperature increased from ambient to higher temperatures. Similarly, Haghjoo *et al.* [23], Mariut [27] and Kuanhong [47] observed the same trends despite conducting studies on XLPE insulation material different from those in [9]. In addition, Illias *et al.* [21] conducted simulation studies by making use of Finite Element Analysis and obtained similar results. It is important to note that although the studies by Illias *et al.* considered cavity temperature changes owing to PD activity rather than the insulation material temperature changes, the findings are comparable with the observations in the current studies.

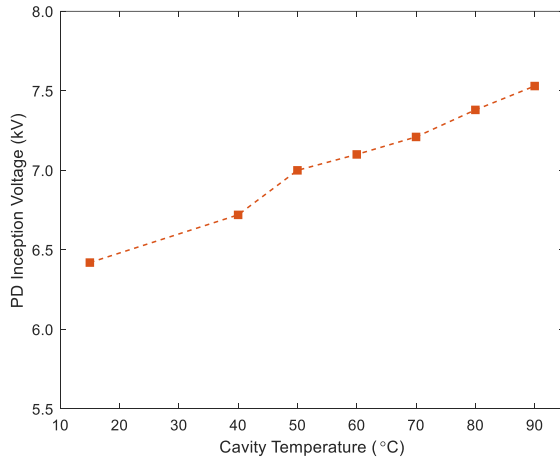
With reference to PDEV measurements, as presented in Figure 5.3, the results show no specific trends of PDEV with varying temperatures. The measured results demonstrate that PDEV remained in the range of 5.5 kV and 6.5 kV throughout the entire test temperature range. The trend was consistent for the three (3) different test specimens that were conducted.



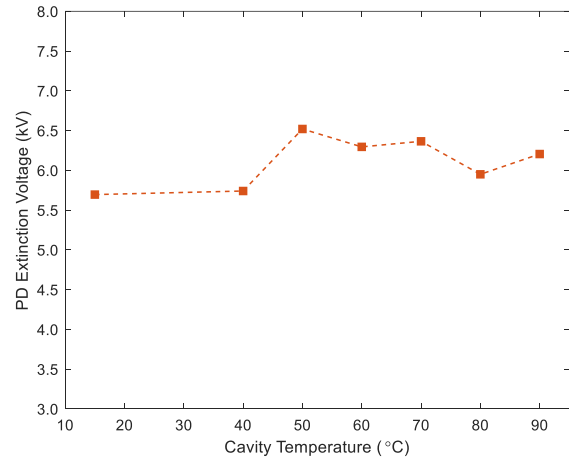
(a) Sample 1 PDIV



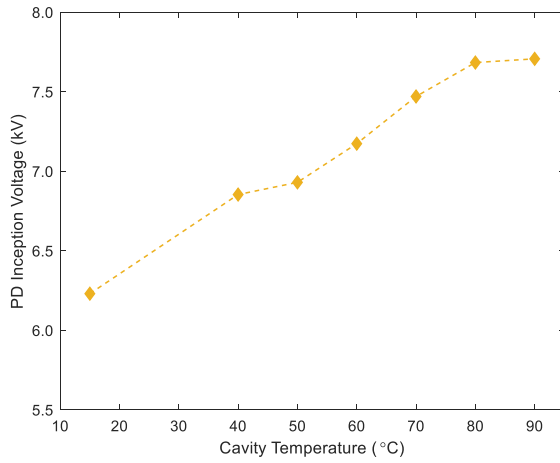
(b) Sample 1 PDEV



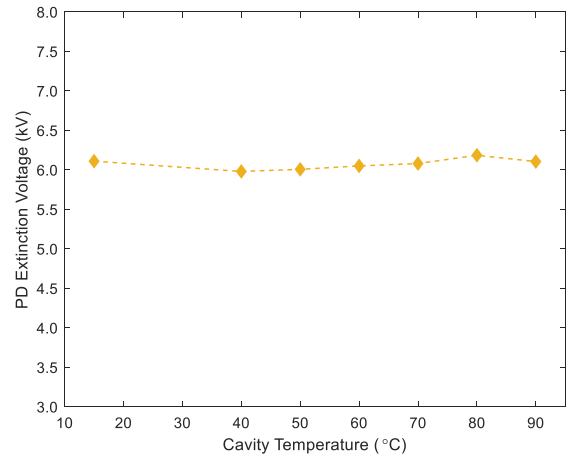
(c) Sample 2 PDIV



(d) Sample 2 PDEV



(e) Sample 3 PDIV



(f) Sample 3 PDEV

Figure 5.3: PDIV and PDEV of air cavity defect in polyethylene as a function of temperature

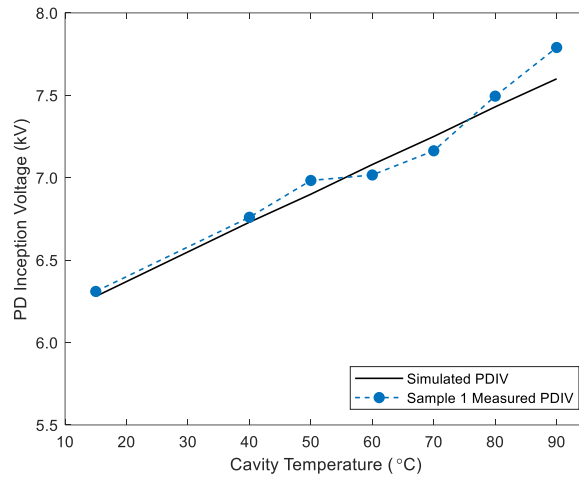
5.1.2 Comparison Between Simulation and Experimentally Measured Results: PDIV

Table 5.2 presents both the measured values of PDIV as well as the simulation results that were derived from the PDIV analytical model that was discussed in Chapter 4. In addition, the plots of the simulated and measured PDIV are presented in Figure 5.4. Similar to the trend observed from the measured PDIV, the analytical model demonstrates that PDIV increases monotonously with an increase in cavity temperature. It is worth noting that the relative error between the experimental and the analytical model results is generally below 4%. Comparing the estimated inception voltage with the experimental results, it can be inferred that the measured results are in good agreement with the estimated inception voltage obtained from the PDIV analytical model.

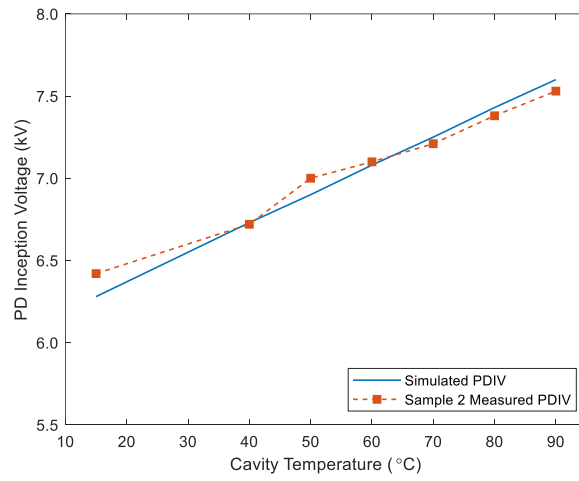
Table 5.2: PDIV Simulation and Experimental Results

Test Temperature	15°C	40°C	50°C	60°C	70°C	80°C	90°C
Simulation Results: PDIV (kV)	6,28	6,73	6,90	7,08	7,25	7,43	7,60
Sample 1 Measured PDIV (kV)	6,31	6,76	6,98	7,02	7,16	7,50	7,79
<i>Sample 1 Percentage Error (%)</i>	0,50	0,40	1,20	-0,90	-1,20	0,90	2,50
Sample 2 Measured PDIV (kV)	6,42	6,72	7,00	7,10	7,21	7,38	7,53
<i>Sample 2 Percentage Error (%)</i>	2,20	-0,10	1,40	0,30	-0,60	-0,70	-0,90
Sample 3 Measured PDIV (kV)	6,23	6,85	6,93	7,17	7,47	7,68	7,71
<i>Sample 3 Percentage Error (%)</i>	-0,80	1,80	0,40	1,30	3,00	3,40	1,40

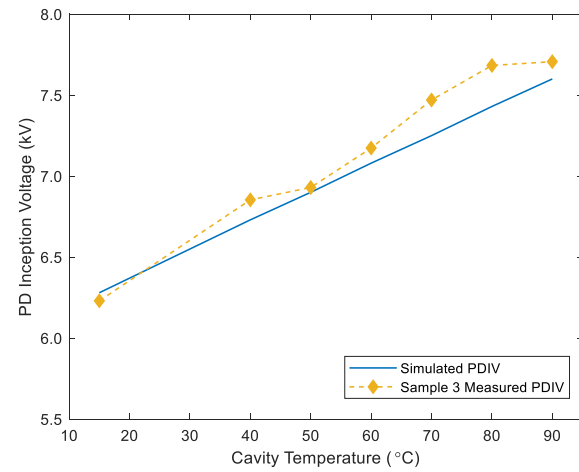
Although the PDIV theoretical model presented in Chapter 4 is frequently used to predict the inception field, its limitations and origins must be noted. This analytical approach was developed as a result of the research into the breakdown characteristics of atmospheric air. In their analyses, the researchers considered the parallel electrode arrangement for gap lengths greater than one centimetre. In PD experiments, particularly cavity partial discharges where bulk insulation surrounds the cavity, the insulation material may exhibit different secondary emissions characteristics than the metallic electrodes, which may influence PDIV. Nevertheless, the results obtained by this analytical approach are in agreement with the experimental findings as shown in Figure 5.4.



(a)



(b)



(c)

Figure 5.4: PDIV as a Function of Temperature (Simulation vs Measurement Results) for air-filled cavity in polyethylene

5.1.3 PD Inception Voltage Results Discussions

Assuming an insignificant delay in the availability of seed electrons and considering that the dimensions and parameters of the cavity do not vary with temperature, the analytical model has demonstrated that PDIV increases monotonously with temperature. Notably, the findings of the experiments are consistent with the conclusions drawn from the theoretical model. Partial discharge inception voltage response to varying temperatures is attributed to changing gas-filled cavity pressure. The relationship between the cavity pressure and temperature is illustrated in Figure 5.5. The results demonstrate that the cavity pressure increases linearly in response to increasing temperature. The observed PDIV trend with temperature can be explained using the fundamental theory of the electrical breakdown of gases.

According to this theory, the first process that governs the electrical breakdown of gases is the ionization process. Ionization is defined as the process in which a neutral molecule or a metastable dislodges an electron, thereby attaining a positive charge. This mechanism is highly dependent on the rate at which electrons are generated, also known as the electron avalanche. Although electrons can be generated in various ways, such as photo-ionization, secondary ionization and collision, it is essential to note that electron production through collision with a neutral molecule is an important mechanism contributing to avalanche and propagation. Assuming that the energy transferred during collision is greater than the ionization energy of the neutral molecule, ionization by collision process can be represented as follows.



Where, A is the neutral molecule, e^{-} is an electron and A^{+} is the positive charged particle. Collision-based production of electrons is highly dependent on various factors, some of which include the energy of the electrons, the mean free path, and the pressure of the surrounding gas [48]. In a given electric field, the ability of an electron to obtain sufficient energy to free an electron from a molecule depends on the distance between molecules, also known as the mean free path. In general, the greater the distance between molecules, the more energy the electron gains during acceleration due to the surrounding electric field. However, if the molecules are

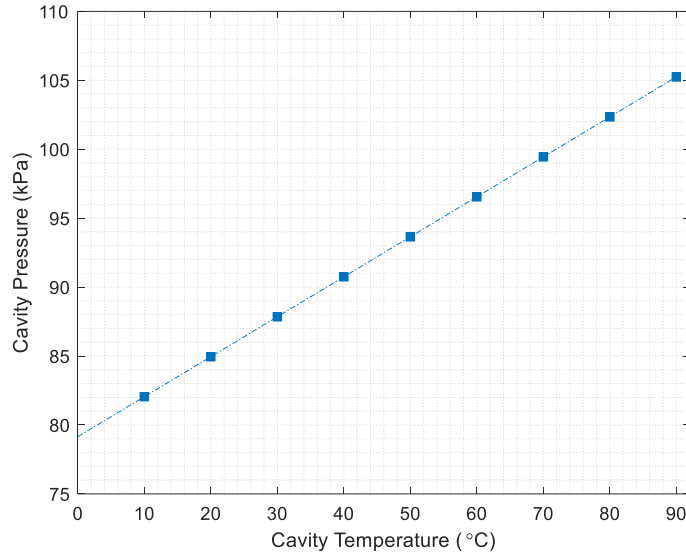


Figure 5.5: Simulated Cavity Pressure as a Function of Temperature

close to each other, the electrons will not gain enough energy to release an electron from the neutral molecule. The ionization of molecules is, therefore, greatly dependent on the mean free path. Thus, it can be reasoned that ionization by collision is more un-demanding in low-pressure environments than in high-pressure environments. Ionization by collision is the most prevalent ionization in gases, making the air breakdown mechanism largely dependent on gas pressure. According to the ideal gas law equation, assuming the cavity volume remains constant, the gas pressure is directly proportional to the cavity temperature.

$$\lambda \propto \frac{1}{p} \quad (5.2)$$

Thus, an increase in temperature increases the cavity pressure, impacting the mean free path and subsequently, the gas ionization process. Equation 5.2 illustrates the mathematical expression that governs the mean free-path. Where λ is the mean free path between the molecules and p is the gas pressure within a specific volume, the molecules are subjected to. Equation 5.2 demonstrates that the mean free path is inversely proportional to the cavity pressure. That is, the mean free path decreases with increased temperature. Consequently, reduced mean free path inhibits the ionization process owing to insufficient energy gained by electrons during the collision process. Because of this, substantially stronger electric fields must be present for the

breakdown to occur. For that reason, the partial discharge inception voltage increases with an increase in cavity pressure. Assuming that the cavities in the present work are largely unvented, the phenomenon explains the response of the measured and modelled PDIV with an increase in temperature from ambient to 90°C.

