Using an optical fibre anemometer to measure the speed of the electric wind in a negative polarity, atmospheric corona discharge

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Abstract. Coronas are partial discharges that occur in regions of non-uniform electric fields adjacent to conductors stressed to high voltages. Negative, Trichel-pulse coronas in air occur when a dc, negative-polarity, high voltage is applied to a conductor. Trichel pulses in atmospheric air generate significant amounts of ozone as well as electrical and acoustic noise. Under the right conditions these coronas can be a precursor to complete electrical breakdown of the air gap due to a reduction in the density of neutral molecules resulting from a combination of localised heating and convective air flow generated by the movement of negative ions. An optical fibre anemometer, based on a Mach-Zehnder interferometer has been constructed to measure the speed of the wind generated in the point-plane gap of a negative, Trichel-pulse corona discharge in atmospheric air. The sensing arm of the fibre interferometer is subjected to controlled, repetitive bursts of infrared radiation from a CO₂ laser and the combination of localised heating and convective cooling by the corona wind results in fringe shifts which are directly calibrated to the speed of the wind. This paper reports on the nature of the calibration process and presents some radial profiles of wind speed in the corona gap.

1. Introduction

In a gas under the influence of a strong external electric field, free electrons are accelerated and undergo collisions with neutral gas atoms or molecules. Depending on the gas density (\(N\), the number of atoms or molecules m\(^{-3}\)) and local the electric field (\(E\)), electrons may gain sufficient energy to undergo ionising collisions with the gas species, thereby producing more electrons and positive ions, or if there are electronegative atoms/molecules present, may become attached to form negative ions. Photons produced in certain electron-capture collisions may result in further ionisation via photoionisation. If the electric field is sufficiently high, such that ionisation exceeds attachment, complete breakdown of the gas may occur via electron avalanches, especially where photoionisation occurs as this provides a mechanism for very fast, and relatively extensive ionisation events to occur. In addition to the role played by the ratio of \(E/N\), the exact form of electrical breakdown in a gas will also be determined by the divergence of the external electric field. In a uniform electric field in air, electrical breakdown results in significant levels of ionisation occurring in the entire gaseous region. However in the case of a highly divergent field in air, ionisation may exceed attachment in the high field region only, but collisions will be dominated by attachment to electronegative oxygen molecules.
in the low field region. This is the situation that usually occurs near the surface of an open-air electrical conductor stressed to high voltages, especially if its surface is scratched, pitted or coated with dust or crystals. The end result is a localised, or partial, discharge known as a corona discharge \[1, 2\]. Electrical coronas are described according to the polarity of the stressed conductor; positive or negative in the case of a dc voltage, or ac. Electrical coronas are an unwanted phenomena in the high-voltage industry as they produce charged particles, electrical and acoustic noise, chemical by-products (including ozone in air [3], or oxyfluorides and HF in SF$_6$ – a widely used gaseous insulator [4]) and may be a precursor to complete arc or spark breakdown through their effect on reducing $N$ in the gaseous medium [5]. However, some of these properties, namely charge and chemical production sees them also applied in electrostatic precipitators in industrial chimneys and photocopiers, or in ozone generators.

One other by-product of electrical coronas is the corona wind [6]. Ions produced in electrical coronas drift in the low field region and collide with neutral species via elastic collisions. The resulting momentum transfer generates a flow of gas away from the highly-stressed region and this is manifest as a wind. The phenomenon is much the same as that wind which occurs at the base of waterfalls or in your bathroom shower. As this gas flow results in a reduction of $N$ [7], and can impact on the characteristics of the electrical discharge itself, measuring the speed of the corona wind assists in the understanding of the dynamics of these partial discharges as well as their contribution to more catastrophic electrical breakdown phenomena such as arcs or sparks. However, measuring the speed of the corona wind poses numerous challenges; namely the spatial extent is likely to be very small (centimetres), and the environment in which they occur is characterised by strong electric fields. This precludes the use of bulky sensing devices such as fan- or cup-anemometers, or conventional electronic sensors involving electrical conductors. A class of sensors based on optical fibres, however, is potentially applicable in this adverse environment.

Optical fibres are generally circular dielectric waveguides made of fused silica or plastics. A central fibre core, of higher refractive index is surrounded by concentric cladding of lower refractive index, and this in turn is encapsulated in a plastic, protective jacket. The difference in refractive indices of the core and cladding is such that light, when directed (or coupled) into the core of an optical fibre, is trapped and propagates along the fibre core via total internal reflection at the core-cladding interface. Typical optical fibres have cores ranging from 10 to 1000 $\mu$m in diameter and are most widely known for their role in telecommunications. However, optical fibres also find many uses, both as extrinsic and intrinsic components of chemical and physical sensors [8, 9]. A combination of their small dimensions, their construction from dielectric materials and the fact that the propagating radiation is impervious to EM interference makes them a suitable modality for their application in high-voltage environments.

