Modeling of Degradation Mechanism at the Oil-Pressboard Interface due to Surface Discharge

Presented by :

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INTRODUCTION

- **Surface discharge** is a **type of partial discharge** at the **interface of oil-impregnated cellulose-based pressboard** within power transformer.

- It is classified as a **serious fault condition** as it can occur under normal operating conditions. It can continue from minutes to months or even years, until the creeping conductive path or also known as tracking becomes an essential part of a powerful arc.

- The **tracking** appears in the form of **white and carbonised marks** on the pressboard surface from the discharge source towards the earth electrode.

- Generally, the formation of these degradation marks is believed due to **drying out** and **carbonization processes** during surface discharges at the oil-pressboard interface.

INTRODUCTION

Figure 1: Flashover failure along barrier board

Figure 2: Pressboard surface with white and carbonised marks due to surface discharge experiment

SIMULATION MODEL GEOMETRY

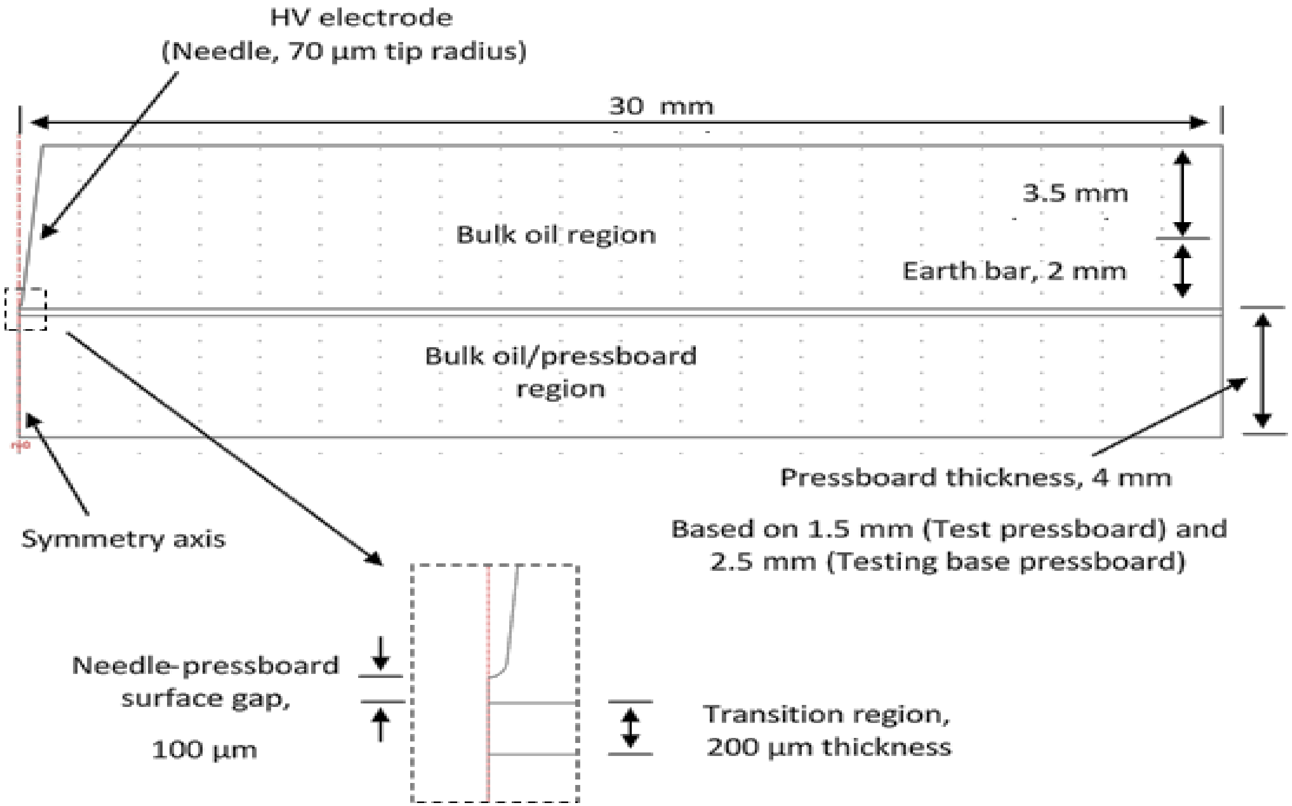

Figure 3. Model geometry for surface discharge simulation using the 2-D axial symmetry plane.