5.2 The Influence of Temperature on PD Charge Magnitude

5.2.1 Measurements and Observations

Table 5.3 shows the results of the measured PD Charge magnitude at different temperatures for a polyethene dielectric having a cavity with a diameter of 2.5 mm under a voltage stress of 11 kV 50 Hz AC. The dielectric had a thickness of 4.5 mm. Each data point displayed on the PD charge magnitude is an average value from the data points that were recorded during a period of 3000 cycles of the sinusoidal voltage waveform. The results show that the apparent PD charge magnitude initially decreased with temperature from 15°C to 60°C and then rose from 60°C to 90°C. It is worth highlighting that similar trends were observed in the other two test specimens.

Table 5.3: PD Charge Magnitude Experimental Results

Test Temperature	15°C	40°C	50°C	60°C	70°C	80°C	90°C
Sample 1 Mean PD Charge (pC)	115,6	92,2	74,4	69,1	77,3	81,0	96,4
Sample 2 Mean PD Charge (pC)	178,5	133,1	121,5	110,1	110,9	135,5	153,3
Sample 3 Mean PD Charge (pC)	113,2	75,2	65,0	52,1	60,8	86,2	95,9

It is interesting to note that, although the PD charge magnitude increased as the temperature rose from 60°C to 90°C, the observed apparent charge magnitude was less than that measured at ambient temperature (15°C). Further analysis shows that the apparent charge magnitude at 90°C is lower by approximately 16% compared to the apparent charge measured at ambient temperature. The plots of the measured PD charge magnitude for a range of material insulation temperatures are presented in Figures 5.6 and 5.7, respectively. The plots illustrate the apparent charge magnitude observed over the period of 3000 cycles.

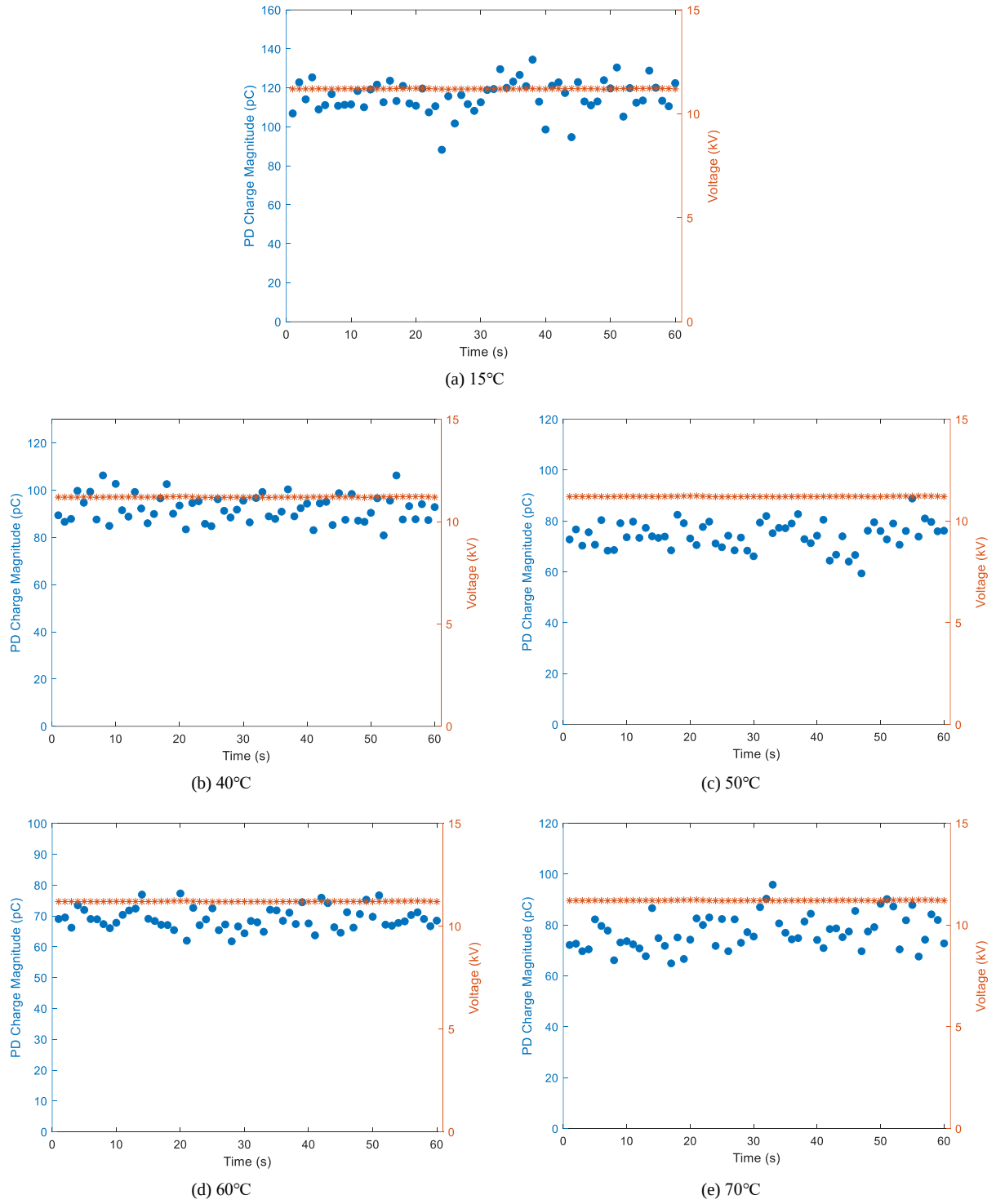


Figure 5.6: PD Charge Magnitude Measurements at temperatures 15°C to 70°C

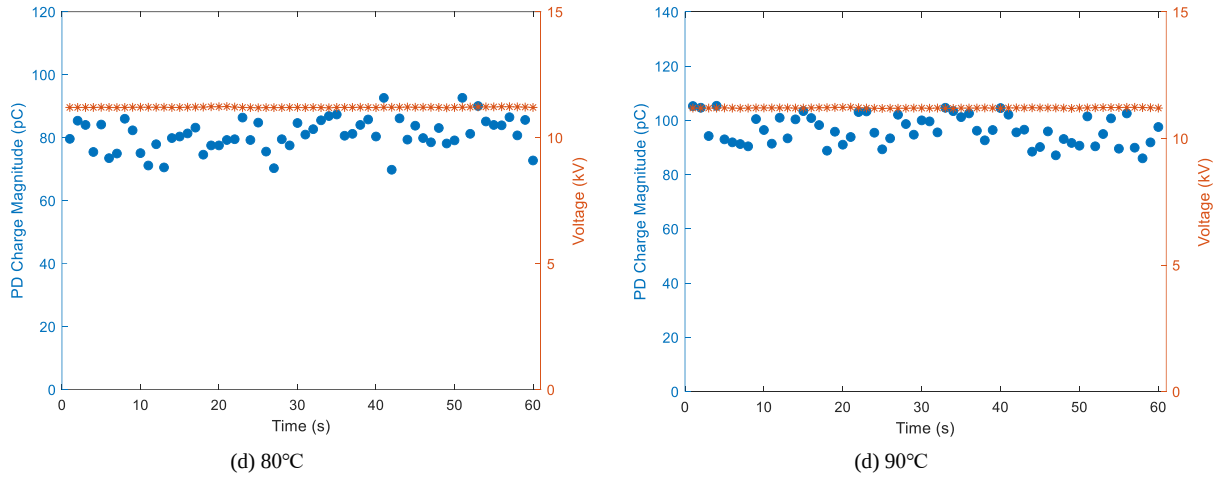
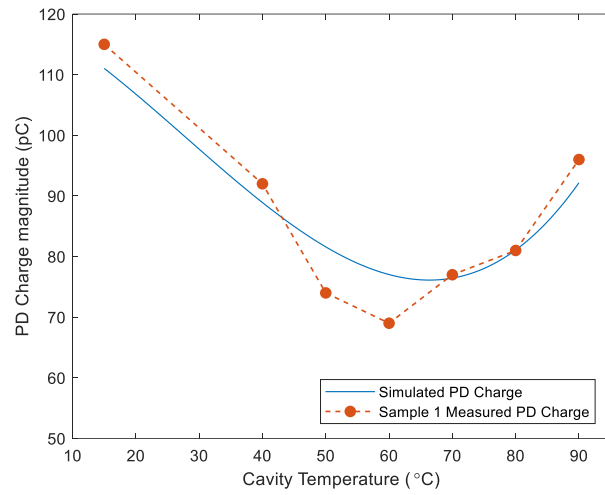


Figure 5.7: PD Charge Magnitude Measurements at temperatures 80°C to 90°C

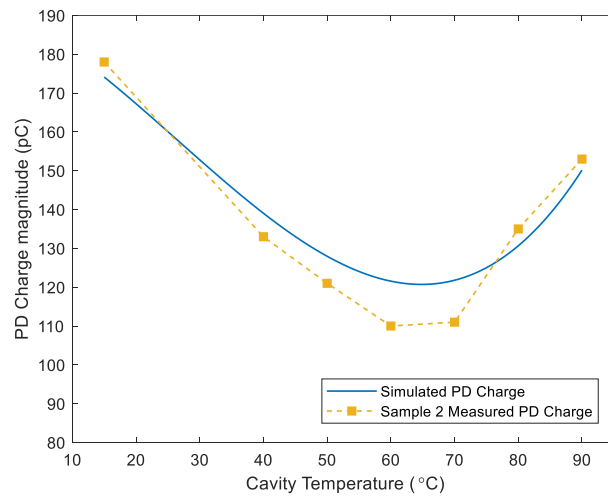
5.2.2 Comparison Between Simulation and Experimental Results of PD Magnitude Response to Temperature Variations.

Figure 5.8 presents both the measured values of PD charge magnitude as well as the simulation results that were derived from the PD charge analytical model discussed earlier in Chapter 4. Similar to the trend observed from the measured PD charge magnitude, the analytical model demonstrates that PD charge magnitude initially decreased with temperature from 15°C to 60°C and then increased from 60°C to 90°C. The approach employed in that regard is to ‘curve-fit’ the analytical model equation on the experimentally measured data, as presented in Figure 5.8. The theoretical trend is fitted to the measured data by adjusting the parameters representing the residual charge associated electric field, E_{res} . Where the residual charge electric field E_{res} is represented by $\gamma A \delta$. Since A and δ are constants, the parameter that is responsive to temperature is the free parameter γ .

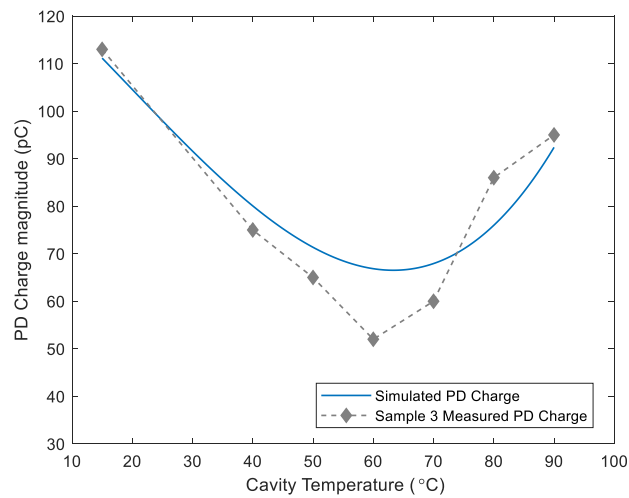
Although the induced charge theoretical model presented in Chapter 4 is commonly used to predict the PD apparent charge magnitude, its limitations and origins must be noted. The implementation of the induced charge model is based on the assumption that the PD activity affects the entire cavity volume. In reality, the discharge area might not be the entire cavity volume. Nevertheless, comparing the estimated PD charge magnitude with the experimental results, it can be deduced that the measured results agree with those obtained from the PD charge analytical model.



(a)



(b)



(c)

Figure 5.8: PD Charge Magnitude as a Function of Temperature (Simulation vs Measurement Results)

5.2.3 PD Apparent Charge Temperature Dependence Results Discussions

The observed apparent PD charge magnitude trends with varying temperatures are attributed to changes in the cavity surface conductivity and can be explained by the residual charge dynamics. Numerous investigations have demonstrated that the stochastic nature of PD mechanism is caused by the residual charges within the defect [36][37][49]. Even though all other experimental parameters can be fixed, residual charges influence PD characteristics by altering the electric field within the cavity as a result, PD parameters such as the statistical time lag, PDIV, PDPRP and the charge magnitude are influenced.