In previous work, an optical fibre anemometer was constructed for sensing the corona wind in positive-polarity coronas [10]. Here a Mach-Zehnder interferometer was constructed using 125 $\mu$m-diameter optical fibre, and a CW CO$_2$ laser beam used to heat a small section of the sensing arm of the interferometer in the presence of the cooling effects of the corona wind. Fringe shifts, resulting from the localised heating, and cooling were initially calibrated to known gas flow rates and laser heating times. The same arm of the interferometer was then inserted within the inter-electrode gap of a 20-mm, point-plane, positive glow corona in atmospheric air. Corona wind speeds of up to 5.5 m s$^{-1}$ were observed in the discharge axis at 1 mm below the point electrode, reducing to 2.6 m s$^{-1}$ in the discharge axis at 8 mm below the point electrode.

The aim of this present paper is to report on measurements of the corona wind speed in negative Trichel-pulse corona discharges in atmospheric air using a refined version of the optical fibre anemometer described by Lamb and Woolsey [10]. To date, the corona wind speed in negative-polarity atmospheric coronas has only been measured using laser-Doppler anemometry (LDA) [11]; an
optical technique whereby two coherent laser beams (generated by splitting a single beam) are crossed in the inter-electrode space of a corona discharge and the light scattered by seed particles crossing the interference zone within the crossed beams is detected by a nearby photodetector. However, LDA has a number of limitations which include the fact that the presence of seeding particles have been observed to perturb the corona discharge [11], and, if they become electrostatically charged, have a velocity that is also influenced by Coulomb forces between the local electric field and the seed particles themselves [12, 13, 14]. The latter is most likely to be the reason why theoretical calculations of the corona wind speed (in negative Trichel-pulse coronas) and actual measurements using LDA do not appear to agree [11].

2. Materials and methods

A schematic diagram of the electrical corona apparatus, and refined anemometer arrangement, is depicted in Figure 1.

![Schematic diagram of the negative polarity, Trichel-pulse corona apparatus and Mach-Zehnder interferometer assembly for measuring the speed of the corona wind. For calibration of the interferometer, the high-voltage electrode was replaced with a hollow nozzle through which varying flow-rates of air was introduced.](image)

A negative polarity, Trichel-pulse corona discharge was generated in atmospheric air by applying a negative voltage of 12 kV from a dc power supply (0-50 kV, Glassman, Series EH, Whitehouse, New Jersey USA) to a hyperboloidal point electrode (6° hyperboloidal tip) in a 20-mm point-plane gap configuration. The discharge voltage was monitored using a high-voltage probe (Fluke, Model 80K, Everitt WA USA) connected to a digital voltmeter (DataPrecision, Model 1350, Wakefield MA USA). A Mach-Zehnder interferometer was constructed using two –3dB 1 x 2 couplers (single-mode at 633 nm) (AOFR,Model S500605, Symonston ACT Aust.). Light from a polarised 5mW He-Ne laser (λ = 633 nm, Meredith Instruments, Glendale AZ USA) was coupled into the ‘upstream’ fibre of the first coupler using a precision optical coupler (M-F-91TS, Newport, Irvine CA USA). This light emerged from the coupler, split equally, into the two downstream fibres of the coupler, and was subsequently recombined into a single fibre via the reverse process using a second –3dB 1 x 2 coupler. Due to interference between the beams re-combined in the second coupler, interference fringes, fringe shifts were observed as a change in intensity of the radiation emerging downstream from the coupler. One of the two fibres between the two couplers was designated the
sensing fibre of the interferometer, and to this fibre an additional short length of single-mode (633 nm) optical fibre (Newport FSV, Irvine, CA USA) was patched in between the two couplers. This fibre was destined to be subjected to the CO2 laser beam and cooling effects of the corona wind. The second of the two fibre ‘arms’ of the interferometer, designated the reference arm, was insulated from the corona wind and CO2 laser beam.

Controlled bursts of infrared radiation ($\lambda = 10.6 \mu m$) were directed from the CO2 laser (20 W, Synrad Model D-48-1-115, Bothell WA USA) at the section of the sensing fibre immersed in the region of corona wind to be measured. The section of heated fibre was estimated to be 2 mm in length. Radiation bursts, of 235 msec duration and a duty cycle of 80%, were produced at a frequency of 850 MHz using a TTL control pulse provided from a waveform generator (Hewlett Packard, Model 3312A, Palo Alto, CA USA). In response to the localised heating of the sensing fibre, a fringe shift was observed to occur at the downstream fibre of the second –3dB coupler. Fringe shifts were observed using a photodiode (UDT Pin 6D1, Hawthorne, CA USA) connected to a digital storage oscilloscope (150 MHz, LeCroy Model 9410, Chestnut Ridge, NY USA).