SIMULATION MODEL GEOMETRY

- There are **three media** which are:
  (a) bulk oil region
  (b) transition region
  (c) bulk oil/pressboard region.

- Transition region

The **porous part** of the pressboard so that the streamer can be modelled to propagate through it.

- Bulk oil/pressboard region

Assumed as a **perfect insulator**, i.e. this region is assigned zero conductivity ($\sigma = 0$).

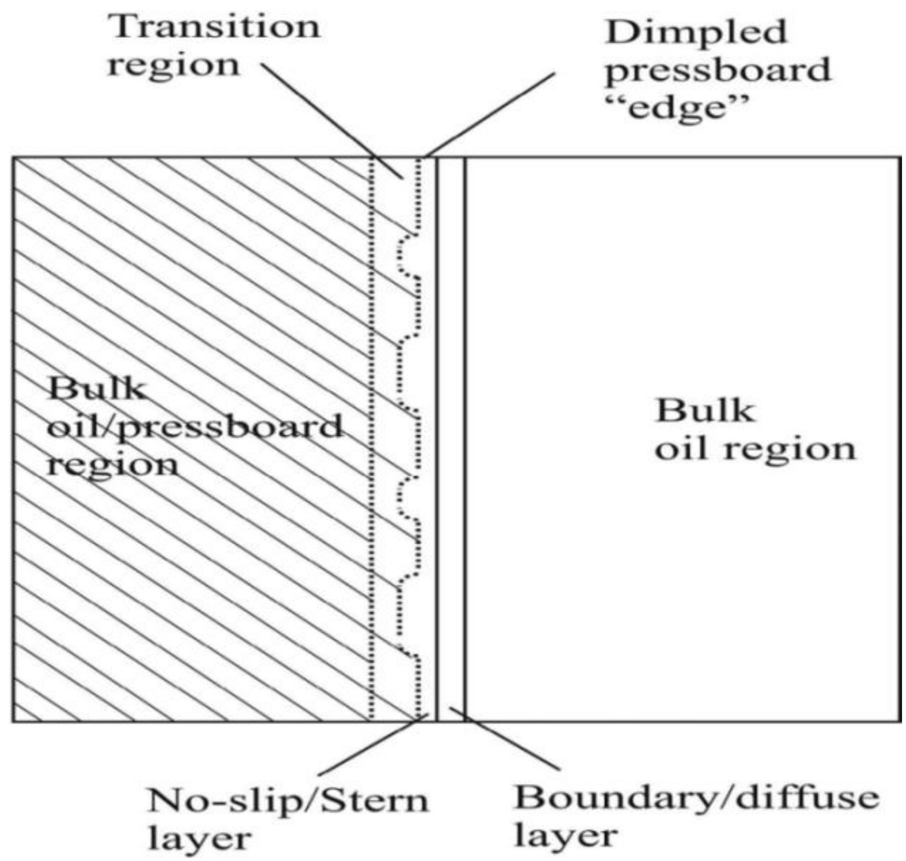

Figure 4. Physical model of the oil-pressboard interface [1].

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[1] P. M. Mitchinson, P. L. Lewin, B. D. Strawbridge, and P. Jarman, "Tracking and surface discharge at the oil-pressboard interface," *IEEE Electrical Insulation Magazine*, vol. 26, pp. 35-41, (March/April 2010).

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- Charge transport continuity equation :

$$\frac{\partial N_i}{\partial t} + \nabla \cdot \overrightarrow{F_i} = G_i - R_i$$

✓ N_i is the density of each charge carrier ($mol \cdot m^{-3}$), i.e. positive ion, N_p or negative ion, N_n or electron, N_e

✓ $\overrightarrow{F_i}$ is the total flux density vector ($mol \cdot m^{-2} \cdot s^{-1}$) due to the movement of each charge carrier.

