

# Partial Discharges in Cavities and their Connection with Dipoles, Space Charges, and Some Phenomena Below Inception Voltage

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**Abstract**—This paper tries to relate Pedersen's model on partial discharges and work carried out by Bruning and co-workers on the possibility of the existence of charging phenomena below inception voltage, which may eventually cause deterioration of polymeric insulation. Moreover, with the aid of the Electromagnetic theory, some aspects of the Pedersen's model are tried to be clarified, especially those which are correlated with space charges, electric dipoles, charge distribution, charge dynamics, and partial discharge activity.

**Keywords**—Pedersen's model; partial discharges; dipoles; inception voltage; space charges

## I. INTRODUCTION

Pedersen's model [1] was proposed as an alternative to the traditional capacitive model [2, 3] for the interpretation and/or prediction of partial discharges in enclosed cavities in solid dielectrics. This model is based on electromagnetic theory and gives the magnitude  $q$  induced on the measuring electrode by the partial discharge in a cavity, in terms of a variety of parameters, as is shown in (1):

$$q = k\Omega\varepsilon_r\varepsilon_0 (E_i - E_l) \vec{\nabla}\lambda_0 \quad (1)$$

where  $k$  is the geometrical cavity factor,  $\Omega$  the cavity volume,  $E_i$  the inception electric field for streamer inception,  $E_l$  the limiting electric field for ionization,  $\varepsilon_r$  and  $\varepsilon_0$  are the relative permittivity of the surrounding dielectric material and the permittivity of the free space respectively, and  $\lambda_0$  is the function giving the ratio of the electric field at the position of the cavity (in the absence of the cavity) to the voltage between the electrodes. According to [1], the charge deposited on the cavity surface  $S$  can be considered as an electric dipole, the moment of which  $\mu$ , is given as:

$$\mu = \int r\sigma dS \quad (2)$$

where  $r$  is a radius vector which locates the position of the surface element  $dS$ . The induced charge which will eventually arise from the dipole is given as:

$$q = -\vec{\mu} \cdot \vec{\nabla}\lambda \quad (3)$$

with  $\lambda$  being a dimensionless scalar function which depends on

the position of  $dS$  only. Function  $\lambda$  is given by Laplace's equation:

$$\vec{\nabla}(\varepsilon\vec{\nabla}\lambda) = 0 \quad (4)$$

where  $\varepsilon$  is the permittivity of the insulating material and with the following boundary conditions:

- $\lambda=1$  at the electrodes where  $q$  is distributed,
- $\lambda=0$  at all other electrodes.

Moreover, authors in [4] utilized the principle of superposition with the calculation of D-field (Maxwellian approach) and the calculation of P-field (quasi-molecular description). In addition to this, the induced charge, according to [4], can be expressed as the difference between the charge on an electrode following discharge activity and the charge on the same electrode prior to the activity. At the Maxwellian approach (D-field) and the corresponding establishment of  $\lambda$ -function, all electrodes are supposed to hold at zero potential and the resulting electric field owned only to the space charges (and surface charges) in the interelectrode volume. Also in [5], the PD event is separated into two distinct time intervals:

- The 1<sup>st</sup> time interval is determined as the duration of the void discharge development  $0 < t < T_1$
- The 2<sup>nd</sup> time interval is the time following the cessation of discharge development  $T_1 < t < T_2$

where  $t$  denotes time,  $T_1$  denotes the duration of the void discharge development, and  $T_2$  is the time of occurrence of the next discharge. For  $T_1 < t < T_2$ , the induced charge  $q$  is given by either (12) for D-field analysis or (13) for P-field analysis

$$q = - \iint \lambda \sigma dS \quad (12)$$

$$q = - \iiint \delta P \cdot \nabla \varphi d\Omega - \iint_S \varphi \sigma dS \quad (13)$$

It is evident from the above that the notion of dipole and/or dipole moment plays a decisive role in Pedersen's model which tries to relate the partial discharge taking place in a cavity with the dipole moment of the charge distribution on the surface (or in the interior) of the cavity.