The discharge axis was vertical. In order to obtain corona wind measurements at different radial locations within the point-plane gap, the discharge chamber was mounted on cylindrical bearings and the chamber could be continuously displaced horizontally using a threaded drive, calibrated to millimetres of displacement. In order to collect these radial measurements at different vertical positions along the discharge axis, the entire sensing arm of the interferometer was mounted on a mechanical arm attached to a vertical displacement stage.

Initial calibration of the optical fibre interferometer was completed by replacing the high-voltage electrode with a hollow stainless-steel tube of 5 mm diameter. This could be inserted within the hv feed-through of the discharge chamber without disturbing the interferometer apparatus or chamber housing. Dry cylinder air was fed through the tube, and over the sensing arm of the interferometer, at speeds ranging from 0 – 2 m s$^{-1}$ and the speed monitored using a volume flowmeter (Top-Trak, Model 824-1, Monterey CA USA) previously calibrated to gas flow speed emerging from the nozzle using a miniature fan-anemometer (Silva Windwatch, 0.1 m s$^{-1}$ sensitivity, Silva Sweden).

3. Results and discussion

A reproduction of the fringe shifts resulting from a burst of CO2 laser radiation on the sensing arm of the interferometer is depicted in figure 2. While often noisy, the fringe shifts that occurred during each pulse could easily be counted to an accuracy of $1/8$ of a fringe. The calibration curve resulting from heating the sensing fibre in the presence of known flow speeds of dry air is reproduced in figure 3.

![Figure 2. Re-created oscilloscope trace showing fringe shifts (lower trace) resulting from the CO2 laser pulse (upper trace). Note the reversal of fringe movement upon cessation of pulse duration = 235 ms](image)

![Figure 3. Calibration curve generated by heating the sensing fibre in the presence of known flow speeds of air emerging from a nozzle.](image)
the heating pulse.

Radial profiles of the corona wind speeds, as measured at two axial positions in the gas discharge, are given in figure 4.

**Figure 4.** Radial wind-speed profiles for a −12kV, Trichel pulse corona in atmospheric air, $I \approx 16 \mu A$. Radial profiles are acquired 5 mm (♦) and 10 mm (○) below the point.

Foremost evident in these data is the fact that the wind speeds observed in our negative corona discharges are approximately one order of magnitude lower than those observed in other work using similar discharge configurations and the LDA technique [11]. These present data suggest that the LDA method of earlier work may indeed be measuring the speed of seed particles that have been accelerated by Coulomb forces in addition to collisions with negative ions/neutrals. It has been estimated that seed particles with diameters of the order of 1 μm may acquire an additional speed component of the order of metres per second as a result of electrostatic charging [14].

At 5 mm below to the point, the wind speed in figure 4 actually increases with increasing radial distance in the range $0 < r < 2.5$ mm, and then decays with further increases in radial distance above 2.5 mm. At $r = 0$ there is likely to be a maximum in electrostatic repulsion of negative ions formed in the ionisation region close to the point. However, the bulk gas motion established by subsequent collision between negative ions and neutrals is being fed by neutrals from above the point, as depicted in figure 5. It is therefore conceivable that a small region of relatively slow gas flow exists close to the electrode on the discharge axis.
At 10 mm below the point the radial profile is more constricted as gas flow is not influenced by inflow from the top of the discharge chamber. This region also constitutes the low-field region in the point-plane electrode configuration. Here a combination of lower accelerating field and the effect of previous multiple elastic collisions between ions and neutrals, and neutral and neutrals results in a decrease in flow speed.

4. Conclusion

This paper has described the construction and operation of an optical fibre anemometer, based on a Mach-Zehnder interferometer configuration, capable of measuring the speed of the electrostatic wind generated by a high voltage, negative point, Trichel-pulse, corona in atmospheric air. The optical fibre anemometer works by heating a small segment of optical fibre that constitutes the sensing arm of the interferometer using controlled, repetitive bursts of radiation from a thermal-infrared CO$_2$ laser. The observed fringe shifts result from a combination of the heating pulse from the laser and the cooling effects of the corona wind. The interferometer was initially calibrated to measure wind speed by subjecting the heated section of the interferometer to the cooling effects of known flow rates of air. The corona wind speeds were found to range from 0.2 to 0.7 m s$^{-1}$ in the discharge gap, significantly lower than those speeds observed by other workers using laser Doppler anemometry. It is suggested that previous LDA measurements are likely to have been corrupted by electrostatic charging of seed particles introduced into the discharge gap.

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