The role of cavity surface charges on the PD mechanism:

Figure 5.9 illustrates how the residual charge field E_{res} within the cavity influences the charge magnitude of the next PD activity by altering the electric field [50]. The residual electric field due to the positively charged particles is denoted by $E_{res (P)}$, while $E_{res (N)}$ denotes the residual electric field due to the negatively charged particles. The electric field due to the supply voltage is given as E_o , and it is also called the background electric field. The vector sum of the background field E_o and the residual charge field E_{res} gives the total electric field E_{net} within the cavity. In a case where $E_{net} \geq E_{inc}$, PD activity will occur, provided that there is a seed electron to initiate an avalanche process. In the next section, Figure 5.8 is explained chronologically in detail.

(a) At Position A: This is the zero crossing position where the supply voltage transitions from the negative to the positive half cycle. The background electric field E_o is zero at this position as the supply voltage is zero. Thus, the net electric field within the cavity is primarily due to the residual electric field owing to negative charge carriers, which is given by $E_{net} = E_{res (N)}$. PD activity will occur if $E_{net} \geq E_{inc}$ provided there is a seed electron to start an avalanche process. It is important to note that if there was no previous PD activity, it is unlikely that PD activity will occur at the zero crossing of the supply voltage.

(b) At Position B: This is the rising edge of the positive half cycle of the supply voltage. The net electric field within the cavity comprises of a background electric field E_o , the positive charge carriers electric field $E_{res (P)}$ and the negative charged electric field $E_{res (N)}$. The positive and

negative charge carriers electric fields are as a result of the previous PD activity. The net electric field within the cavity is then given by $E_{net} = (E_o + E_{res(N)}) - (E_{res(P)} \cdot E_{res(P)})$ decreases the electric field within the cavity, while $E_{res(N)}$ increases the electric field within the cavity. PD activity will occur if $E_{net} \geq E_{inc}$ provided there is a seed electron to start an avalanche process. It is worth noting that in some cases, there is a delay in the availability of a seed electron to initiate an avalanche process after the inception field has been exceeded. In that regard, an increased electric field results in much higher PD charge magnitudes. Research studies reported that the PD charge magnitudes observed at this position manifest as an overall shape resembling a rabbit ear. These are commonly referred to as the “rabbit ear” PDPRP characteristics.

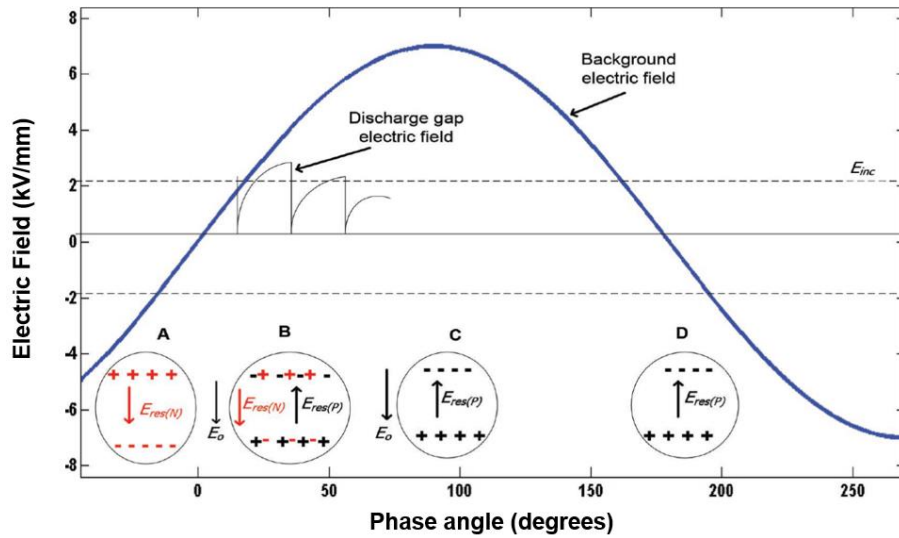


Figure 5.9: Illustration of residual charge effect on PD activity [50]

(c) At Position C: This is the falling edge of the positive half cycle of the supply voltage. The net electric field within the cavity comprises the background electric field E_o and the positive charge carriers electric field $E_{res(P)}$. The assumption is that the residual electric field due to the negative charge carriers has dissipated completely. Therefore, the net electric field within the cavity is then given by $E_{net} = E_o - E_{res(P)}$. PD activity will occur if $E_{net} \geq E_{inc}$ provided there is a seed electron to start an avalanche process. $E_{res(P)}$ decreases the electric field within the cavity, at the same time, the background field E_o is decreasing as the positive half cycle of the supply voltage is at the falling edge. Thus, PD activity with lower magnitudes is observed at this

position. Research studies have demonstrated that the PD charge magnitudes observed at this position are the body part of the “rabbit ear” PDPRP characteristics.

(d) At Position D: This is the zero crossing position where the supply voltage transitions from the positive to the negative half cycle. The background electric field E_o is zero at this position as the supply voltage is zero. Thus, the net electric field within the cavity is primarily due to the residual electric field owing to positive charge carriers, which is given by $E_{net} = E_{res} (P)$. PD activity will occur if $E_{net} \geq E_{inc}$ provided there is a seed electron to start an avalanche process. It is significant to note that if there was no previous PD activity, it is unlikely that PD activity will occur at the zero crossing of the supply voltage.

The previous section demonstrated that the residual charges deployed within the cavity greatly influence the PD characteristics. These charges produce a residual electric field, E_{res} , which has a finite life. The life of these residual charges is dependent on the surface conductivity of the cavity walls. In the next section, the role of surface conductivity on the life of residual electric field E_{res} is discussed in detail.

The role of surface conductivity on surface charges:

Several studies have shown that the charges deployed within the cavity during a PD event have a finite life. Cheng *et al.* [36] reported that these charge carriers decay through different mechanisms, such as charge neutralization, electric conduction through the dielectric volume and lastly, electric conduction along the cavity walls. The decay time of these charges is mainly controlled by the bulk surface conductivity of the cavity walls and it obeys equation 5.2 given below [36][51]. Where q_{so} represents the initial surface charge and τ is the time decay constant, which is given by $(a\epsilon_r\epsilon)/(2\gamma_s)$, where a is the radius of the cavity, ϵ_r is the relative permittivity of the insulation material, ϵ is the relative permittivity of free space and lastly, γ_s is the surface conductivity.

$$q_s = q_{so} \exp(-t/\tau) \quad (5.2)$$

Equation 5.1 above shows that the surface charges deployed in the cavity dissipate with time and by inspecting this equation, the parameter which varies with temperature is the surface conductivity. Liu *et al.* [51] reported an exponential increase in surface conductivity with the insulation temperature. The interpretation of the obtained results is that charges deployed on the void surface after a PD event greatly influence the discharge magnitude of the next PD by altering the electric field within the cavity. These residual charges have a finite life which is dependent on the cavity surface conductivity [16] [52].

From ambient temperature to 60°C, the analytical model shows that the conductivity of the cavity surface is such that the space charge decay time is much longer than the period of the applied electric field. As a result, the electric field due to the space charge reduces the total electric field within the cavity. Consequently, the PD charge magnitude decreases with temperature from ambient to 60°C. Beyond 60°C, the cavity surface conductivity increases, thereby causing the residual charge to disperse more quickly than at lower temperatures. In the simulation model, the decreasing E_{res} is represented by decreasing the free parameter γ . Consequently, the resultant apparent charge increases, as depicted in Figure 5.8.

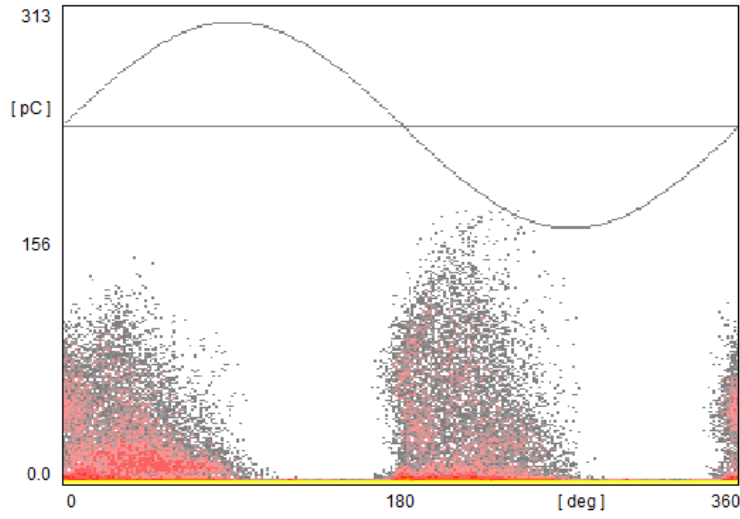
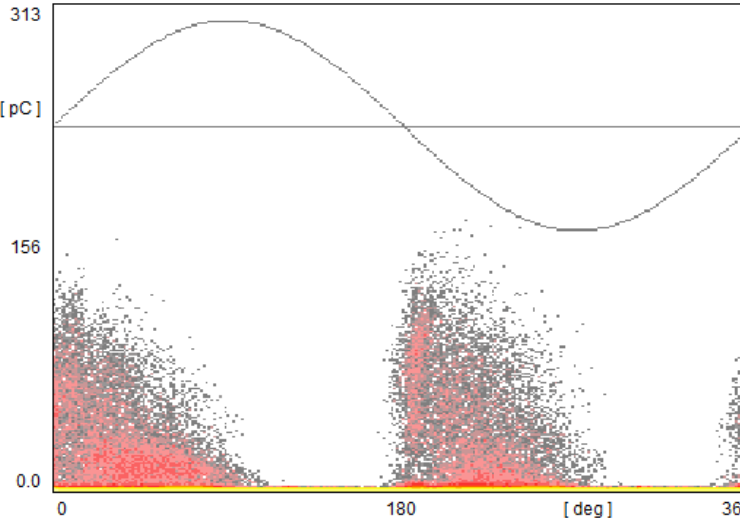
5.3 The Influence of Temperature on PDPRP of Cavity Discharges in Polyethylene

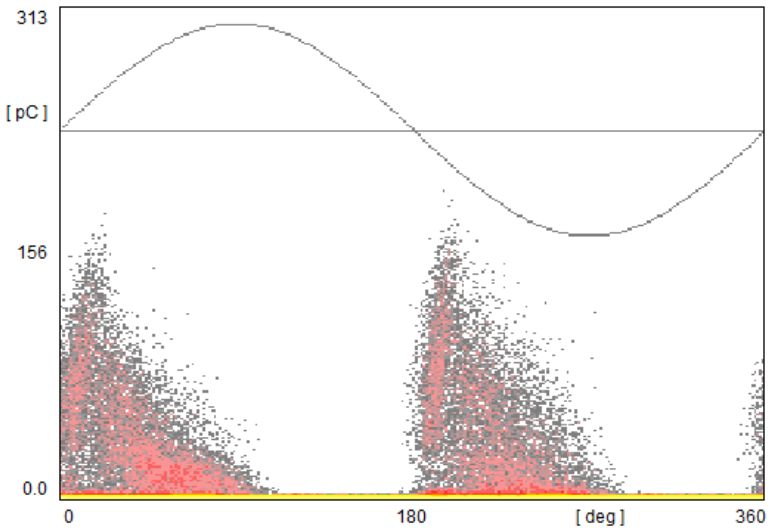
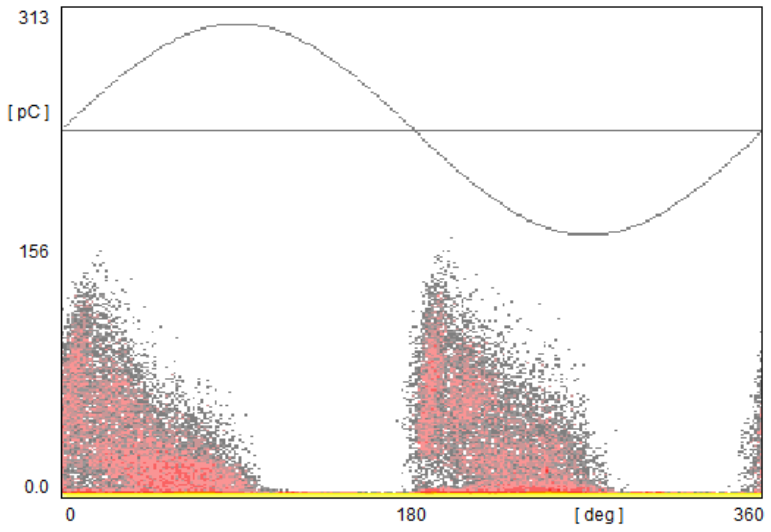
Table 5.4 shows the characteristics of PDPRP for a cavity partial discharge with varying temperatures. The results show that the PD phase-resolved patterns are generally symmetrical throughout the test temperature range. This observation confirms that the PD source or gas-filled cavity is positioned at the bulk insulation centre. Moreover, it can be seen that partial discharge pulses are generally clustered between 0° and 110° on the positive half cycle and between 170° and 300° on the negative half cycle of the supply voltage. This characteristic was evident throughout the entire test temperature range.

