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# INFLUENCE OF THERMAL ENERGY ON THE CHANNEL OF ELECTRIC BREAKDOWN

**Abstract**: Mathematical and physical analysis of the process in the vicinity of the breakdown channel in polymer insulation is given in the paper. Breakdown goes along with irreversible change of status of polymer insulation close to breakdown channel which is possible to observe both optically and electrically. This degradation of certain layers of insulation is caused by thermal process due to development of the channel and gasification of polymer. Three different types of polymer insulations were observed: cable polyethylene, silicone resin and epoxy resin.

**Key words**: electric breakdown, breakdown channel, polymer insulation, thermal energy, polyethylene, silicone, epoxy

## 1. Introduction

At microscopic observation of channel after thermal and electric breakdown in case of cable polyethylene, transparent silicone resin (LUKOPREN) or epoxy potting resin (without filling) it has been found that relatively high temperature during electric discharge in the channel impacts on its walls; small carbon grains are created discontinually during thermal degradation of the polymer on the walls of breakdown channel. This layer is not very conductive, its thickness is less than 1 mu m and its conductivity is given by geometry of created carbon grains. The channel is conductive again after ignition of discharge.

From the point of view of electrical and thermal degradation, the layer coaxially enclosed around the core of channel is very important. We have proved that in certain thickness (several tens of micrometers, if the diameter of channel was 200 micrometers), the structure of polymer is changed and for that reason its optical properties are changed, too. This phenomena was observed independently on us [2] by Japan authors [1].

For explanation of above mentioned phenomena it is necessary to focus on the influence of strong electric fields ($E \geq 10^7$ $Vm^{-1}$) on chemical bonds of polymers. For that reason the mat-

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ter connecting with cutting bond energies by electric field has become the main subject of research related to degradation of polymer insulations.

## 2. Balance of energy during creation of breakdown channel

Considering facts mentioned above, electrical and thermal breakdown caused by influence of strong electrical field will be analyzed. There are two possibilities of breakdown: pulse thermal breakdown, breakdown at critical value of the strength of electrical field.

Both pre-breakdown state and breakdown will be observed in strong electric field between needle electrodes with small radius of curvature. The process of local activity of electrical field was described in [3]. From facts mentioned in [3] it follows that extraction and emission of electrons in the space between electrodes is responsible for creation of narrow channel with small cross-section. Very important role in this case plays the value of relative permittivity and loss factor of observed material.

Creation of electric breakdown channel is time and thermal dependent process accompanying by gasification. Moreover, the last stage of dependence of temperature on time in pre-breakdown region is characterized by steep curve. If temperature $T$ in each volume elements in dependence on time is constant and if $T$ is only function of position $T = f(x,y,z)$, then the process can be considered to be stationary. In our case the process is time dependent. It means that $T = f(x,y,z,t)$ which leads to non-stationary process.

If electric power supplied to system ($\gamma E^2$) is in balance with generated temperature, we get balance of energy which considers absorbed heat, emitted heat and thermal losses in surrounding environment. If the breakdown channel is coaxial, equation describing balance of energy can be written as:

$$W_e = W_v + W_c + W_{od} \tag{1}$$

or:

$$\gamma E^2 = W(T) + C\frac{dT}{dt} + \frac{1}{r}\frac{d}{dr}\left(r\lambda\frac{dT}{dr}\right) \tag{2}$$

where $\gamma$ is specific conductivity of insulation; $E(t,T)$ is electric strength; $W(T)$ is emitted power to the environment to volume unit; $r$ is radius of channel; $T$ is temperature; $\lambda$ is thermal conductivity of observed medium; $C$ is specific thermal capacity to volume unit. Behaviour of $\gamma$ and $E$ before and during discharge in channel is shown in Figure 1.

Electric breakdown is accompanied by speedy formation of heat which causes local rise of temperature of insulation. This phenomena leads to pulse thermal breakdown and strongly ionized gas in breakdown channel reaches the temperature of plasma. Because the channel is located inside the polymer, emitted power $W(T)$ can be neglected. We solve Equation (2) per partes:

$$\gamma E^2 = C_1\frac{dT_1}{dt} + C_2\frac{dT_2}{dt} + C_3\frac{dT_3}{dt} \tag{3}$$

considering different specific capacity of breakdown channel $C_1$ filled by plasma of temperature $T_1$, which is enclosed by polymer (capacity $C_2$ and temperature $T_2$). $C_3$ and $T_3$ is capacity and temperature of needle electrodes.