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II. PEDERSEN’S MODEL RE-CONSIDERED

A criticism leveled against Pedersen’s model was that it is confined to a certain type of partial discharges, namely that of streamer-type discharges and it cannot be applied to all types of discharges. It is a model rather for initial experimental conditions and not for an estimate of the long-term developed discharges [6]. Moreover, as was noted in [6],  $\lambda$  does not seem to be a function without physical meaning but it is the relative potential and can be expressed in terms of a percentage. However, even though there is a disagreement as to whether the net charge within the cavity remains zero [1, 6], it is evident from [1] that Pedersen’s model tries to relate dipole moment with charge dynamics inside the cavity and thus with even minute discharge currents. The resulted electric field at the void exerts forces causing charge generation, which consequently has as a result, electric dipoles appearance within the cavity. The partial discharge activity inside the void leads to charge distribution and redistribution inside the void, and thus, induced charge appears at the electrodes [1]. Shortly, dipole moments within the cavity are supposed to induce charges and eventually cause the recorded partial discharge currents. Consequently, it is reasonable to assume that, agreeing with [6], the net charge within the cavity is not zero. If the opposite is valid (i.e. net charge is zero), this cannot explain the findings of [7] as well as some ideas put forward by other people [8]. Charge dynamics means that even elementary charge motion can cause somehow minute currents that may circulate inside the insulating material. Such minute currents, related to charging phenomena below inception voltage, were noticed in [7], where it was remarked that chemical by-products below

and above the inception voltage were quite similar. Further work on polymers and nanocomposite polymers reinforced this viewpoint, namely that there were some below-inception charging phenomena [9-12]. To be sure, previous published work does not prove that such phenomena exist in all insulating materials but, at least, there are some indications that this may be the case. Further evidence that that may be the case comes from other sources as well [13].

The topic of very small partial discharges (barely detectable from partial discharge detectors) was dealt with in numerous publications [14-19], where it was discussed whether such small events are of pulsive or of non-pulsive nature. In [10, 20], it was remarked that, having an enclosed cavity in polyethylene, a conducting path caused the magnitude of quite low current pulses (1-10mA) which is substantially different and quite lower than current pulses of about 1A measured with other more conventional arrangements [21]. It was mentioned in [6] that there are doubts whether the net charge in a cavity is zero or can supposed to be equal to zero. However the fact that inside the cavity we have a dipole (or a number of dipoles or a distribution of dipoles) does not necessarily mean that the total electric charge is zero. Various approaches point out the possibility of having small currents (or small charge displacements) inside the dielectric causing phenomena that may not be detected, but which may still provoke damage. Thus the discussion of the pulsive or non-pulsive nature of partial discharge phenomena at and/or above inception voltage is shifted to a more fundamental question whether charge movement inside the dielectric causes deterioration, even below the inception voltage.

TABLE I. SHORT PRESENTATION OF THE D-FIELD AND P-FIELD ANALYSIS [4]

D-field (Maxwellian analysis)	P-field (Quasi-Molecular analysis)
<p>The induced charge depends in a unique way on the location and magnitude of the space charge. An infinitesimal <math>dQ</math> located anywhere in the interelectrode region induces charges <math>dq_i</math> at all over electrodes:</p> $dq_i = -\lambda dQ_i \quad (5)$	<p>The polarization <math>P</math> in the dielectrics is an important property, especially in insulating materials containing polarizable regions. The polarization effect is included in the <math>\lambda</math>-function in the D-field analysis. The whole interelectrode region is considered as a vacuum supposing that the solid dielectric itself is a distribution of electric dipoles, with polarization (density) <math>P</math>.</p> $d\mu = Qdr \quad (6)$
<p>Applying Green’s reciprocal theorem (7), two states are discriminated. In the first state, all electrodes are held at ground potential and the only charge left on the electrode will be the induced charge associated with the space charge, deposited in the space subtended by these electrodes. In the second state, <math>\rho=0, \sigma=0</math> everywhere, so all electrodes are at zero potential (8), (9).</p> $\iiint \rho \cdot V' d\tau = \iiint \rho' \cdot V d\tau \quad (7)$ $q_i \cdot U_{ci} + \iiint V_{ci} \rho d\Omega + \iint V_{ci} \sigma dS = 0 \quad (8)$ $q_i = - \iiint \lambda_i \rho d\Omega - \iint \lambda_i \sigma dS \quad (9)$	<p>The polarization <math>P</math> in a point of a solid dielectric depends on :</p> <p>Applied voltages (<math>P_a</math>) and space charge formed by partial discharge (<math>\Delta P</math>).</p> $P = P_a + \Delta P \quad (10)$ <p>The resulting induced charge on the <math>i</math>-th electrode is given by (11):</p> $q_i = - \iiint (\varphi_i \rho + \Delta P \cdot \nabla \varphi_i) d\Omega - \iint \varphi_i \sigma dS \quad (11)$