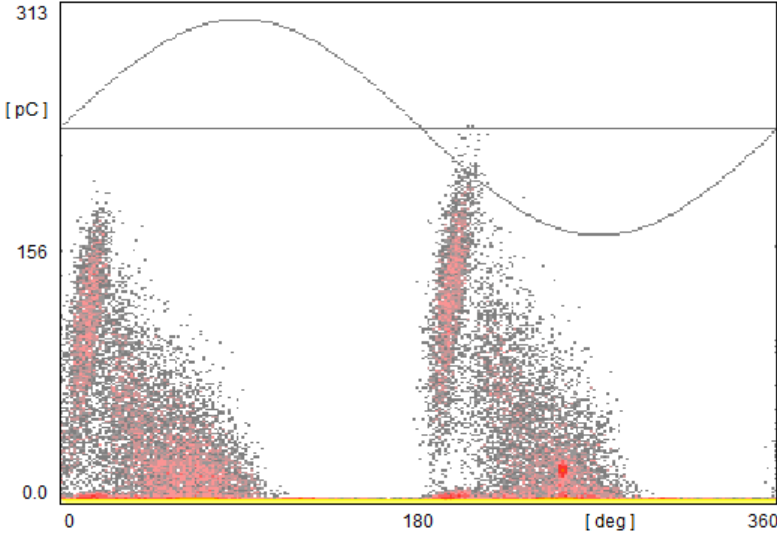
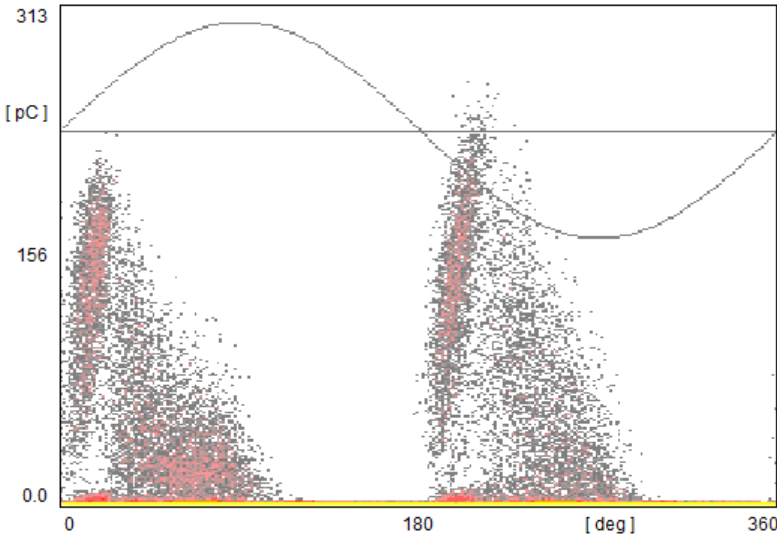
By inspecting the measured PD phase-resolved patterns with varying temperatures, it can be seen that at 15°C, turtle-like phase-resolved PD patterns were prevalent. Moreover, the discharge mechanism on the positive and negative half-cycle waveform initiates before the start of each half-cycle. The interpretation is that the presence of surface charges on the cavity walls creates

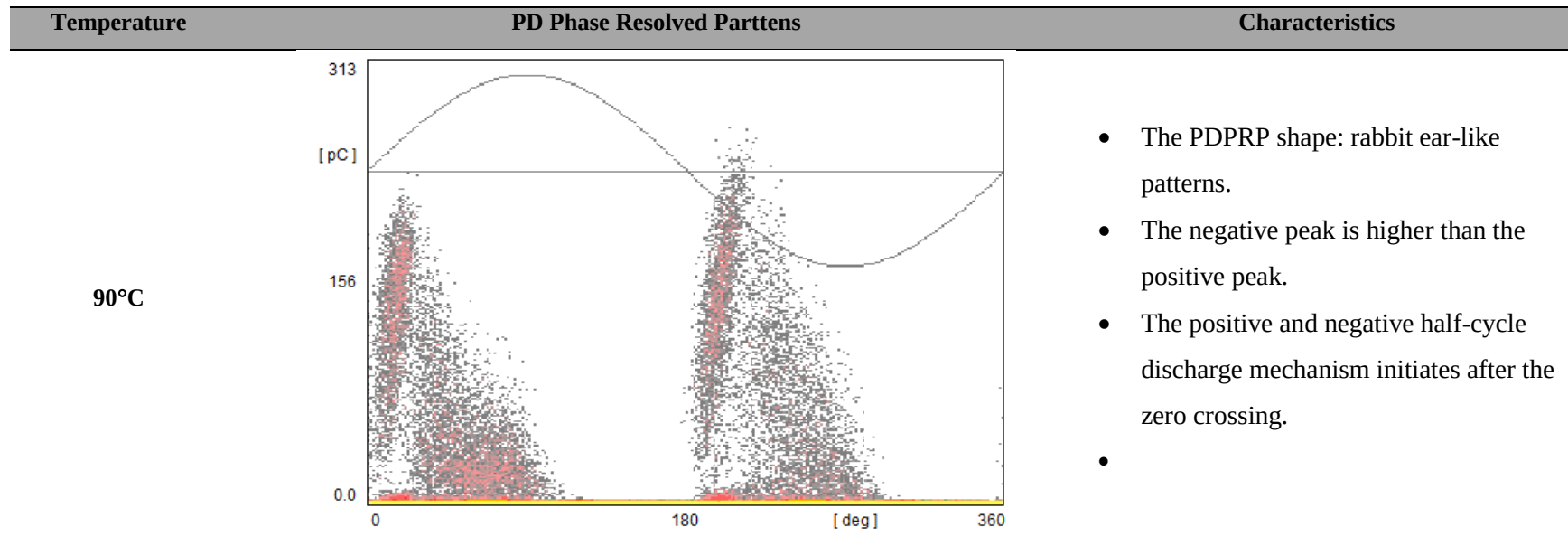
a favourable setting for PD activity. This is achieved by enhancing the electric field within the cavity and providing the seed electron required for an avalanche process. The turtle-like patterns then transitioned into a rabbit-like phase resolved patterns beyond 60°C up to 90°C. Additional observed PDPRP characteristics are highlighted in detail in Table 4.10. The transition from turtle-like to rabbit-ear is attributed to increased dynamics of the residual charge in each half-cycle period. At lower temperatures, there is a minimal change in E_{res} , while at higher temperatures, there is increased cavity surface conductivity. Therefore, increased variations of E_{res} during the half cycle and hence more bigger PDs in the rabbit ear followed by relatively more smaller PDs in the “rabbit body”.

Table 5.4: Evolution of PDPRP with Temperature increase

Temperature	PD Phase Resolved Parttens	Characteristics
15°C		• The PDPRP shape: Turtle-like partterns. • PDPRPs are generally symmetrical. • The negative peak is higher than the positive peak. • The discharge mechanism on the positive cycle of the waveform initiates before the start of the cycle.
40°C		• The PDPRP shape: Turtle-like partterns. • The negative peak is higher than the positive peak. • The discharge mechanism on the positive cycle of the waveform initiates before the start of the cycle.

Temperature	PD Phase Resolved Parttens	Characteristics
50°C		• The PDPRP shape: Turtle-like developing into rabbit ear-like patterns • The negative peak is higher than the positive peak. • The discharge mechanism on the positive cycle of the waveform initiates before the start of the cycle.
60°C		• The PDPRP shape: Turtle-like developing into rabbit ear-like patterns. • The negative peak is higher than the positive peak. • The discharge mechanism on the positive cycle of the waveform initiates before the start of the cycle.

Temperature	PD Phase Resolved Parttens	Characteristics
70°C		• The PDPRP shape: rabbit ear-like patterns. • The negative peak is higher than the positive peak. • The positive and negative half-cycle discharge mechanism initiates after the zero crossing. •
80°C		• The PDPRP shape: rabbit ear-like patterns. • The negative peak is higher than the positive peak. • The positive and negative half-cycle discharge mechanism initiates after the zero crossing.



5.4 Practical Equipment PD Diagnosis Implications of Temperature Dependence

Despite various interpretations of PD parameters as a function of temperature in polyethylene, the present study demonstrated that temperature significantly influences PD parameters. The possible practical implications of this knowledge in PD diagnostics practice for power cables is the possible misinterpretation of PD diagnostic information. As an example, for offline PD measurements, the loaded power cable will be switched off for PD measurements. However, the insulation temperature does not drop to the ambient temperature immediately. Due to operational restrictions and time constraints, allowing the power cable to cool down to ambient temperature is sometimes impossible before performing a maintenance test. Therefore, the possibility exists where PD measurements can be performed at different temperatures.

The possible practical implications of increased PD inception voltage with temperature on practical PD diagnosis is that when performing an offline PD test on a power cable that has just been switched off and the power cable has not cooled down to ambient temperature, the test voltage will have to be increased for PD to occur. In that case, a possibility exists for PD not to occur depending on the insulation temperature, even though the defect exists within the insulation. As for online PD monitoring, a possibility exists for PD activity to stop at higher equipment loading and higher temperature and ignition to occur if the power cable is lightly loaded.

Regarding PD charge magnitude, the non-monotonous behaviour of PD charge magnitude with temperature opens up the possibility of exempting the power cable to be PD-free erroneously. For example, the study reported a decrease in PD charge magnitude from 15°C to 60°C. If a pre-defined PD charge magnitude is set as a rule of thumb to either pass or fail the power cable, a possibility exists to pass a power cable erroneously at certain temperatures. It is therefore, essential for the engineers to be aware of the effect of temperature on PD parameters. With the growing interest in online PD monitoring, the knowledge of how PD parameters respond to temperature becomes valuable in interpreting PD diagnostic information. These findings imply that the correct interpretation of PD diagnostic information requires that the influence of dielectric temperature be considered.

6 Conclusions

In this research work, cavity partial discharges in polyethylene dielectric material as a function of temperature were examined from ambient temperature to 90°C. The study primarily focused on conventional partial discharge parameters such as PDIV, PDEV, PD charge magnitude and PD phase-resolved-patterns. The response of conventional partial discharge parameters with varying temperatures was observed and analysed experimentally. The theoretical model was used to validate the measured data and to gain insights into how surface conditions and dielectric properties influence PD characteristics under varying temperatures.

The results showed that PDIV increases linearly with temperature, which is attributed to an increase in cavity pressure with temperature. An increase in temperature increases the cavity pressure, impacting the mean free path and, subsequently, the gas ionization process, i.e. the mean free path decreases with increased temperature. Consequently, a reduced mean free path inhibits the ionization process owing to insufficient energy gained by electrons during the collision process. Because of this, substantially stronger electric fields must be present for the breakdown to occur. For that reason, the partial discharge inception voltage increases with increase in cavity pressure caused by increased temperature.

Regarding PD charge magnitude, the results show that the charge magnitude initially decreased in the temperature range of 15°C to 60°C and then increased from 60°C to 90°C. PD charge magnitude response to varying temperatures is attributed to changes in the cavity surface conductivity in polyethylene in stages as summarised below.

From 15°C to 60°C:

The surface charge decay time is relatively longer, such that the resultant charge magnitude is reduced and the corresponding PDPRP are predominantly turtle-like.

From 60°C to 90°C:

The life of the surface charges is relatively shorter and as a result, the PD charge magnitude is increased. The corresponding PDPRP are predominantly rabbit-ear.

This dissertation answered the research question as follows;

How and why do cavity partial discharge characteristics respond to variations in the temperature of the polyethylene solid insulation?

The overall conclusion is that in polyethylene, cavity discharge characteristics respond to temperature changes. The variations in PD characteristics are monotonous for PDIV and non-monotonous for apparent charge magnitude as well as PDPRP. The cavity pressure and the surface conductivity are the significant factors responsible for PD characteristics with temperature variations. These findings imply that in practice correct interpretation of PD diagnostic information requires that the influence of dielectric temperature be taken into account.

Recommended Future Work

The future extension of this research work will be considering simulations using other modelling approaches to gain more insights into how residual charges and electron generation rate respond to temperature variations, thereby affecting PD characteristics.

Appendix A: The Heat Transfer Model

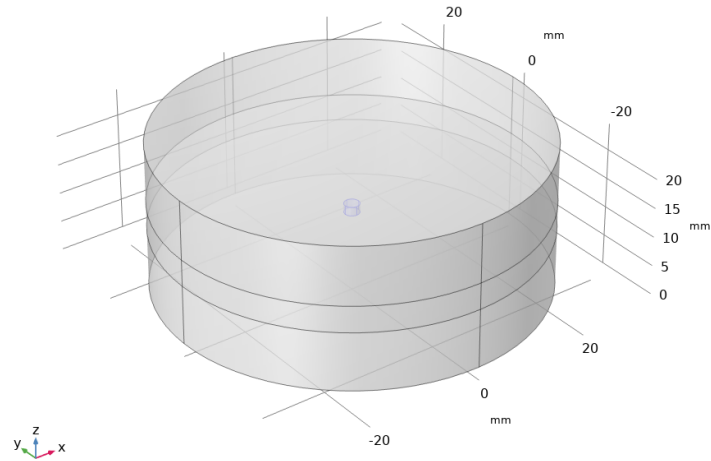
A.1 Heating Cycle Experiment

In this experiment, the heating cycle setup was required to adjust the cavity temperature to the desired test temperature. To raise the temperature, a heat source with a thermostat was employed. Temperatures for the tests were set at 15, 40, 50, 60, 70, 80, and 90 degrees Celsius. A metallic oil bath chamber, a heat source, a temperature control mechanism, and a temperature-measuring sensor were all part of the system. The temperature of the cavity was raised by heating the oil bath to the desired degree and causing the oil to circulate in order to transfer heat to the test specimen.