✓ G_i is the generation rate of the charge carriers.

✓ R_i is the recombination rate of the charge carriers.

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- The **surface discharge streamer** is assumed to be dominated by **conduction currents.**

- The **total flux** only considers the **electro-migration of each charge carrier** due to the influence of the electric field and neglects any charge carrier movements due to diffusion process and fluid convection.

- The **total flux density vector** for each charge carrier :

$$\overrightarrow{F_i} = \pm N_i \mu_i \vec{E}$$

- ➢ $\vec{E}$ is the electric field vector (V·m^{-1})
- ➢ μ_i is the mobility (m^{2}·s^{-1}·V^{-1}) for each charge carrier.
- ➢ The '$\pm$' sign accounts for the direction of charge migration :
  - '+' sign for positive ion
  - '−' sign for negative polarity charge carriers (negative ion and electron).

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Charge generation** : field dependent molecular ionisation (**Zener Model** [2]).

$$G_i(|\vec{E}|) = \frac{qN_0 a|\vec{E}|}{h} exp\left(-\frac{\pi^2 m^* a\Delta^2}{qh^2|\vec{E}|}\right)$$

- $G_i(|\vec{E}|)$ is the charge generation rate (mol·m^{-3}·s^{-1}) for positive ion and electron
- q is the elementary charge (1.6022×10^{-19} C),
- N_0 is the density of the ionisable species (mol·m^{-3})
- a is the molecular separation distance (m),
- h is the Planck's constant (6.626×10^{-34} J·s)
- m^* is the effective electron mass (kg)
- Δ is the molecular ionisation energy (J).

[2] C. Zener, "A theory of the electrical breakdown of solid dielectrics," *Proceedings of the Royal Society of London. Series A*, vol. 145, pp. 523-529, (1934).

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Charge generation** follows this relationship :

A free electron and a positive ion are extracted from a neutral molecule

$$\boldsymbol{G_i}\left(\left|\vec{\boldsymbol{E}}\right|\right) = \boldsymbol{G_p}\left(\left|\vec{\boldsymbol{E}}\right|\right) = \boldsymbol{G_e}\left(\left|\vec{\boldsymbol{E}}\right|\right)$$

➢ $G_p\left(\left|\vec{E}\right|\right)$ and $G_e\left(\left|\vec{E}\right|\right)$ are the generation rates ($mol \cdot m^{-3} \cdot s^{-1}$) for positive ions and electrons correspondingly.

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Charge Recombination :**
  - Between +ve and –ve ions, $\boldsymbol{R_{pn}}$

$$\boldsymbol{R_{pn} = N_p N_n K_{rpn}}$$

  - Between +ve ions and electron, $\boldsymbol{R_{pe}}$

$$\boldsymbol{R_{pe} = N_p N_e K_{rpe}}$$

  - Electron attachment with neutral molecules, EA to form negative ions and reduce the number of electrons.

$$\boldsymbol{EA = \frac{N_e}{\tau_a}}$$

> - τ_a is the time constant (s) for the electron attachment.
> - K_{rpn} and K_{rpe} are the recombination coefficients ($m^3 \cdot s^{-1} \cdot mol^{-1}$) between positive and negative ions and between positive ions and electrons respectively determined using **Langevin's equation.**

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Langevin's equation:**

$$K_{rpn} = \frac{q}{\varepsilon_0 \varepsilon_r}(\mu_p + \mu_n) N_A$$

➢ μ_p and μ_n are the mobility ($m^2 \cdot s^{-1} \cdot V^{-1}$) for positive and negative ions

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Poisson's equation :**

$$\nabla \cdot (-\varepsilon_0 \varepsilon_r \vec{E}) = (N_p - N_n - N_e) q N_A$$

- ε_0 and ε_r are the permittivity of free space (8.854×10^{-12} F·m^{-1})
- relative permittivity of the material respectively, N_p, N_n and N_e are the density of positive ions, negative ions and electrons (mol·m^{-3}) respectively.
- N_A is the Avogadro's number (6.023×10^{23} mol^{-1})

GOVERNING EQUATIONS IN BULK OIL AND TRANSITION REGIONS

- **Heat transfer** equation :

The **heat conduction** as a result of **thermal diffusivity.**

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_P}\left(k_T \nabla^2 T + \vec{E} \cdot \left(\sum \left|\vec{F_i}\right|\right) q N_A\right)$$

The **heat source from the electrical power dissipation** as a result of **conduction current** heating from the **movement of charge carriers** during the partial discharge under the influence of local electric field.

