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DC negative corona discharge characteristics in air flowing transversely and longitudinally through a needle-plate electrode gap

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ABSTRACT

The electrical characteristics of a steady-state DC negative corona discharge in air flowing transversely or longitudinally in relation to the needle-to-plate (or mesh) electrode axis were experimentally investigated. The velocity of air flowing into the corona discharge chamber was limited to a range from 0 to 6 m/s, typical of electrostatic precipitators, gas ionisation sensors and EHD pumps. The investigations showed that in this airflow velocity range three discharge current modes of the DC negative corona could exist: the Trichel-pulse corona mode, the 'Trichel pulses superimposed on the steady current (or DC) component' mode and the steady glow (the steady current or DC) corona mode, regardless of the airflow direction. The average corona discharge current, which is a macroscopic corona discharge parameter, was almost not affected by the airflow. However, both microscopic corona discharge parameters: the electric charge and the repetition frequency of Trichel pulses were influenced by the airflow. The transverse airflow caused an increase in the electric charge and a decrease in the repetition rate of Trichel pulses, the both by about 25% at a velocity of 6 m/s. In the case of longitudinal airflow the average corona current slightly increased when the airflow was directed towards the mesh and decreased when the airflow was directed towards the needle tip. Similarly as in the case of transverse airflow, the electric charge and the repetition frequency of Trichel pulses were affected by the longitudinal airflow. The electric charge and the repetition frequency of Trichel pulses increased and decreased, respectively, with growing airflow in the direction towards the needle electrode. The airflow growing in the direction towards the mesh electrode produced the opposite effect - the electric charge and the repetition frequency of Trichel pulses decreased and increased, respectively. The opposite behaviours of the electric charge and the repetition frequency of Trichel pulses with growing airflow velocity could explain the weak dependence of the negative corona average current on transverse or longitudinal airflow. Therefore, the independence of the negative corona average current of the airflow cannot be considered as sufficient proof that the airflow (up to 6 m/s) does not affect the negative corona parameters.

1. Introduction

The DC negative corona discharges have been subjected to intensive experimental and theoretical studies for more than 80 years. The vast majority of these studies concerned the negative coronas in air which has not being subjected to any external flow-inducing forces (a secondary electrohydrodynamic (EHD) flow induced by the corona in air is not regarded as an external flow actuator). According to the commonly accepted results of these studies, the steady-state discharge in air above the corona threshold results in the generation of regular current pulses the frequency range of which may extend to megahertz. The early (1938–1962) basic studies of the regular current pulses (named the Trichel pulses) of DC negative corona in air, were carried out by Trichel [1], Loeb's group and others [2]. The main results of these early studies were analytically summarised and experimentally verified in Ref. [3]. The basic data and results of the negative corona studies until the 1980s were also collected in Refs. [4,5]. Afterwards hundreds of new contributions to the knowledge of DC negative coronas in still air (subjected only to the internal EHD flow after the onset) have been published.

In contrast, there are scarce works on the fundamentals of DC negative corona discharges in flowing air caused by external forces. This is surprising because in many industrial applications of corona discharges, the discharge is run in air flowing through the corona devices (e.g. in electrostatic precipitators [6], gas ionisation sensors [7] and EHD pumps [8]).