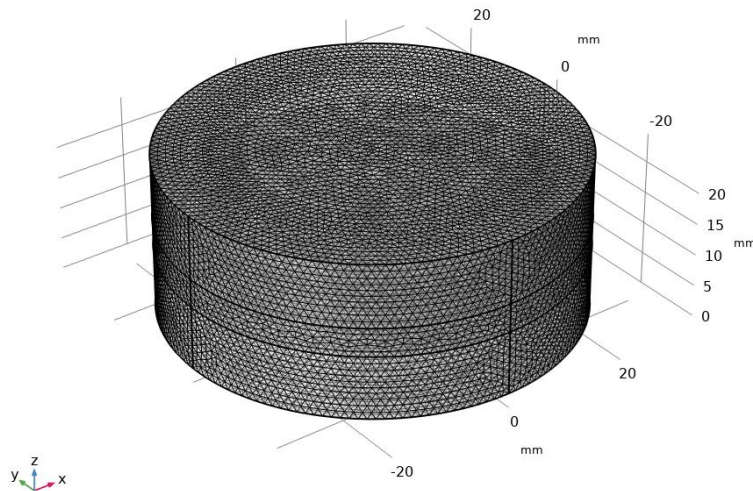
It is worth mentioning that the measurement of the cavity temperature was difficult since it was impossible to directly place the temperature sensor within the encapsulated air cavity. Nonetheless, the temperature sensor was placed next to the bulk insulation material to monitor the temperature. As a result, it was then necessary to estimate the time required for the temperature of the test specimen to be uniform and, most importantly, the time taken for the air cavity to reach the desired test temperature, referred to as the settling time. The settling time was evaluated using the COMSOLTM Multiphysics software heat transfer model. In the sections that follow, the COMSOLTM Multiphysics heat transfer model and simulation results are described in detail.

A.2 COMSOL Heat Transfer Model Geometry

The heat transfer in solids and fluids physics interface was used in the time-dependent domain to study the heat transfer through conduction from the external environment to the cavity. The model geometry is tailored to the experimental arrangements, and it is constructed with a three-dimensional (3D) coordinate system, as illustrated in Figure A1 (a). The model is made up of a homogeneous dielectric material that has a thickness of 4.5 mm and a diameter of 62 mm. It also includes an encapsulated air cavity that has a diameter of 2.5 mm. The dielectric material is bounded by two brass electrodes. Table A1 shows the material properties that were used to define each model domain. The mesh parameter was set to extremely fine meshing, yielding a sample geometry with 678192 elements in the mesh and 117344 degrees of freedom. The meshed geometry model is depicted in Figure A1 (b).



(a)



(b)

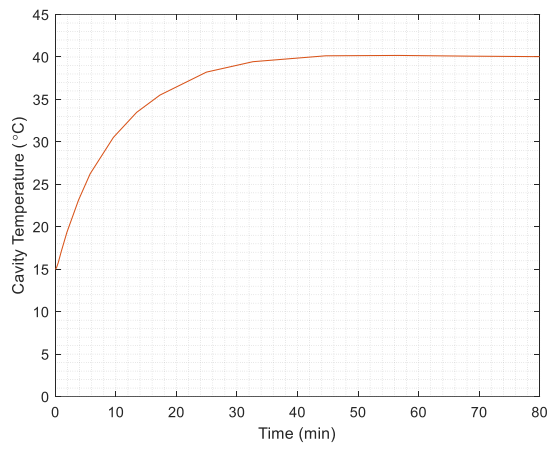
Figure A1: Cavity Temperature Settling Time Model

In addition to the parameters that are noted in Table A1 below, the model requires several other parameters in order to acquire the solution from COMSOLTM Multiphysics. These additional parameters include the domain initial values and the heat flux. The domain initial values define the initial temperature, while the heat flux represents the heat source of the model. All the heat flux boundaries were modelled using the convective heat flux.

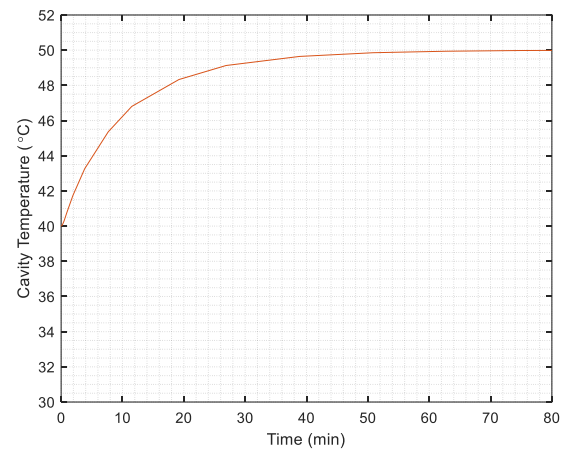
TableA1: The Heat Model Parameters

Parameter	Symbol	Value	Unit
Specific Heat Capacity (PE)	C_p	1900	J/(kg.K)
Thermal Conductivity (PE)	K	0.38	W/(m.K)
Density (PE)	ρ	930	Kg/m ³
Heat Transfer Coefficient	h	0.38	W/(m ² .K)
Specific Gas Constant (Air)	R_s	287	J/(kg.K)
Thermal Conductivity (Air)	K	0.025	W/(m.K)
Specific Heat Capacity (Air)	C_p	1005	J/(kg.K)
Specific Heat Capacity	C_p	920	J/(kg.K)
Thermal Conductivity	K	109	W/(m.K)
Density	ρ	8700	Kg/m ³
Heat Transfer Coefficient	h	100	W/(m ² .K)

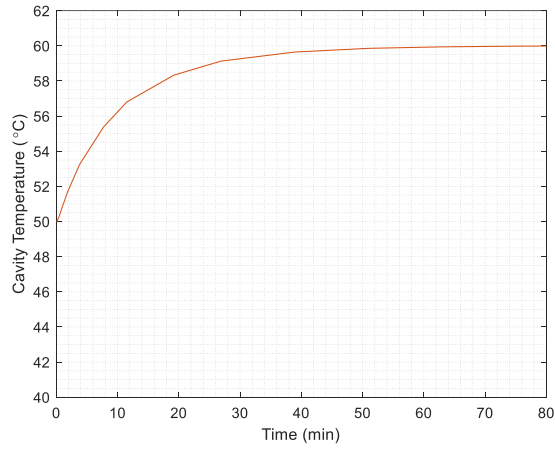
A.3 The Simulation Results



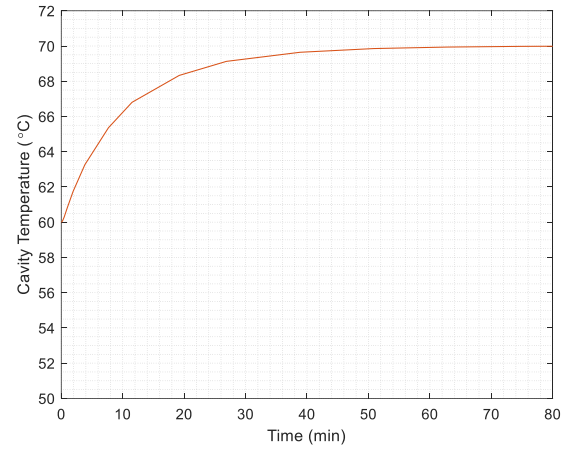
(a)



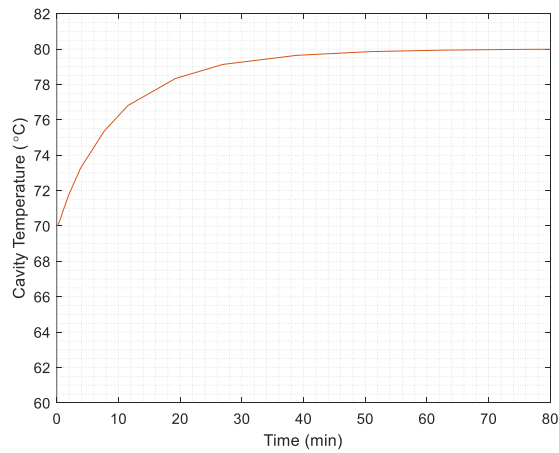
(b)



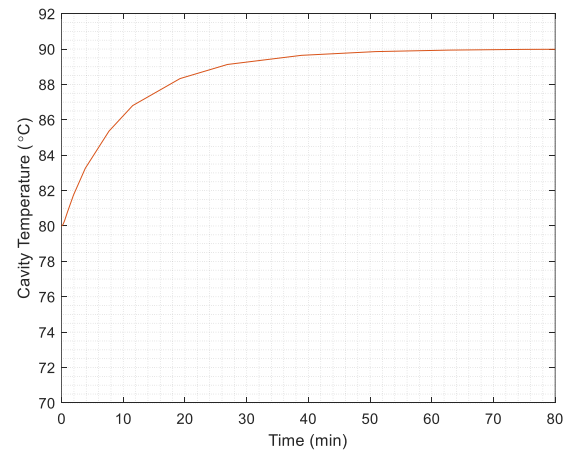
(c)



(d)



(e)



(f)

Figure A2: Cavity Temperature Settling Time Simulation Results

Appendix B: Determination of Inception Voltage

Paschen's law is traditionally used to estimate the gaseous insulation medium breakdown voltage between two electrodes. The law states that the breakdown or sparking voltage is a function of the electrode distance (d) and gas pressure (p) product [53][54][55]. The law reflects the Townsend breakdown mechanism in gases, namely, an avalanche of electrons emitted by collisions within the gap and secondary electrons extracted from the cathode by ionic bombardment. The product (pd) measures the number of collisions an electron experiences while crossing the air gap in the electric field direction.

$$V_{spark} = \frac{Bpd}{\ln(Apd) + \ln[\ln(1+1/\gamma)]} \quad (B.1)$$

Equation B1 shows an analytical expression to estimate breakdown or sparking voltage for a uniform field air gap [56][57]. Where A and B are gas-dependent constants, p is the gas pressure between the electrodes, γ is Townsend's second ionization coefficient and d is the air gap distance. The gas dependent constants have the following values, A is $365 \text{ V.torr}^{-1}.\text{cm}^{-1}$, γ for copper electrodes is 0.025 and B is 14.6.

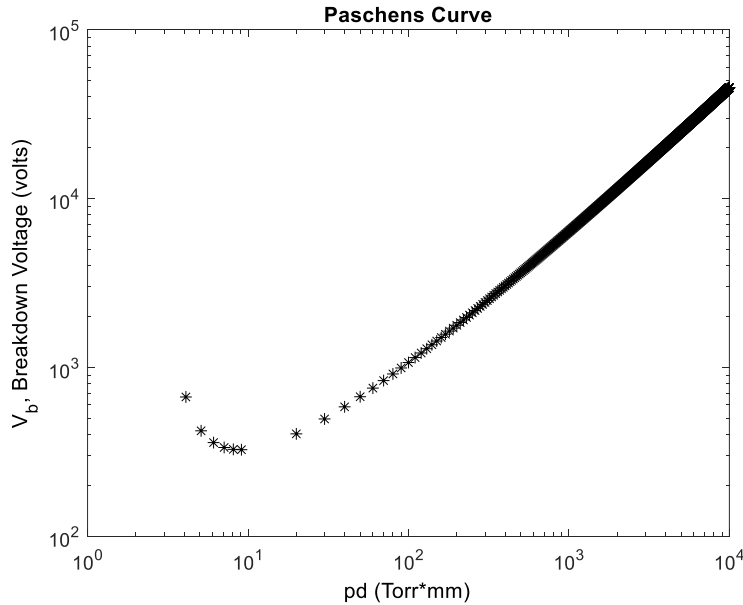


Figure B.1: Paschen Law Curve

Figure .B.1 above shows the relationship between the breakdown voltage (V_b) and the product (pd). It is worth noting that for any gaseous insulating material, there exists a unique minimum breakdown voltage (V_b) $_{min}$ at a particular product value of (pd) $_{min}$. The composite dielectric system under study comprises three insulation medium layers. The first and third layers are free from defects, while the middle layer consists of an artificial void. The dielectric constant or relative permittivity of polyethylene material is much higher than that of the air; under applied voltage, the electric field stress is much higher in the void than in the polyethylene insulation. Therefore, partial discharge occurs at voltages much lower than the breakdown voltage of the composite system. The voltage applied across the electrodes of the composite dielectric system to initiate partial discharge activity inside the void is called partial discharge inception voltage and is given by equation B 2 below.

$$V_s = E_g \left[d_1/\epsilon_r + d_g + d_2/\epsilon_r \right] \quad (B.2)$$

Where V_s is the applied voltage across the electrodes, E_g is the breakdown electric field inside the cavity, d_1 is the thickness of the first layer, d_2 is the thickness of the third layer, d_g is the thickness of the third layer, and ϵ_r is the relative permittivity of polyethylene insulation material. Studies by Yousfi *et al.* [58] on simulation of partial discharges initiation in voids in medium voltage cables insulators indicated that for the application of Paschen's Law on composite dielectric with air-filled cavities, it is imperative to consider the difference in the nature of electrodes used for both systems.