- ➢ ρ is the mass density (kg·m^{-3})
- ➢ C_P is the specific heat capacity (J·kg^{-1}·K^{-1})
- ➢ k_T is the thermal conductivity (W·m^{-1}·K^{-1}) of the material
- ➢ T is the temperature (K)

GOVERNING EQUATIONS IN BULK OIL/PRESSBOARD REGION

- With the **assumption** that the **bulk oil/pressboard region is a perfect insulator,**
  - The **charge transport equation is not applicable** in the modelling of this region.

$$\nabla \cdot (-\varepsilon_0 \varepsilon_r \vec{E}\,) = 0$$

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_P}\left(k_T \nabla^2 T\right)$$

BOUNDARY CONDITIONS

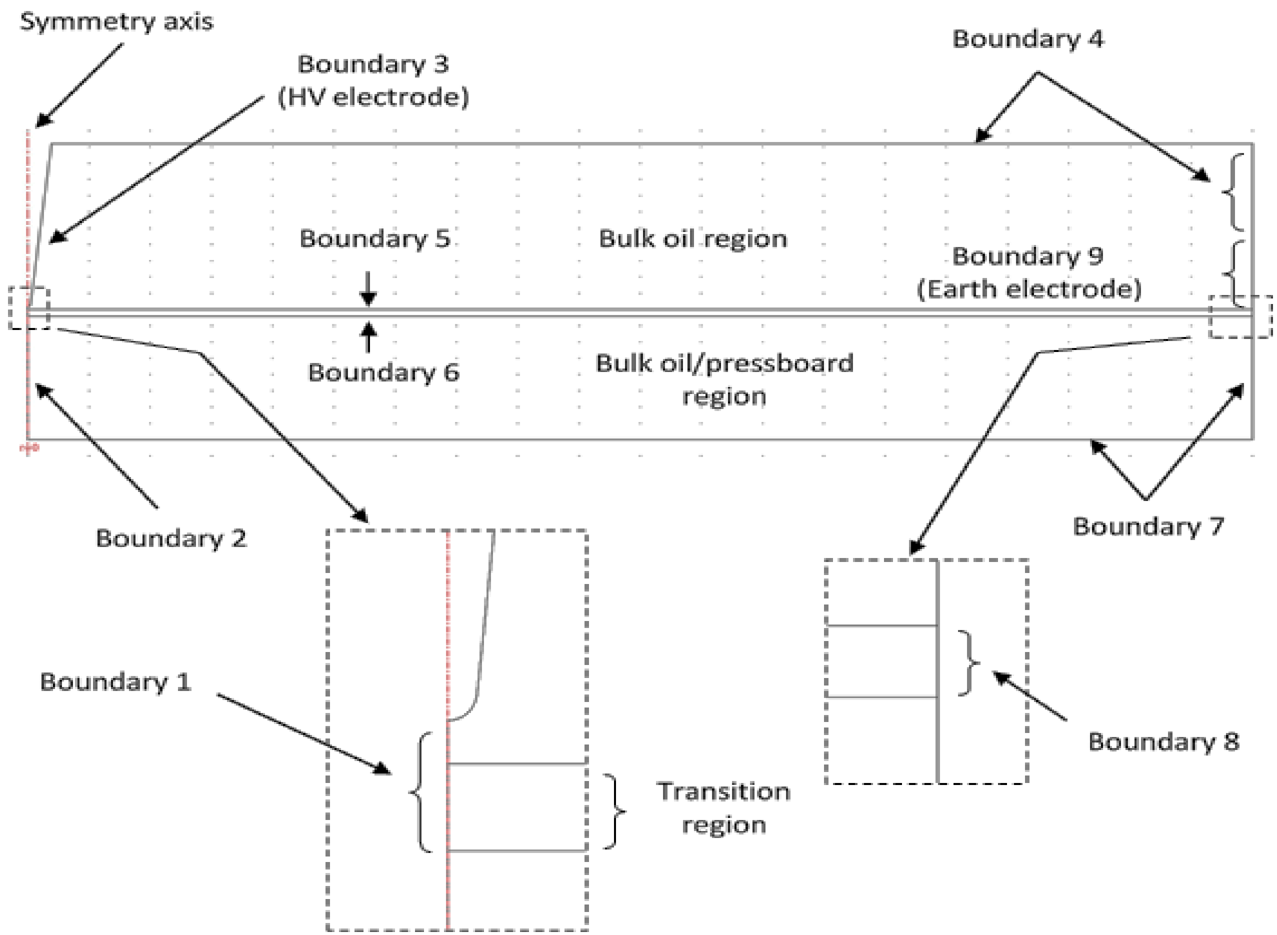

Figure 5. Boundary numbers for the model geometry

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BOUNDARY CONDITIONS

Table 1: Boundary conditions for the model

<table>
<tr><th>Governing Equation</th><th>Charge Transport</th><th>Poisson's</th><th>Heat Conduction</th></tr>
<tr><td>Boundary 1</td><td>Axial symmetry
$r = 0$</td><td rowspan="2">Axial symmetry
$r = 0$</td><td rowspan="2">Axial symmetry
$r = 0$</td></tr>
<tr><td>Boundary 2</td><td>NA</td></tr>
<tr><td>Boundary 3</td><td>$\hat{n} \cdot (-D_i \nabla N_i) = 0$</td><td>$V = V_{app}$</td><td rowspan="2">$-\hat{n} \cdot (-k_T \nabla T) = 0$</td></tr>