III. REMARKS ON CAVITIES IN RELATION TO PEDERSEN’S MODEL: DISCUSSION AND COMMENTS

There is a large amount of experimental data on cavities enclosed in insulating materials. Very often, however, the experimentalists do not go below 1mm or 0.1mm in radius [1, 22]. There is though some evidence that cavities may become dangerous even below such dimensions [23]. Certainly this is a topic needing further investigation. Further confirmation of the above is offered in [24], where computer calculations indicated that, in the case of electrical machine insulation, cavities as small as 0.01mm (or even smaller) in radius near a conductor, there may be electric fields as high as 25kV/mm. Other

evidence regarding the existence and effect of small cavities (in the range of up to 120µm) was recorded in [25], where work was carried out with photovoltaic modules and components. Moreover, a lot of emphasis was given in the past decades on the role of partial discharge detection by electrical means. In [25] offers another perspective, since it stresses the importance of both optical and electrical measurements. In [26] stresses also the limitations of the electrical measurements of PD. According to [26], simultaneous imaging and PD measurements may reveal the successive stages of some treeing growth phenomena. Studying a cavity, one should not forget that its surface may not necessarily be smooth. In other words, its surface may have protrusions, not necessarily metallic but

consisted of dielectric material. Recent research reveals that dielectric protrusions may be the sites of high field intensifications and thus contribute to the breakdown mechanism [27]. Such data agree with preliminary efforts in [9, 10], where it was indicated that even small irregularities on the surface of the cavity can contribute to the rise of minute currents below inception. A further remark concerning the PD-extinction voltage: this can be determined with limited accuracy because of the influence from temperature and humidity [28]. Even without such parameters, PD-extinction voltage may somehow vary from measurement to measurement due to the highly statistical nature of PD phenomena. This may be a further indication as to the possibility of charging events below inception.

The whole issue of damage below inception voltage (which we try to relate with charge packets) is not unrelated to the uncertainties of defining the level of inception [29]. Moreover, material composition plays a crucial role in determining the inception voltage [30]. Cavity position affects also the inception voltage [31]. Yet on another question related to considerations developed in [7], namely that charging phenomena are possible below inception voltage (because of some minute irregularities on the cavity surface), there is some indirect confirmation in [32], where the morphology and surface topography of polyethylene may affect space charge packet characteristics. Although the authors of [32] do not mention partial discharges and related phenomena, it is evident that surface treatment plays a role in determining charge packets. In agreement to the above, in [33] it is noted that the formation of packet-like charge is a result of a high conductivity region that is caused when traps are filled by electronic carriers (electrons or holes). In [34], various partial discharge models are presented. In all models, the role played by surface charge accumulation is evident. Furthermore, gas conductivity inside a cavity is also important. Such comments – on gas conductivity – were made earlier [7,9]. However, gas conductivity may appear even in the absence of partial discharges, conductivity which will not necessarily be “translated” (or transformed) into something detectable. Such ideas conform to [35], where it was reported that in minute cavities partial discharges may have very long statistical time lag and the number of initial electrons may indeed be very small. In relatively low voltages, ionization processes of low energy may occur, which means that charges appearing in the cavity may result to clusters of space charges on the cavity walls. Such a space charge results in an electric field which – in the case of AC fields - is added to the applied electric field on the insulation [36]. Although what was described is the normal process of a PD, no one can exclude the possibility of having such events even below the inception voltage.

A careful reader can observe that the whole approach of space charge phenomena is related to the model proposed many years ago by some distinguished researchers [37], namely that the electrodes, under AC conditions, inject and extract charges. Some electrons are emitted or injected into the dielectric during the negative half cycle for a short distance, limited by the declining stress away from the points. They will be drawn back into the point on the positive half cycle and re-injected in the following cycle. On each cycle some of the electrons will gain

sufficient energy to cause some polymer decomposition and thus create space charges in the bulk of the polymer. The estimated distance within which injected electrons can interact with the material to produce electrical trees near the tip of a needle is thought to be less than 20µm. Tree initiation time (*t*) is related to the electric field (*E*), the effective work function  $\phi$  (i.e. the difference between the work function of a metal and the electron affinity of a dielectric) with the following equation

$$\ln(t) = B\phi^{3/2} / E + \ln(C/A) \quad (14)$$

where *A*, *B*, and *C* are constants.