The studies postulated that the difference in electrode characteristics influences minimum coordinate parameters, namely V_{spark} (min) and (pd) min, attributed to difficulties of extracting electrons from solid dielectric compared to copper electrodes. The Paschen curve for a composite dielectric system under study is shown in Figure B.2 above. The curve is derived using equations B.1 and B.2 at a pressure of 83.5 kPa (626.3 torrs). The product pd for a gap distance of 1.5mm is given as 940 torrs.mm as indicated from the above figure and provides the inception voltage of 10.8 kV. Thus, the rms breakdown voltage is 6.24 kVrms.

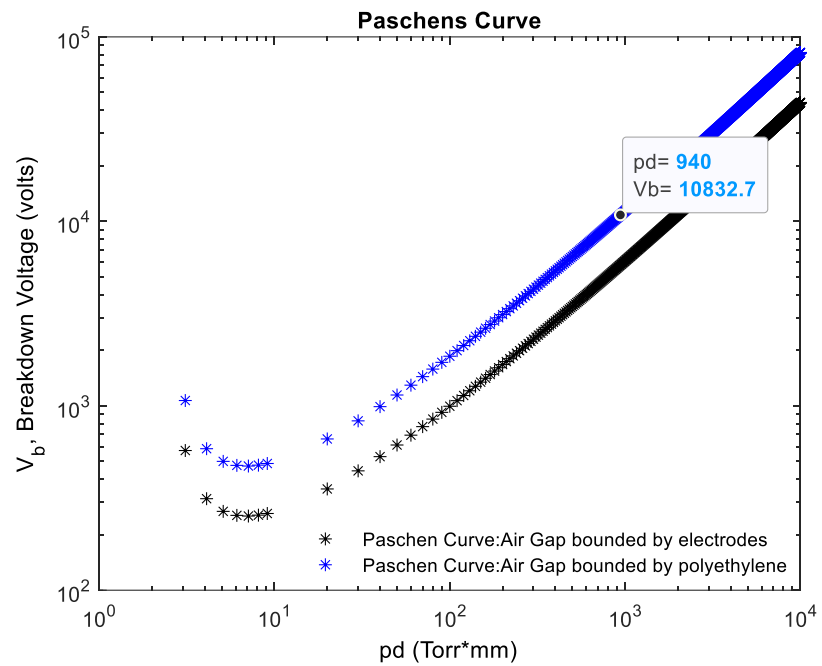


Figure B.2: Paschen Law Curve for Cavity Bounded with Polyethylene

Appendix C: Electric Field Simulations

This section describes the simulation model used to study the electric field profile. The COMSOLTM Multiphysics software was used to observe the electric field profile. The model geometry was tailored to the experimental arrangements, and it was constructed as an asymmetrical two-dimensional (2D) coordinate system, as illustrated in Figure C1. The model is made up of a homogeneous dielectric material (polyethylene) with a thickness of 4.5 mm and a diameter of 62 mm. The model also includes an encapsulated air cavity that has a diameter of 2.5 mm. The mesh parameter was set to extremely fine meshing, yielding 7536 degrees of freedom. The meshed geometry model is depicted in Figure C2.

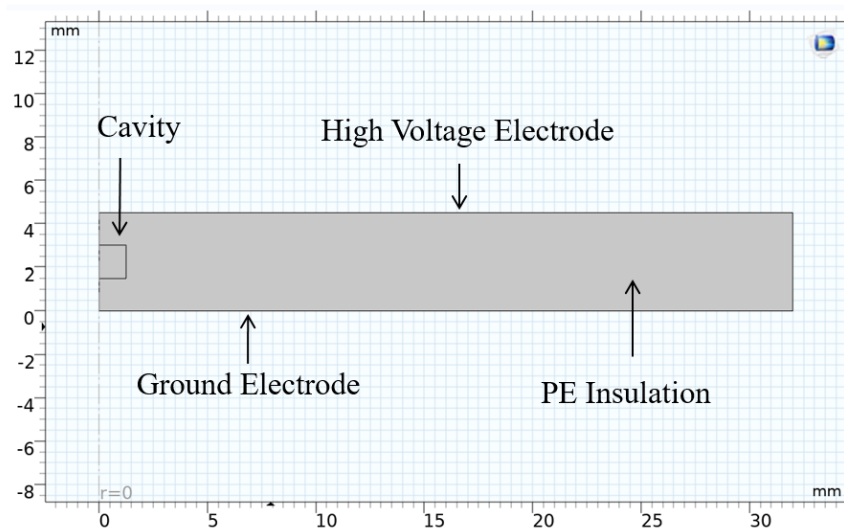


Figure C1: 2D asymmetric model geometry

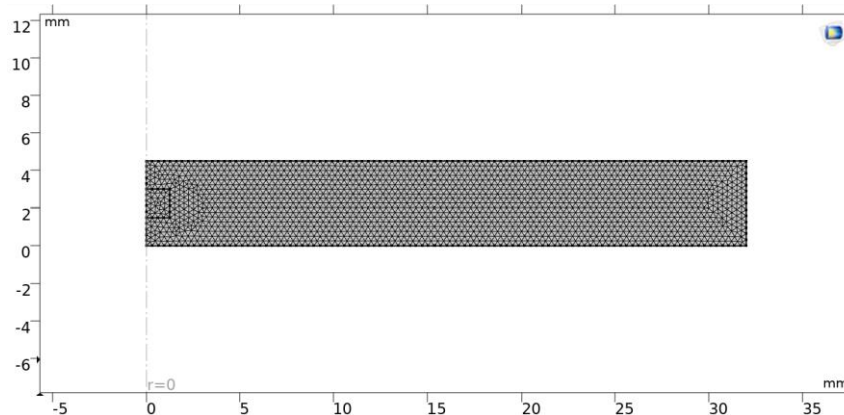


Figure C2: 2D asymmetric model geometry mesh

Appendix D: Matlab Code

D.1 PD Inception Voltage Estimation

```
%% .....  
  
                Determination of PD Inception voltage  
  
%% .....  
clc;  
clear;  
close all;  
  
%% Input Parameters  
A=24.2;          % Gas Constant (V/Pa.m)  
B=8.6;           % Gas Constant (Pa1/2.m1/2)  
P=83500;         % Initial Cavity Pressure (Pa)  
dg=1.5;          % Cavity Height (mm)  
d1=1.5;          % The Height of Polyethylene Layer (mm)  
d2=1.5;          % The Height of Polyethylene Layer (mm)  
a=0.00125;       % Cavity Radius (m)  
b=0.0015;        % Cavity Height (m)  
e1=2.3;          % Relative Permittivity of Polyethylene  
e2=1.0;          % Relative Permittivity of air  
t1=15;           % Test Temperature 1 (°C)  
t2=40;           % Test Temperature 2 (°C)  
t3=50;           % Test Temperature 3 (°C)  
t4=60;           % Test Temperature 4 (°C)  
t5=70;           % Test Temperature 5 (°C)  
t6=80;           % Test Temperature 6 (°C)  
t7=90;           % Test Temperature 7 (°C)  
  
%% Inception Voltage at 15 degrees Celsius  
Einception_15=(A*P)*(1+(B/(sqrt(P*(a+b)))))/(1e+6);  
k=(e2/e1)*(d1)+(e2/e2)*(dg)+(e2/e1)*(d2);  
Vinception_15=((Einception_15)*(k))/(sqrt(2))  
%% Inception Voltage at 40 degrees Celsius  
  
P_1=((273+t2)/(273+t1))*(P);  
Einception_40=(A*P_1)*(1+(B/(sqrt(P_1*(a+b)))))/(1e+6);  
Vinception_40=((Einception_40)*(k))/(sqrt(2))  
  
%% Inception Voltage at 50 degrees Celsius  
P_2=((273+t3)/(273+t2))*(P_1);  
Einception_50=(A*P_2)*(1+(B/(sqrt(P_2*(a+b)))))/(1e+6);  
Vinception_50=((Einception_50)*(k))/(sqrt(2))  
  
%% Inception Voltage at 60 degrees Celsius  
P_3=((273+t4)/(273+t3))*(P_2);
```

```

Einception_60=(A*P_3)*(1+(B/(sqrt(P_3*(a+b)))))/(1e+6);
Vinception_60=((Einception_60)*(k))/(sqrt(2))

%% Inception Voltage at 70 degrees Celsius
P_4=((273+t5)/(273+t4))*(P_3);
Einception_70=(A*P_4)*(1+(B/(sqrt(P_4*(a+b)))))/(1e+6);
Vinception_70=((Einception_70)*(k))/(sqrt(2))

%% Inception Voltage at 80 degrees Celsius
P_5=((273+t6)/(273+t5))*(P_4);
Einception_80=(A*P_5)*(1+(B/(sqrt(P_5*(a+b)))))/(1e+6);
Vinception_80=((Einception_80)*(k))/(sqrt(2))

%% Inception Voltage at 90 degrees Celsius
P_6=((273+t7)/(273+t6))*(P_5);
Einception_90=(A*P_6)*(1+(B/(sqrt(P_6*(a+b)))))/(1e+6);
Vinception_90=((Einception_90)*(k))/(sqrt(2))

%% Plot PDIV vs Temperature
PDIV=[Vinception_15;Vinception_40;Vinception_50;Vinception_60;Vinception_70;Vinception_80;Vinception_90];
x=[t1;t2;t3;t4;t5;t6;t7];
plot(x,PDIV);
xlim([10 100]);
ylim([5.5 8.0]);
xlabel('Temperature (\circC)');
ylabel('PDIV (kV)');
colordef white;

```

D.2 PD Apparent Charge Magnitude Estimation

```

%%.....

                Determination of PD Charge Magnitude

%%.....

clc;
clear;
close all;
clear all;
%% Input Parameters
e0=8.85e-12;           % Relative Permittivity of free space
er=2.3;                % Relative Permittivity of polyethylene
a=0.00125;             % Cavity Radius (m)
b=0.0015;              % Cavity Height (m)
A=25.2;                % Gas Constant (V/Pa.m)
B=8.6;                 % Gas Constant (Pa1/2.m1/2)
P=83499.8;             % Cavity Initial Pressure (Pa)
d1=0.0015;             % The Height of Polyethylene Layer (m)

```

```

t1=15; % Test Temperature 1 (°C)
t2=40; % Test Temperature 2 (°C)
t3=50; % Test Temperature 3 (°C)
t4=60; % Test Temperature 4 (°C)
t5=70; % Test Temperature 5 (°C)
t6=80; % Test Temperature 6 (°C)
t7=90; % Test Temperature 7 (°C)
%% Calculate Charge Magnitude at 15 degrees Celsius
q_measured15= 115;
gamma_15 = 0;
q_15 = 0;
while abs(q_measured15+q_15) > 0.05
    gamma_15 = gamma_15+0.02;
    Einc_15=(A*P)*(1+(B/(sqrt(P*(a+b)))));
    Eres_15=gamma_15*A*P;
    q_15=((e0*er*a.^2*b*pi*(Einc_15-Eres_15))/(d1))*(1e12);
    if q_15 < q_measured15
        break
    end
end
%% Calculate Charge Magnitude at 40 degrees Celsius
q_measured40= 92;
gamma_40 = 0;
q_40 = 0;
while abs(q_measured40+q_40) > 0.05
    gamma_40 = gamma_40+0.02;
    P_1=((273+t2)/(273+t1))*(P);
    Einc_40=(A*P_1)*(1+(B/(sqrt(P_1*(a+b)))));
    Eres_40=gamma_40*A*P_1;
    q_40=((e0*er*a.^2*b*pi*(Einc_40-Eres_40))/(d1))*(1e12);
    if q_40 < q_measured40
        break
    end
end
%% Calculate Charge Magnitude at 50 degrees Celsius
q_measured50= 74;
gamma_50 = 0;
q_50 = 0;
while abs(q_measured50+q_50) > 0.05
    gamma_50 = gamma_50+0.02;
    P_2=((273+t3)/(273+t2))*(P_1);
    Einc_50=(A*P_2)*(1+(B/(sqrt(P_2*(a+b)))));
    Eres_50=gamma_50*A*P_2;
    q_50=((e0*er*a.^2*b*pi*(Einc_50-Eres_50))/(d1))*(1e12);
    if q_50 < q_measured50
        break
    end
end
%% Calculate Charge Magnitude at 60 degrees Celsius
q_measured60= 69;