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Probably the first regular laboratory studies on the sensitivity of corona discharges (the average corona current in the minisphere-to-minisphere electrode configuration) to airflow have been carried out at the turn of the 1940s and 1950s the by Fucks and his group [9]. Afterwards, this kind of research was continued outdoors in the so-called point-corona discharges (from a point electrode attached to a captive balloon or an earthed point electrode raised above the earth's surface) in the atmospheric potential gradient [10]. Then the point-corona discharge experimental investigations were transferred into wind tunnels [11,12]. Concurrently, theoretical works on explanation of the observational results were carried out [13–15]. These early works, experimental and theoretical, established clearly the influence of the airflow on the average corona discharge current. The first laboratory investigation on the airflow effect on Trichel pulses generated between the needle-to-plate electrode arrangement was seemingly carried out by Chalmers in 1965 [16]. Our analysis of this and later published literature will be limited to those results which pertain to airflow velocities lower than 6 m/s in the needle-to-plate electrode arrangement. Besides, analysing the literature, we will take into account not only the effect of airflow magnitude, but also the effect of airflow direction in relation to the negative corona main current flow from the needle tip. We will distinguish: a transverse airflow direction (in which the air flows perpendicularly to the needle-to-plate axis), and two longitudinal airflows (in which the air flows along the needle-to-plate axis either away from the needle tip or towards it). All directions can have a different influence on the behaviour of the negative corona. It is also important to define the negative corona mode (the Trichel-pulse corona mode, the ‘Trichel pulses superimposed on the steady current component’ mode and the steady glow corona mode), to which the previous results pertain. Chalmers, mentioned above, studied the effect of longitudinally flowing air from the needle tip (along the direction of the corona main current flow) in Trichel-pulse mode [16]. Surprisingly, the conclusions derived by Chalmers from his rather preliminary investigation (no records of the average corona discharge, the Trichel pulse amplitude, charge and repetition frequency, and Trichel pulse “shape”) have remained incontestable to date. Chalmers concluded that with the air flowing along the direction of the corona main current flow from the needle tip the average discharge current increases, the amplitude and charge of the Trichel pulse increases, the Trichel pulse frequency decreases and the Trichel pulse “shape” remains unaltered by the airflow. In 1966 Nygaard studied the effect of transverse airflow (the velocity up to 18 m/s) on DC corona Trichel pulses between a needle and a plate at atmospheric pressure [17]. He found that at a constant applied voltage, the average corona current increased with increasing the airflow velocity. At a constant average discharge current, an increase in the airflow velocity resulted in a pronounced decrease in the Trichel pulse repetition frequency, which meant an increase in the average number of electric charges per Trichel pulse. Nygaard, however, did not confirm that obvious expectation by measurement. It is interesting that the majority of the Trichel pulse repetition frequency increase occurred in an airflow velocity range below 7 m/s. This is in contrary to the common opinion that higher airflow velocities should influence the negative corona more strongly. The 1960s and 1970s, studies of DC negative corona discharges in flowing air were also motivated by interest in ion sources (e.g. for the gasdynamic energy conversion). In 1969, Bortnikov et al. published a paper [18] on the influence of longitudinal airflow with relatively high velocities (up to 440 m/s, for comparing the velocities of the “air” ions in still air is below 100 m/s) on the average negative point-to-plane corona current. They reported that in the longitudinal airflow against the needle electrode tip, the average corona current decreased with increasing airflow velocity (by about 2.5% at a velocity of 8 m/s), while in the air flowing along the needle-to-plate axis away from the needle tip, the average corona current increased (by about 0.8% at a velocity of 8 m/s). The authors explain the decrease and increase in the average corona current by a decrease and increase of the ion velocities in the corona drift region, respectively. None of the data on the negative corona mode were reported in Ref. [18]. Akishev et al. (1997) [19,20] studied the possibility of active control of the amplitude and repetition frequency of Trichel pulses by changing the velocity (in a range up to 120 m/s) of air flowing towards the needle tip along the corona discharge needle-to-mesh electrode arrangement. In agreement with the earlier results, they recorded an increase in the amplitude of the Trichel pulses (by about 5% when increasing the velocity to 6 m/s) and a decrease in their repetition rate (by about 2.5%). Jaworek and Krupa [21,22] studied a multipoint-to-plate corona configuration in transverse airflow. They found that even for low airflow velocities (up to 4 m/s) the DC positive corona discharge current-voltage characteristics were modified significantly, while in the case of a DC negative corona, they did not observe changes in the discharge current amplitude. However, their conclusions pertaining to the multipoint-to-plate corona cannot directly be transferred to the case of the single needle-to-plate configuration. Ichikawa et al. (2005) [23] investigated Trichel pulse formation varying the transverse airflow velocity near the needle electrode tip from 0 to 7 m/s. They found that the most sensitive corona region to the transverse airflow is 1 mm around the needle electrode tip, where the accumulation of the positive and negative ions occurs. The observed decrease in the Trichel pulse repetition rate with increasing airflow velocity is attributed by the authors to blowing off the negative and positive space charges from the needle tip region. Recently, using telemicroscopy Amirov et al. (2016) [24] studied the effect of transverse airflow (velocity of 5–100 m/s) on the behaviour of the negative corona discharge on the needle electrode tip surface. They found that the Trichel pulse discharge localisation on the needle tip surface changed (with respect to that in the flow-absent case), when the incoming flow velocity exceeded 10 m/s. The relocation of the Trichel pulse discharge on the tip surface is attributed by the authors to the removal of negative and positive ions by the airflow from the cathode surface area (i.e. similar to what Ichikawa et al. claimed). The authors, however, did not study any relations between the Trichel pulse discharge relocalisation on the needle tip surface and the characteristics of the Trichel pulses (pulse repetition frequency, current magnitude, etc.).

A numerical simulation study of the influence of longitudinal airflow (velocity up to 30 m/s) on the negative corona properties in the needle-to-mesh electrode arrangement was carried out by Zhao and Adamiak in 2009 [25]. Their conclusions were that at a constant applied voltage, the average corona current increases (by about 8% at 6 m/s) with the increase of the airflow directed towards the mesh electrode (in the negative ion drift direction), and it decreases (by about 2.5% at 6 m/s) when the airflow direction is opposite (against the negative ion drift direction). Also Deng et al. (2013) [26] studied numerically the Trichel pulse mode of negative coronas in transverse and longitudinal airflows (velocity up to 18 m/s). Their numerical calculations show that the Trichel repetition rate decreases (by 12% at 6 m/s) and the Trichel pulse amplitude increases (by 6% at 6 m/s) when the transverse airflow velocity increases, which is qualitatively consistent with the previous experimental results. However, according to the authors, this is due to a decrease of the secondary electron emission on the discharge electrode rather than due to the removal of the negative ions from the vital corona region. In the case of the longitudinal airflow, Deng et al. found that when the air flowed towards the needle tip, an increase in the airflow velocity resulted in a decrease of the Trichel pulse repetition (by about 2.5% at 6 m/s). When the airflow was directed towards the mesh electrode, an increase in the airflow velocity caused an increase in the repetition frequency of Trichel pulses (by about 2% at 6 m/s). These effects can be fully explained by the slowing down or speeding up of the removal of the negative ions by the airflow.

As this short overview clearly shows, the role of airflow in the changes of the characteristics of the negative corona have not been studied sufficiently. There was a lack of comprehensive experimental and theoretical studies in this subject. The existing data are scarce, selective and sometimes controversial. The other papers are only