Moreover, in [1], it is stated that  $\lambda$  function is given by:

$$\vec{\nabla}(\epsilon\vec{\nabla}\lambda) = 0 \quad (4)$$

where  $\epsilon$  is the permittivity of the dielectric. Solving the above equation in the appropriate area of interest,  $\lambda$  can be evaluated. Initially, none can ignore that the space where the above equation is solved, includes, conducting (electrode, ionized air void), non-conductive (dielectric) and of course interfaces between the aforementioned materials. The analysis in [1, 5], needs more clarification, because (4) is Laplacian, while in all interfaces, in the interior of the solid dielectrics, at the electrodes and inside the air void, space charges are present, determining the electric potential distribution. Shortly, in [1, 5], the authors prove with a Maxwellian approach for  $\lambda$  function :

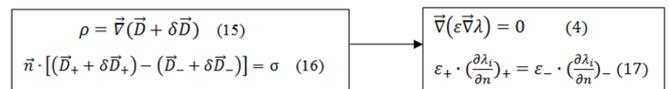


Fig. 1. After PD activity, the presence of space charge in the void is considered to be Poissonian (left rectangle). In [5], after a Maxwellian analysis, (4) with the conditions (17) which are Laplacian, are finally utilized (right rectangle).

So, in [5], it is stated clearly that the defining equation of  $\lambda_i$  is:

$$q_i = - \iiint \lambda_i \rho d\Omega - \iint \lambda_i \sigma dS \quad (9)$$

The first integral corresponds to the space charge in all space  $\Omega$  between the electrodes (consequently including air void) and the second integral calculates the surface charge between dielectrics (at the interfaces between them). The discrimination of electric field into basic Laplace and Poisson (general and basic) field also needs more clarification since, among others, uses in [5]:

$$\rho = \vec{\nabla}\delta\vec{D} \quad (18)$$

while the divergence of electric displacement *D* depends only on the free charge density [38]:

$$\rho_{total} = \rho = \rho_f + \rho_b = \rho_f - \vec{\nabla} \cdot \vec{P} \quad (19)$$

$$\oint \vec{D} \cdot \vec{dS} = Q_f = \int_{\tau} \rho_f d\tau \quad (20)$$

$$\oint \vec{D} \cdot \vec{dS} = \int_{\tau} \vec{\nabla} \cdot \vec{D} d\tau \quad (21)$$

Comparing (20) and (21), results to:

$$\rho_f = \vec{\nabla} \cdot \vec{D} \quad (22)$$

In addition to this, in [5], the electric field is assumed to be Laplacian, before the PD activity and after PD activity, the presence of space charges in the void dictates us to solve Poisson's equation. In a mixed system, constituting from at least 2 electrodes, one solid dielectric and one air void enclosed in the aforementioned solid insulator, the voltage application  $U$  at the electrodes, creates space charges. The existence of space charges does not depend on the occurrence of a PD activity or not. Generally speaking, space charges are localized states of charge, deriving from various sources.

A first source of space charges is the polarization that took place at the dielectric. Every molecule of the solid dielectric in the interelectrode area, before the electric field application, may exist in two states. Either the molecule has symmetrical distribution of the electric charge, with a coincidence of the negative and positive charge (zero dipole moment), or it is polarized due to the asymmetry in the negative charge distribution (non-zero dipole moment or permanent dipole moment). After the electric field application, the molecules of the first category gain an induced dipole moment due to the separation of the centers of positive and negative charge distributions. Molecules of the second category rotate into the direction of the field. As it is known from Fundamental Electromagnetism, dielectric hysteresis loop appear in solid dielectrics, but in the present paper relaxation time for solid dielectrics is not taken into account, similarly with [1, 5]. Moreover, the interelectrode system includes the air void. It is known that the electric field inside an air slit enclosed in a solid dielectric is  $k$  times bigger than the mean electric field.