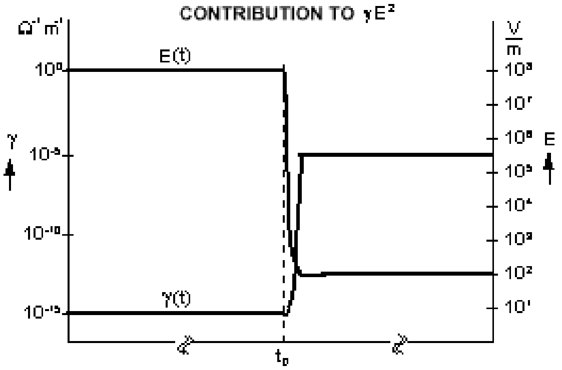


**Fig. 1.** *Behaviour of* $\gamma$ *and E in dependence on time*

In this case it is impossible to eliminate mutual coherence of temperature and electric strength during pulse electric stress. This mutual relation it is possible to evaluate as:

$$\gamma E^2 = C \frac{dT}{dE} \cdot \frac{dE}{dt}. \tag{4}$$

It is necessary to emphasize that specific conductivity $\gamma$ is dependent on temperature, so it is possible to write $\gamma = \gamma_0 \, exp(-A/kT)$, where $\gamma_0$ is inception specific conductivity and *A* is activating energy.

When solving the second part of Equation (2) it is necessary to focus on influence of thermal conductivity $\lambda$ on propagation of heat considering the analysis of degraded walls of the channel. This problem will be solved in the next part. Above mentioned hypothesis is vouched by photographs in Fig. 2.

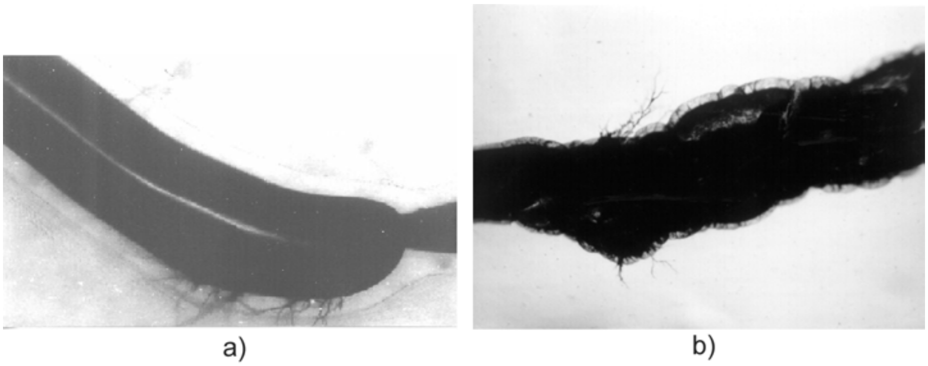


**Fig. 2.** *Degradation of walls of breakdown channel in polyethylene (a) and epoxy (b)*

At observation it was found out that breakdown channel is thermally degraded equally along its length and the most expressive influence of temperature is observed at the interface of metal needle and breakdown channel. Above mentioned heat goes across the sheath of channel in discrete bounded volume. Calculation of thermal energy across the sheath of cylindrical shape is made for common radius *x* from channel axis. The surface of channel *S* at the length *l* is $S=2\,\pi xl$.

In such case it is possible to evaluate the amount of heat as:

$$Q=-\lambda\, 2\pi\, x\, l \frac{dT}{dx}\, t \tag{5}$$

This relation expresses the heat going through the cross-section of the breakdown channel in the site, where temperature gradient is *-dt/dx*. From our research follows that considering very short time of breakdown (from $10^{-6}$ to $10^{-8}$ s) in cabel polyethylene or in silicone or epoxy resin, conduction of heat is said to be stationary. In cylindrical shape it is $T = f(r)$. When the conduction process is non-stationary, it is possible to write $T = f(r,t)$.

Considering $\partial T/\partial t = 0$ (reducing $\Delta T = 0$), it is possible to write partial differential equation

$$\Delta T = divgradT = div\left(\frac{\partial^2 T}{dr}\cdot\frac{r}{r}\right)=\frac{\partial^2 T}{\partial T^2}+\frac{1}{r}\frac{\partial T}{\partial r} \tag{6}$$

In our case temperature *T* as a function of position ($T = f(r)$) can be expressed as:

$$\frac{d^2T}{dr^2}+\frac{1}{r}\frac{dT}{dr}=0 \tag{7}$$

By solution of this simple differential equation we get for temperature in certain location the following relation:

$$T=T_1-\frac{T_1-T_2}{\ln r_2\,\ln r_1}(\ln r_2-\ln r_1\,) \tag{8}$$

Due to long-time process of development of discharge channel, time needed for internal heating of polymer insulants in the surroundings of electric tree is not negligible and it is within the range of time that is necessary for development of pure electric breakdown and time that is necessary for thermal breakdown. For that reason we solve the equation of conduction of heat in observed cylindrical formation in non-stationary status:

$$\frac{\partial T}{\partial t}=a\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \phi^2}+\frac{\partial^2 T}{\partial x^2}\right) \tag{9}$$

where $a=\frac{\lambda}{c\gamma}$, where $\lambda$ is thermal conductivity of surroundings, *c* is specific heat and $\gamma$ is constant dependent on specific density of material.