<tr><td>Boundary 4</td><td>$\hat{n} \cdot \overrightarrow{F_i} = 0$</td><td>$\hat{n} \cdot \overrightarrow{D} = 0$

Where, $\overrightarrow{D} = \varepsilon_0 \varepsilon_r \overrightarrow{E}$</td></tr>
<tr><td>Boundary 5</td><td>$\hat{n} \cdot (\overrightarrow{F_1} - \overrightarrow{F_2}) = 0$</td><td>$\hat{n} \cdot (\overrightarrow{D_1} - \overrightarrow{D_2}) = 0$</td><td>$\hat{n} \cdot (\overrightarrow{Q_1} - \overrightarrow{Q_2}) = 0$

Where, $\overrightarrow{Q} = -k_T \nabla T$</td></tr>
<tr><td>Boundary 6</td><td>$\hat{n} \cdot (\overrightarrow{F_1} - \overrightarrow{F_2}) = F_0$</td><td>$\hat{n} \cdot (\overrightarrow{D_1} - \overrightarrow{D_2}) = N_s q N_A$</td><td>$\hat{n} \cdot (\overrightarrow{Q_1} - \overrightarrow{Q_2}) = Q_s$</td></tr>
<tr><td>Boundary 7</td><td>NA</td><td rowspan="2">$\hat{n} \cdot \overrightarrow{D} = 0$</td><td rowspan="3">$-\hat{n} \cdot (-k_T \nabla T) = 0$</td></tr>
<tr><td>Boundary 8</td><td>$\hat{n} \cdot \overrightarrow{F_i} = 0$</td></tr>
<tr><td>Boundary 9</td><td>$\hat{n} \cdot (-D_i \nabla N_i) = 0$</td><td>$V = 0$</td></tr>
</table>

RESULTS AND ANALYSIS

- The **hottest spot** at a particular time appears at the **tip of streamer** along the pressboard surface :

  About **12.3 μm** apart from the needle tip.