$$E_0 = \varepsilon \cdot E_{mean} \quad (23)$$

where  $E_0$  is the value of the electric field inside the air void,  $\varepsilon$  is the relative permittivity of the dielectric (dielectric constant) and  $E_{mean}$  is the mean value of the electric field inside the dielectric. The bigger value of  $E_0$  is due to the polarization charges in the interior of air void. Of course, (23) is valid whether partial discharge sparks inside the air void or not. Thus, a dielectric after a voltage application shows polarization and/or polar charges at various positions, which in turn is itself one of the major factors for the space charge existence, independently or not from the PD activity.

$$\rho_b = -\vec{\nabla} \cdot \vec{P} \quad (24)$$

A second source, contributing to space charges, independently again from the PD occurrence or not, are the free charges. In our system (electrodes, solid dielectric, air void, interfaces), free charges exist at:

- electrodes (before PD as charge  $q$  and after PD as  $q+q_{induced}$ ) and
- air void (before PD and after PD).

at the region in front of the injecting electrode. This procedure is most common and usual from point electrode. The space charge injection distorts the electric field and reduces or enhances the local electric strength, in the region around the tip of the needle electrode. In case of homocharges, reduces the electric field  $E$  and in case of heterocharges enhances the local electric field. This category is free charges which have lost

their kinetic energy to break bonds and they have converted to thermal ones.

TABLE II. TWO SITUATIONS FOR POTENTIAL AND CHARGE BEFORE AND AFTER INDUCED CHARGE APPEARANCE ON THE ELECTRODE.

1 <sup>st</sup> state (before PD)	2 <sup>nd</sup> state (after PD)
Volume and surface density are equal to zero $\rho=0, \sigma=0$ .	All electrodes are held in ground potential.
One electrode (the $i$ -th electrode) has potential $U_{ci}$ .	Almost all charges (linked with partial capacitances) are zero.
All other electrodes are at zero potential.	The only charges left on the electrode will be the induced charges associated with space charges.

So, it is evident, that space charges (free charges and polarization charges), exist at the interelectrode area, after the voltage application and their existence is not dependent from the occurrence or not of the partial discharge activity in the interior of the enclosed air void. Thus, the electric field, after voltage application is not Laplacian but it is clearly Poissonian. The electric field, of course, is Poissonian before and after PD activity. It must be pointed out that in [4], a fundamental theorem of Electromagnetism, Green's Reciprocal Theorem, [39, 40] is utilized according the following:

According to [39], the Green reciprocal theorem states that if separate charge densities  $\rho$  and  $\rho'$  then give rise to electric potentials  $V$  and  $V'$  respectively having as a result :

$$\iiint \rho \cdot V' d\tau = \iiint \rho' \cdot V d\tau \quad (25)$$

In case, the charge resides solely to the surfaces of  $n$  fixed conductors:

$$\sum_{i=1}^n q_i \cdot V_i' = \sum_{i=1}^n q_i' \cdot V_i \quad (26)$$

where charges  $q_i$  on the conductors correspond to respective potential  $V_i$  and charges  $q_i'$  correspond to  $V_i'$ .

Applying Green's reciprocal Theorem in a system containing electrodes, void, dielectric and interfaces before and after partial discharge activity (Table I), the following equation is used in [39]:

$$q_i \cdot U_{ci} + \iiint V_{ci} \rho d\Omega + \iint V_{ci} \sigma dS = 0 \quad (27)$$

where  $U_{ci}$  is the applied Voltage and  $V_{ci}$  is the scalar potential at  $d\Omega$  and  $dS$ .

A point of further investigation is the application of (26), which refers to charges residing solely to conductors (e.g. electrodes). At conductors, normally there are free charges  $\rho_f$  and not polarized charges. In (27), volume charge density  $\rho$  includes, among others, the polarized charges (bound charges per unit area) in the interior of the solid insulating material. These charges are not free charges. Furthermore in (27), charges before PD activity (either in the form of volume density  $\rho$  or in the form of surface density  $\sigma$  are equal to zero  $\rho=0, \sigma=0$ ). This is the reason which the second term in (27) (or the second term in (25), (26)), is equal to zero. This hypothesis neglects the various charges, mostly bound polarized charges which form and appear inside solid dielectric in the time period, after the voltage application and before the partial discharge activity. Finally, in [1] it is stated that the dipole