```

```

gamma_60 = 0;
q_60 = 0;
while abs(q_measured60+q_60) > 0.05
    gamma_60 = gamma_60+0.02;
    P_3=((273+t4)/(273+t3))*(P_2);
    Einc_60=(A*P_3)*(1+(B/(sqrt(P_3*(a+b)))));
    Eres_60=gamma_60*A*P_3;
    q_60=((e0*er*a.^2*b*pi*(Einc_60-Eres_60))/(d1))*(1e12);
    if q_60 < q_measured60
        break
    end
end
%% Calculate Charge Magnitude at 70 degrees Celsius
q_measured70= 77;
gamma_70 = 0;
q_70 = 0;
while abs(q_measured70+q_70) > 0.05
    gamma_70 = gamma_70+0.02;
    P_4=((273+t5)/(273+t4))*(P_3);
    Einc_70=(A*P_4)*(1+(B/(sqrt(P_4*(a+b)))));
    Eres_70=gamma_70*A*P_4;
    q_70=((e0*er*a.^2*b*pi*(Einc_70-Eres_70))/(d1))*(1e12);
    if q_70 < q_measured70
        break
    end
end
%% Calculate Charge Magnitude at 80 degrees Celsius
q_measured80= 81;
gamma_80 = 0;
q_80 = 0;
while abs(q_measured80+q_80) > 0.05
    gamma_80 = gamma_80+0.02;
    P_5=((273+t6)/(273+t5))*(P_4);
    Einc_80=(A*P_5)*(1+(B/(sqrt(P_5*(a+b)))));
    Eres_80=gamma_80*A*P_5;
    q_80=((e0*er*a.^2*b*pi*(Einc_80-Eres_80))/(d1))*(1e12);
    if q_80 < q_measured80
        break
    end
end
%% Calculate Charge Magnitude at 90 degrees Celsius
q_measured90= 96;
gamma_90 = 0;
q_90 = 0;
while abs(q_measured90+q_90) > 0.05
    gamma_90 = gamma_90+0.02;
    P_6=((273+t7)/(273+t6))*(P_5);
    Einc_90=(A*P_6)*(1+(B/(sqrt(P_6*(a+b)))));
    Eres_90=gamma_90*A*P_6;
    q_90=((e0*er*a.^2*b*pi*(Einc_90-Eres_90))/(d1))*(1e12);
    if q_90 < q_measured90
        break
    end
end

```

```

    end
end
%% Plot PD charge Magnitude vs Temperature
PD_Charge=[q_15;q_40;q_50;q_60;q_70;q_80;q_90];
x=[t1;t2;t3;t4;t5;t6;t7];
PD_Chargei = smooth(PD_Charge);
PD = fit(x,PD_Chargei,'poly3','Normalize','on');
plot (PD);
xlim([10 100]);
ylim([50 120]);
xlabel('Cavity Temperature (\circ C)');
ylabel('PD Charge magnitude (pC)');
colordef white;
hold on;
PD_Measured=[q_measured15;q_measured40;q_measured50;q_measured60;
q_measured70;q_measured80;q_measured90];
plot (x,PD_Measured);

```

Appendix E: Publication

This appendix contains the conference paper presented at the International Symposium on High Voltage Engineering (ISH2023), Glasgow, UK, 27 August to 01 September 2023

O5.1.05 A STUDY OF THE EFFECT OF TEMPERATURE ON CAVITY PARTIAL DISCHARGES IN POLYETHYLENE INSULATION

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Abstract

This paper examines cavity partial discharge (PD) mechanisms in polyethylene insulation material as a function of temperature. Experimental PD measurements were carried out in accordance with the IEC 60270 standard. A test voltage of 11 kV ac and frequency of 50 Hz was used. The test temperatures studied were 15°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C. Test specimens with a cavity diameter of 2.5 mm were assembled using three 1.5 mm thick polyethylene sheets sandwiched between two flat brass electrodes. Partial discharge parameters such as the charge magnitude, inception voltage and PD phase resolved pattern (PDPRP) were measured and analysed at varying temperatures. Results showed that Partial Discharge Inception Voltage (PDIV) increased linearly with temperature for the entire test range. PD charge magnitude initially decreased with temperature from 15°C to 60°C and then increased from 60°C to 90°C. The evolution of PDPRP with temperature was characterised by a turtle-like pattern at ambient temperature, which transitioned into a rabbit ear PDPRP as the temperature increased to 90°C. The findings are interpreted using the mean free path effect on ionisation probability as well as the residual charge dynamics in the cavity as a function of temperature.

1 Introduction

Synthetic polymers such as polyethylene are commonly used as insulation in electrical equipment because of their remarkable insulating and dielectric properties [1]. However, it has been reported that the insulation medium is the weakest link for high and medium voltage electrical equipment [2]. Insulation degradation mechanisms are usually driven by various operational stresses. Partial Discharge (PD) activity is among the dominant mode of failure of solid polymeric insulation. Studies have shown that PD activity is a complex mechanism due to its non-stationary behaviour and multi-factor dependence. PD is a precursor to insulation degradation leading to premature failure of electrical equipment. Studies in partial discharge mechanisms have received significant attention over the years in the quest to improve the physical understanding and, ultimately, to allow conclusions to be drawn on the parameters affecting PD mechanisms. These studies have shown that different mechanisms and parameters influence partial discharge activity. In particular, the IEEE standard 400.3 of 2006 [3] states that, amongst other factors, environmental conditions such as temperature affects partial discharge phenomena. Despite significant work in this research area, there are still contradictory opinions on the influence of temperature on PD parameters. Although the effect of temperature on PD charge magnitude has received substantial attention in the past, various interpretations have been presented by researchers. As an example, researchers reported an increasing PD magnitude with temperature [4], [5][6][7], decreasing trend [8], a slight increase [9] and a slight decrease [10]. Florkowska [6] attributed an increase in PD

magnitude with temperature to changes in the electrical properties of the insulation medium at higher temperatures. Vibhakar and Kanitkar [11] postulated rapid structural changes in the cavity defect itself at higher temperatures.

Although the variation of PD Inception Voltage (PDIV) with temperature has received limited attention, the literature has reported an increase in PDIV with temperature [4]. The studies attributed this trend to changes in cavity pressure with temperature. Similarly, Haghjoo *et al.* [8] and Mariut [12] observed the same trends despite conducting studies on XLPE insulation material different from that by Illias [4]. In contrast, experimental studies by Saadati *et al.* [13] on the temperature dependence of PD under ac stress and combined ac/dc field stress observed a decrease in PDIV with an increase in temperature. The studies suggested that at elevated temperatures, the probability of having a seed electron to initiate the avalanche process is high therefore reducing PDIV. From these studies, it is evident that the influence of temperature on the physical processes before, during and after a discharge activity is still not fully understood. Some researchers have closely correlated the simulation models with the experimental measurements. However, it is notable that many free parameters, such as the material work function, surface conductivity, cavity gas pressure, relative permittivity, rate of de-trapping charges, and surface charge time decay constant, are often used concurrently. Therefore, identification of critical parameters and physical processes that influence PD activity is still a knowledge gap. Furthermore, most research studies on the effect of temperature on partial discharge parameters consider only two temperature test points that is

ambient and the maximum operating temperature [14][15][7] and then draw out generalised conclusions on PD behaviour as a function of temperature. It is, therefore, evident that the extent to which variations in insulation temperature affect PD phenomena over the entire temperature range still needs further research. In the present paper, experimental and analytical modelling techniques are used to explore the behaviour of partial discharge mechanisms at varying temperatures.

Section 2 of this paper deals with the theoretical model for predicting partial discharge inception voltage and PD charge magnitude. The third section details the experimental procedure followed to realise PD as a function of temperature, then section 4 reports on the findings and lastly, section 5 concludes the work.

2 PD Analytical Model

2.1 PD Model Geometry

A PD test specimen with an artificial cavity is modelled as shown in figure 1. The model consists of an air cavity with a diameter of 2.5 mm and a height of 1.5 mm. The air cavity is encapsulated within the polyethylene bulk solid insulation medium creating a multilayered dielectric system. The thickness of the bulk insulation is 4.5 mm and its relative permittivity is 2.3. The test cell is tightly clamped to create an unvented air-filled cavity.

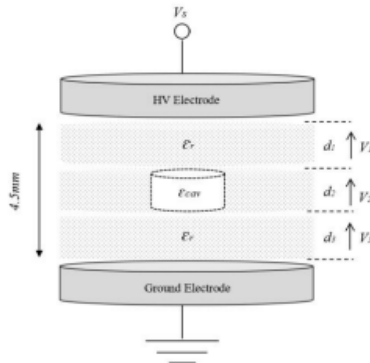


Figure 1: Multilayered dielectrics between parallel electrodes

2.2 Determination of Partial Discharge Inception Voltage

Partial discharge mechanisms in air cavities embedded in bulk insulation are generally modelled as streamer-like discharges [16]. Streamer-like discharges are characterised by a short pulse duration of approximately 100 ns and a relatively large apparent charge magnitude, typically of magnitudes ranging at 10 pC and higher. For partial discharge activity to initiate, two conditions are necessary: an electric field (E_{inc}) higher than the critical field and the availability of an initial seed electron [16]. The E_{inc} is defined as the minimum electric field required to

initiate partial discharge activity and it can be modelled using the mathematical expression in equation 1 [17].

$$E_{inc} = Ap \left[1 + \frac{B}{\sqrt{(a+b)p}} \right] \quad (1)$$

where p is the gas pressure within the cavity in Pa, a and b are the cavity radius and height, respectively, in meters, A is a constant representing the pressure-reduced field, which is 24.2 V/Pa.m, B is constant and equals $8.6 \text{ Pa}^{1/2} \text{ m}^{1/2}$ for air [17]. To estimate the minimum voltage required across the electrode to establish E_{inc} , it is necessary to understand the correlation between the electric field in the insulation medium and that in the cavity. Defects embedded in insulation medium give rise to a multilayered dielectric system. Figure 1 shows the physical model of the multilayered dielectrics system between parallel electrodes. Let V_1 , V_2 and V_3 be the voltages across each dielectric thickness d_1 , d_2 and d_3 , respectively. For parallel plate electrode setup, the electric field is given as $E=V/d$, then $V_1=E_1 d_1$, $V_2=E_2 d_2$, and $V_3=E_3 d_3$. Thus, the voltage across the electrode is given as $V_s = E_1 d_1 + E_2 d_2 + E_3 d_3$. From the relationship that if there is no charge in the dielectric, then the product of the electric field and its relative permittivity will remain constant. Therefore the inception field inside the air cavity is given by equation 2.

$$E_{inc} = \frac{V_s}{\left[\frac{\epsilon_{cav}}{\epsilon_r} d_1 + d_2 + \frac{\epsilon_{cav}}{\epsilon_r} d_3 \right]} \quad (2)$$

where V_s is the inception voltage, ϵ_r is the relative permittivity of the polyethylene insulation medium and ϵ_{cav} is the relative permittivity of air in the cavity. Combining equations (1) and (2), the PDIV (V_{inc}) can be expressed as in equation (3).

$$V_{inc} = Ap \left[1 + \frac{B}{\sqrt{(a+b)p}} \right] \left[\frac{\epsilon_{cav}}{\epsilon_r} d_1 + d_2 + \frac{\epsilon_{cav}}{\epsilon_r} d_3 \right] \quad (3)$$

The present work is interested in exploring the temperature dependence of partial discharge inception voltage V_{inc} . By inspecting equation 3, the parameters that respond to temperature variations are identified and can be expressed as a function of temperature. The temperature correction factors from Peek and Dunbar have been predominant in the studies of the gas breakdown mechanisms [18].

$$\delta = \left[\frac{(t_{n+1} + t_0)}{(t_n + t_0)} \right] p_n \quad (4)$$

Peek and Dunbar derived their temperature correction factors using the ideal gas law equations. Interpreting the relevant literature, Dunbar's correction factor is more applicable to the present work as it is based on adjusting the cavity pressure by the factor (t_{n+1}/t_n) , as shown in equation (4) above where t_{n+1} is the test temperature in a void, t_n is the initial cavity temperature

and p_n is the initial cavity pressure. The term t_0 is the temperature constant and equals 273 K. Substituting the pressure p with the correction factor δ in equation (3) gives equation (5) which is an analytical expression used to estimate PD inception voltage in the cavity as a function of temperature.

$$V_{inc} = A\delta \left[1 + \frac{B}{\sqrt{(a+b)\delta}} \right] \left[\frac{\epsilon_{cav}}{\epsilon_r} d_1 + d_2 + \frac{\epsilon_{cav}}{\epsilon_r} d_3 \right] \quad (5)$$

Assuming an insignificant delay in the availability of seed electrons and considering that the dimensions and parameters in figure 1 do not vary with temperature, the V_{inc} as a function of temperature is presented in figure 2.

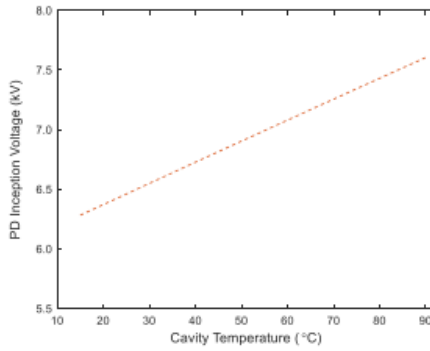


Figure 2: Simulated PDIV variations with temperature

The simulated results show that PDIV increases monotonously with temperature. In the present work, physical measurements were conducted, as presented in section 3. Section 4 then compares the simulated results to the physical measurements.