- The results indicate that streamer branch on the pressboard surface **causes significant temperature increase at a spot that is vicinity of needle tip.**

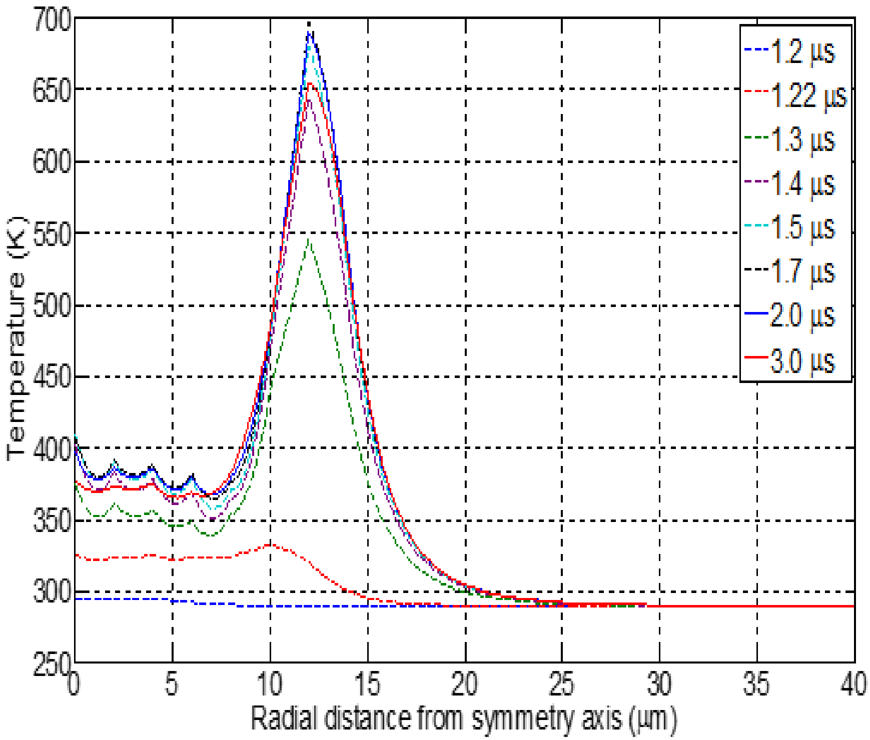

Figure 6. Temperature distribution along boundary 5

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RESULTS AND ANALYSIS

- Temperature increased beyond 500 K - temperature level that may cause **carbonisation of cellulose** through **dehydration** and **pyrolysis processes** is less than 500 K [5].

- Hence, **concentration of high temperature** over a long period of surface discharges, would enhance the **carbonisation** of cellulose pressboard particularly at the vicinity of needle tip.

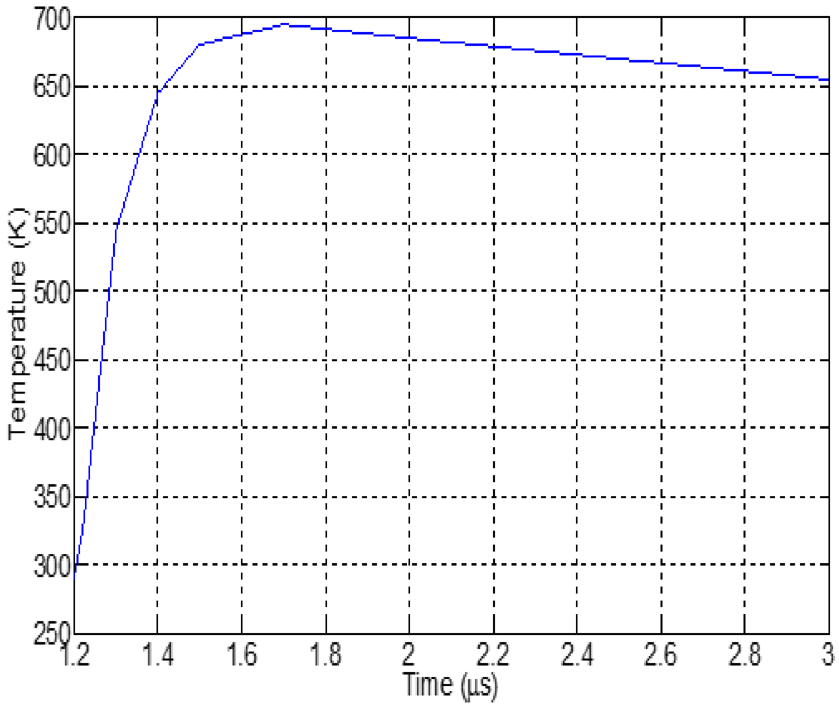

Figure 7. Variation of temperature at the hottest spot.