moment of a charge distribution left on the surface of an ellipsoid is given by the following equation :

$$\vec{\mu} = \frac{8\pi\epsilon}{3A} [\vec{E}_0 - \left[1 + \frac{abcA(\epsilon_0 - \epsilon)}{2\epsilon}\right] \vec{E}_l] \quad (28)$$

where  $a, b, c$  are the semiaxes of the ellipsoid,  $E_0$  is the ambient field when the internal field is equal to the inception field  $E_i$  and  $E_l$  is the limiting field when the discharge is quenched. Equation (28), is one of the basic equations leading finally to (1). However, in [41], there is a clear discrimination for the potential calculation  $\phi$  as can be seen in Table III.

TABLE III. POTENTIAL EXPRESSIONS  $\phi$  FOR TWO KINDS OF ELLIPSOID (CONDUCTING AND DIELECTRIC) INSIDE A PARALLEL ELECTRICAL FIELD [41]

Conducting ellipsoid in parallel field	Dielectric ellipsoid in parallel field
<p>The potential at the ellipsoid is a constant <math>\phi_s</math>,</p> $\phi_s = \phi_0 \left[1 + \frac{c_2}{c_1} \int_0^\infty \frac{d\xi}{(\xi + a^2)R\xi}\right] \quad (29)$	<p>The potential at any interior point of the ellipsoid:</p> $\phi^- = - \frac{E_0 x \chi}{1 + \frac{abc}{2\epsilon_2}(\epsilon_1 - \epsilon_2)A_1} \quad (30)$ <p>And the field intensity in the interior of the dielectric ellipsoid is:</p> $E_x^- = \frac{E_0 x}{1 + \frac{abc}{2\epsilon_2}(\epsilon_1 - \epsilon_2)A_1} \quad (31)$

Equation (31), belonging to the case of a dielectric ellipsoid inside a parallel electrical field, according to [41], is apparently a part of (28), or has close relation with the analysis about a dielectric sphere inside a parallel field. Equation (28), in [1], which calculates the dipole moment inside an ellipsoid needs further clarification because it seems to correspond to the case of dielectric ellipsoid and how it affects the electric field inside and outside the ellipsoid. The ellipsoid after PD activity, is conducting, due to the electrons, positive and negative ions produced during the ionization activity. The ellipsoid, before the PD activity can be considered to be insulating (dielectric e.g. air) but (28) and the final important equation (1), are utilized for induced charge calculation, which is a phenomenon which clearly happened after PD activity. It seems that (28), as referred to [1], is not compatible with the conducting behavior of the void after pd activity.

Recapitulating we may say that the present paper tries to clarify some aspects of Pedersen's model about the induced charge after PD activity. There is no proposal of a new model but a criticism is presented of a very important model from two different aspects. The first aspect is concerned with experimental data below the so-called inception voltage whereas the second aspect is related to the electromagnetic theory and mostly to the conducting behavior of dielectric materials. An effort was made – in the context of the present work – to enlighten some aspects of Pedersen's model. Furthermore, the present paper – as is evident from the title – tries to correlate PD activity with space charges and electric dipoles under the prism of electromagnetic theory.

It is true that a criticism may be levelled in the fact that Pedersen's model is rather old. However, it remains one of the most prominent and used models regarding PD activity and the authors consider that it has significant explanatory power. It is also true that the authors use many references published long time ago. It is also true that more recent criticism of Pedersen's

model has been published [42, 43], their comments, however, are beyond the scope of the present paper since they are concerned with the notion of capacitance.

#### IV. CONCLUSION

The present paper tries to enlighten some aspects of the Pedersen model relating partial discharge activity inside air voids and the induced charge at the electrodes after PD activity and charge redistribution. Electromagnetic analysis is fundamental in Pedersen's model and in the present paper some points which need further investigation are demonstrated. The discrimination between conducting and insulating air void, the presence or not of space charges in the interelectrode area, the precise description of the charge kinetics after the voltage application and before partial discharge activity, the role of dipoles and dipole moments, the partial activity below inception voltage, the cavity dimension (especially those with dimensions less than 0.1mm), the PD extinction voltage are some points which are analyzed in the present paper and an effort of a correlation with Pedersen's model is being made.

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