2.3 Determination of Partial Discharge Charge Magnitude as a function of temperature

The apparent PD charge magnitude can be modelled by using an analytical model called the induced charge or the dipole model. Pedersen introduced this model in the 1980s and reasoned that the transients measured at the electrodes result from the dipole moment established in the cavity owing to a discharge event. Notably, this model assumes that the entire void is involved in the discharge process and that the electric field inside the cavity is uniform. The studies proposed that the measured PD charge magnitude can be estimated using equation 6 [17]

$$q_{app} = -\Omega K \epsilon_r \epsilon_0 [E_{inc} - E_{res}] \nabla \lambda_0 \quad (6)$$

where K is the dimensionless factor which is dependent on the cavity geometry. Ω is the cavity volume, ϵ_r is the relative permittivity of the polyethylene insulation medium and ϵ_0 is the permittivity of free space. The inception and residual fields are denoted by E_{inc} and E_{res} , respectively. The residual electric

field is a function of pressure and is given by $E_{res} = \gamma A p$, where γ is a constant and will be used as a free parameter in the present study. The constant A and p were previously defined in section 2.1. $\nabla \lambda_0$ is the proportionality factor relating the actual charge in the cavity and the measured apparent charge magnitude. Implementing the temperature correction factor into equation (6), the PD apparent charge magnitude is estimated using equation (7).

$$q_{app} = -\Omega K \epsilon_r \epsilon_0 \left[A\delta \left[1 + \frac{B}{\sqrt{(a+b)\delta}} \right] - \gamma A\delta \right] \nabla \lambda_0 \quad (7)$$

The curve fitting approach was used to fit equation 7 into the measured data, as presented in figures 6 to 8. The values of the parameters used in equation 7 were drawn from the literature and are presented in table 1.

Table 1: Parameters used for simulations

Parameter	Value	Reference
Ω	7.36 mm ³	The cavity volume
K	1	[16]
$\nabla \lambda_0$	1/d	[19]

The curve fitting was achieved by varying the free parameter γ to closely fit the calculated values to the measured PD magnitudes as the temperature was varied from 15°C to 90°C. In the next section, the experimental work is presented.

3 Experimental Work

This section presents the experimental procedure implemented to study cavity partial discharge characteristics as a function of temperature. The experimental setup entailed test specimen preparation, the heating cycle experiment and the PD measurement setup. The first sub-section details the process of preparing the test specimen. In particular, the test specimen geometry and its arrangement. The second part describes the experimental setup and testing procedures of the heating cycle and lastly, PD measurement circuit arrangement, testing methodology and data acquisition are described in detail.

3.1 PD Test Specimen Preparation

The type of insulation material used in this research is a synthetic polyethylene dielectric. Polyethylene sheets of 1.5 mm thickness were sandwiched between two disc shaped brass electrodes to create a test cell, as shown in figure 1. The test specimen comprises of three layers and it is arranged such that the layers nearer to the high voltage and ground electrode contain no imperfections. The middle layer is sandwiched between the layers immediately after the electrodes and includes an artificial air cavity. The artificial cavity has a diameter of 2.5 mm and a thickness of 1.5 mm. The test specimen is tightened using clamps made from Perspex and the entire test cell is immersed in an insulating oil to avoid surface discharges during testing. The cell therefore contains unvented artificial air cavity.

3.2 Heating Cycle Experimental Design

The heating experimental setup was necessary to vary the cavity temperature to a desired test temperature. The temperature was increased using a thermostatically controlled heat source. The defined test temperatures were: 15°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C. The setup consisted of a metallic oil bath chamber, heat source, temperature control device and a temperature-measuring sensor. The temperature-measuring sensor was placed in close proximity to the bulk insulation medium. The cavity temperature was raised by heating the oil bath to the desired value and through heat convection, the oil was forced to circulate, transferring heat to the test specimen.

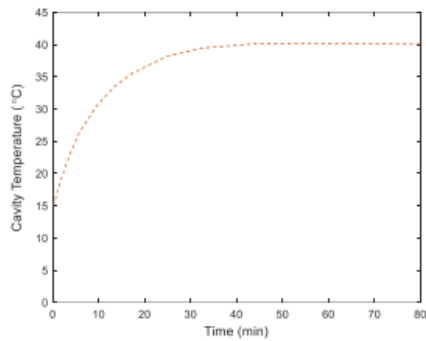


Figure 3: Cavity temperature settling time

The test specimen was heated for 30 minutes in the oil bath for each test temperature point to allow the cavity to reach the desired steady-state temperature before PD measurements were taken. As part of pre-measurements, the settling time was derived from the heat transfer model simulated using COMSOLTM software. Figure 3 shows the simulation results of the temperature distribution profile on the specimen while heated from 15°C to 40°C. It can be deduced that reaching the desired cavity temperature takes almost 30 minutes. The temperature was constantly monitored using a sensor immersed in the oil bath and positioned close to the polyethylene insulation. A computer-controlled software, PicoLogTM, was used to measure and monitor the oil bath temperature.

3.3 The PD Measurement System

Figure 4 shows the circuit arrangement used to measure the partial discharges. The measuring circuit is in accordance with the IEC60270 standard. It comprises a 50 kV 50 Hz ac PD free transformer, current limiting resistor, coupling capacitor, detection impedance, PD measurement device and the test specimen. The PD detector device and the coupling impedance detect partial discharge signals from the test specimen and log the PD signals on a personal computer using the Power Diagnostix ICM CompactTM software tool. As part of pre-measurements, a defect-free sample was tested to identify the voltage at which it starts to generate noise. It was found that

the defect-free sample exhibited partial discharges at 18 kV ac and the extinction voltage was found to be 14 kV ac. Thus, the test specimens were stressed at 11 kV, 50 Hz ac voltage throughout the entire test temperature range. All the PD measurements were recorded for one minute to avoid PD-induced ageing.

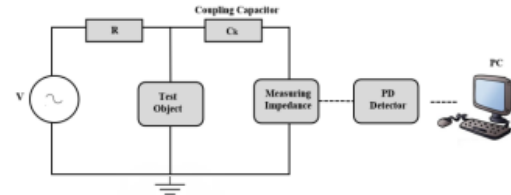


Figure 4: PD measurements circuit arrangement

In the next section, the measured PD and simulated results are presented.

5 Results and Discussions

5.1 Influence of Temperature on PDIV

The measured and simulated PDIV results as a function of temperature are shown in figure 5. The results show that PDIV increases linearly with the cavity temperature. The simulated PDIV were generally in agreement with the experimental results. Similar findings were reported by Illas *et al.* [4], although they used an epoxy insulation medium. PDIV's response to varying temperatures is therefore attributed to changing gas-filled cavity pressure.

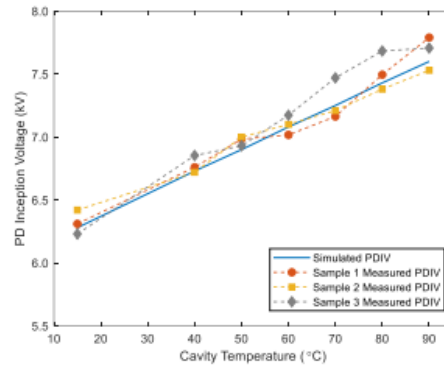


Figure 5: Measured and simulated PDIV

Assuming a constant volume process, the ideal gas law equation states that the gas pressure is proportional to the temperature. Therefore, an increase in cavity pressure impacts the mean free path and, consequently, the gas ionisation and breakdown thereof. Studies have shown that the mean free path decreases with increased temperature. Thus, a reduction in the mean free path inhibits the ionisation process owing to insufficient energy gained by particles during the ionisation by a collision process. For that reason, the partial discharge

inception voltage increases with an increase in the cavity gas pressure caused by increased temperature.

5.2 Influence of Temperature on PD Charge Magnitude

Figures 6 and 7 show the measured and the calculated apparent PD charge magnitude as a function of temperature. The apparent PD charge magnitude initially decreased with temperature from 15°C to 60°C and then rose from 60°C to 90°C. Similar results we obtained with the third test specimen.

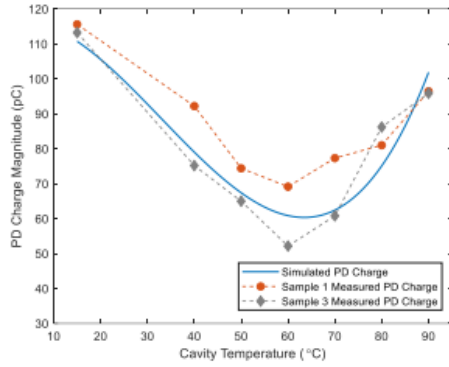


Figure 6: Sample 1&3 PD Charge variation with temperature

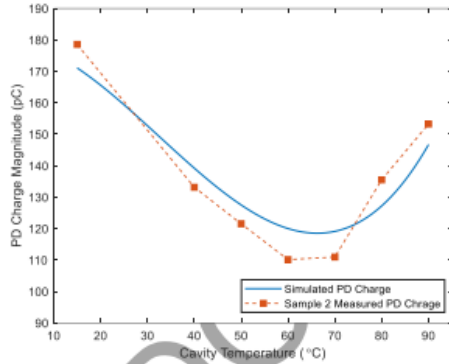


Figure 7: Sample 2 PD Charge variation with temperature

The approach employed in that regard is to 'curve-fit' the equation (7) on the experimentally measured data, as presented in figures 6 and 8. Below 60°C, the theoretical trend is fitted to the measured data by adjusting the parameters representing the residual charge, E_{res} . In equation (7), E_{res} is represented by $\gamma A \delta$. Since A and δ are constant, the parameter that is responsive to temperature is the free parameter γ . The interpretation is that charges deployed on the void surface after a PD event greatly influence the discharge magnitude of the next PD by altering the electric field within the cavity. These space charges have a finite life which is dependent on the cavity surface conductivity [16]. From ambient temperature to

60°C, the analytical model shows that the conductivity of the cavity surface is such that the space charge decay time is much longer than the period of the applied electric field. As a result, the electric field due to the space charge reduces the total electric field within the cavity. Consequently, the PD charge magnitude decreases with temperature from ambient to 60°C. Beyond 60°C, the cavity surface conductivity increases, thereby causing the residual charge to disperse more quickly than at lower temperatures. In the simulation model, the decreasing E_{res} is represented by decreasing the free parameter γ . Consequently, the resultant apparent charge increases, as depicted in figures 6 and 7.

5.2 Influence of Temperature on PD phase resolved patterns (PDPRP)

Figures 8 and 9 present the evolution of the cavity PD phase resolved patterns with temperature. At 15°C, a turtle-like phase resolved PD patterns were prevalent. The turtle-like patterns then transitioned into a rabbit-like phase resolved patterns beyond 60°C up to 90°C.

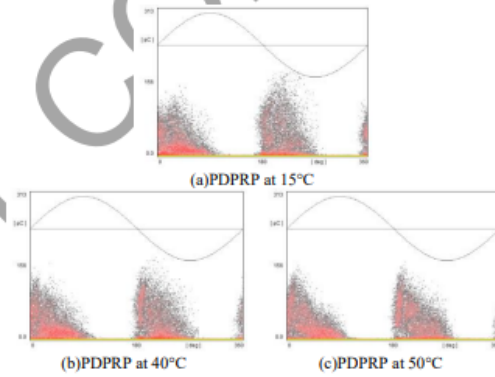


Figure 8: PDPRP variation with temperature (15°C to 50°C)

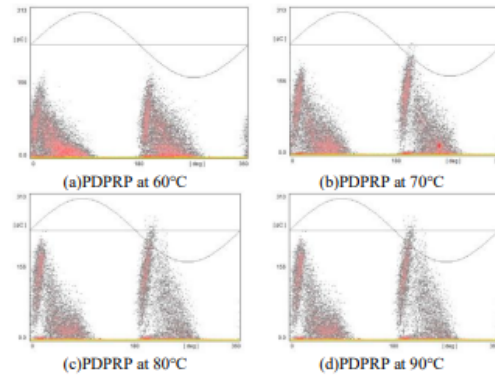


Figure 9: PDPRP variation with temperature (60°C to 90°C)

The transition from turtle-like to rabbit-ear is attributed to increased dynamics of the residual charge in each half-cycle period. At lower temperatures, there is a minimal change in E_{res} , while at higher temperatures, there is increased cavity surface conductivity. Therefore, increased variations of E_{res} during the half cycle and hence more significant PDs in the rabbit ear followed by relatively smaller PDs in the "rabbit body".

5 Conclusion

In this paper, cavity partial discharges in polyethylene insulation material as a function of temperature were studied. The results showed that PDIV increases linearly with temperature and this is attributed to an increase in cavity pressure with temperature. An increase in cavity pressure decreases the mean free path, thus increasing the stress magnitude required to sustain the ionisation process. For that reason, PD occurs at higher voltages. PD charge magnitude initially decreased in the temperature range of 15°C to 60°C and then increased from 60°C to 90°C. PD charge magnitude behaviour with varying temperatures is attributed to changes in the cavity surface conductivity in polyethylene. From 15°C to 60°C, the surface charge decay time is relatively longer, such that the resultant charge magnitude is reduced and the corresponding PDPRP are predominantly turtle-like. From 60°C to 90°C, the life of the surface charges is relatively shorter and as a result, the PD charge magnitude is increased. The corresponding PDPRP are predominantly turtle-like. The experimental results are interpreted through curve fitting the analytical equations onto the measured data. The overall conclusion is that in polyethylene, cavity discharge characteristics respond to temperature changes. The variations in PD characteristics are monotonous for PDIV and non-monotonous for apparent charge magnitude as well as PDPRP.

6 Acknowledgements

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