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[5] D. F. Arseneau, "Competitive reactions in the thermal decomposition of cellulose," *Canadian Journal of Chemistry*, vol. 49, pp. 632-638, (1971).

RESULTS AND ANALYSIS

- The **significant growth of energy dissipation (Figure 8)** causes the **temperature to increase substantially (Figure 7).**

- The moment when the **energy increases steadily**, the **temperature starts to decrease gradually.**

- This **gradual decrease** is caused by the **thermal dispersion** in the system.

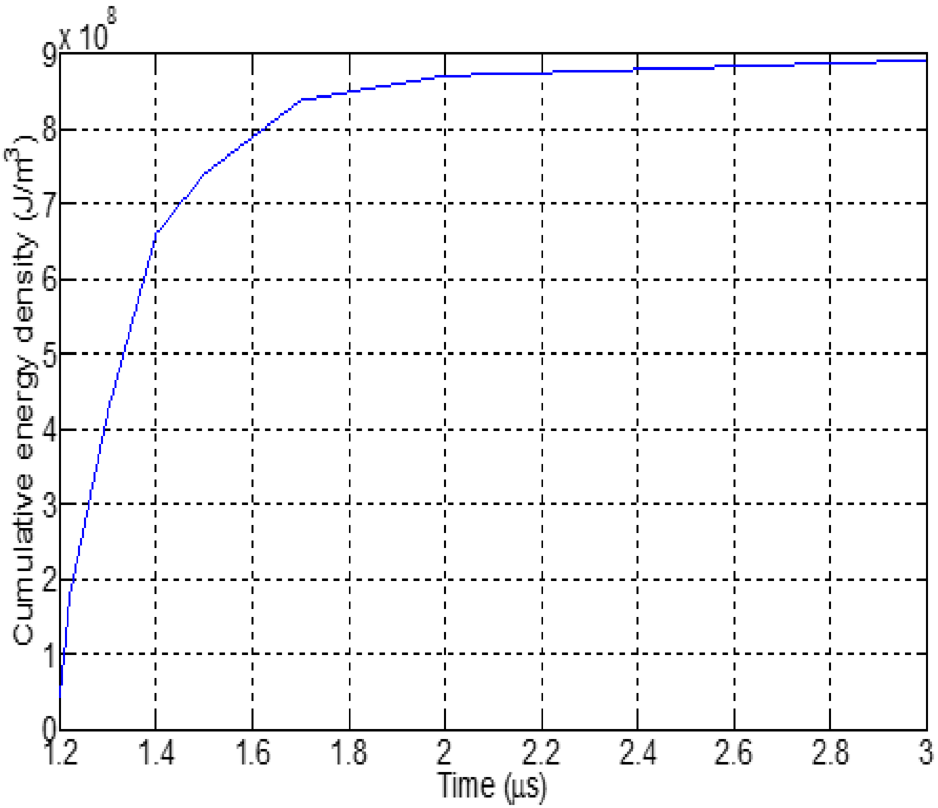

Figure 8. Cumulative energy density

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CONCLUSION

- The results support the hypotheses about the **localised nature** observed in the experiment of surface discharge at the oil-pressboard interface.

- These include the **development of white marks** on the pressboard surface and the **formation of carbonised marks** that predominantly appear on the pressboard surface at the vicinity of needle tip.

- The simulation results have **associated both degradation marks on pressboard surface with high energy of long periods of partial discharge event** that leads to **thermal degradation** at the oil-pressboard interface.

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THANK YOU