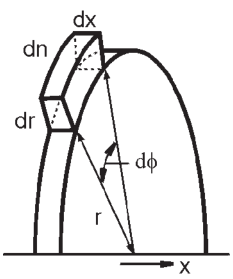


**Fig. 3.**

From mathematical and physical point of view, have a look through the small volume of cylinder (see Fig.3). Its element *dn dr dx* matches to micro-section of channel after electric breakdown.

In Fig. 3, r is distance of the point from the axis of cylinder, *x* is its distance along initial plane, $\phi$ is angle between the plane and *dn* is the length of small arc $rd\phi$. If we apply the common use for setting of thermal balance, we get thermal gradient in the direction of $x$:

$$-\lambda \frac{dT}{dx} dr\, dn \tag{10}$$

in section $x$ and

$$-\lambda \left( \frac{dT}{dx} + \frac{d^2T}{dx^2} dx \right) dr\, dn \tag{11}$$

in section $x+dx$.

Increment of heat in the $x$ direction is:

$$\lambda \frac{d^2T}{dx^2} dx\, dr\, dn \tag{12}$$

In radial direction in the distance $r$ from the axis of cylinder, the amount of heat going through the elementary plane, can be expressed:

$$-\lambda \frac{dT}{dr} dx\, dn = -\lambda \frac{dT}{dr} r\, dx\, d\phi \tag{13}$$

The amount of heat in distance of $r+dr$ from the axis of cylinder is:

$$-\lambda \left( \frac{dT}{dr} + \frac{d^2T}{dr^2} dr \right)(r+dr)\, dx\, d\phi \tag{14}$$

Increment of heat in radial direction consists of

$$\lambda \left( r \frac{d^2T}{dr^2} dr + \frac{dT}{dr} dr + \frac{d^2T}{dr^2} dr^2 \right) d\phi\ dx \tag{15}$$

Neglecting the element with $(dr^2)dxd\phi$ we get:

$$\lambda \left( r \frac{d^2T}{dr^2} + \frac{dT}{dr} \right) dr\, d\phi\ dx = \lambda \left( r \frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} \right) dn\, dr\, dx \tag{16}$$

By the similar way it is possible to derive the increment of heat in plane element in the direction of change $n$:

$$\frac{\lambda}{r^2} \frac{d^2T}{d\phi^2} dn\, dr\, dx \tag{17}$$

Total increment of heat in the element is:

$$\lambda \left( \frac{d^2T}{dx^2} + \frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{1}{r^2}\frac{d^2T}{d\phi^2} \right) dn\, dr\, dx \tag{18}$$

This expression must be equal to the change of thermal energy of our elementary volume:

$$c\gamma \frac{dT}{dt} dn\, dr\, dx = \lambda \left( \frac{d^2T}{dx^2} + \frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{1}{r^2}\frac{d^2T}{d\phi^2} \right) dn\, dr\, dx \tag{19}$$

From this equation we get

$$\frac{dT}{dt} = a\left(\frac{d^2T}{dx^2} + \frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} + \frac{1}{r^2}\frac{d^2T}{d\phi^2}\right) \tag{20}$$

Again we got equation which we came from (Eqn(9)). At the heat propagation in the channel, there is not always radial symmetry in the division of heat. To simplify the task we suppose, that initial temperature is only a function of $r$. In that case $\frac{d^2T}{d\phi^2} = 0$ and $\frac{d^2T}{dx^2} = 0$, so

$$\frac{dT}{dt} = a\left(\frac{d^2T}{dr^2} + \frac{1}{r}\frac{d^2T}{dr}\right) \tag{21}$$

Using other mathematic operations and applying functions expressing the dependence on $r$ – U(r) and on $t$ – F(t) as

$$r^2\frac{d^2U}{dr^2} + r\frac{dU}{dr} + k^2r^2U = 0 \tag{22}$$

and

$$F = C_1 e^{-k^2 at} \tag{23}$$

Equation (22) is called Bessel equation. By its solution we get the division of heat in the section of breakdown channel.

## 3. Conclusions

The goal of this paper was to analyse the degradation processes in the vicinity of channels, which were created due to electric trees leading to breakdown channel in polymer insulations. The analysis was made using theory concerning thermal processes. Experiments have proved that similar behaviour was observed in case of materials of different chemical structure (silicone, epoxy), too. In future the analysis of volume electric forces occurring in electric breakdown channel.

## References

[1] **Lapp A.**: *Dissertation, Fachbereich Elektrotechnik BUGH Wuppertal*, Shaker Verlag 2000.

[2] **Marton K.**: *Thermal Processes in Vicininty of Channel of Electric Breakdown*, VII Sympozjum EUI99, Zakopane.

[3] **Marton K.**: *Classification on Volume Forces Contributed to Ageing of Polymeric Insulation*, Electoinsulating and Cable Technology, 53 No. 3, 2000.