Space charge generated by wind tunnel fires

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Abstract

Plume clouds resulting from wildland fires (pyrocumulus) sometimes produce lightning discharges to ground. These discharges were found to carry positive charge to ground exclusively in several cases. Emission of space charge was observed from woody materials burned in the presence of an external electric field. Measurements done in a large wind tunnel for this study confirm and extend measurements made in open air. The net charge given up by the fire in the wind tunnel has sign appropriate to reduce an applied electric field (negative for the earth’s fair weather field), and magnitude directly proportional to the magnitude of the applied electric field and the fuel consumption: \( Q = 0.034 + 0.0015E \), where \( Q \) is the net charge liberated in nC g\(^{-1}\), and \( E \) is the applied electric field in V m\(^{-1}\) (positive upward). There is a weak dependence of the net charge on wind speed, probably due to wind tunnel airflow characteristics. The net charge in the smoke is a small difference between large amounts of charged ions of both signs liberated by the fire. For fires burning under fair-weather electric fields, the amount and sign of charge released by the mechanism studied cannot be the direct cause of anomalous lightning from pyrocumulus. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

The presence of concentrations of positive space charge associated with large wildfires was noted by Schaefer (1957). The charge concentrations were inferred from corona current measurements made ahead of an ongoing large fire. There was no

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estimate made of charge amount or density, but he did note that the concentrations were apparently positively charged. Latham (1991) presented evidence that a large prescribed fire (an intentionally lit fire designed to accomplish land management objectives) caused a convective cloud that generated a very unusual set of lightning discharges. This set of discharges consisted exclusively of positive cloud-to-ground flashes (i.e., lowered positive charge from cloud to ground.) Preliminary results from the investigation reported here were reported in (Latham, 1992). Vonnegut et al. (1995) (hereafter VLMH) presented the results of burning natural (tumbleweeds, pine boughs) and man-made (aspen excelsior) fuels on a large platform in the open under the influence of the fair-weather and artificially generated electric fields.

This paper presents the results of an investigation of charge generated by free-burning woody fuels in a physically controlled environment. The mechanism involved in the generation of charged ions seems to be a combination of chemionization and thermionization, with the former more important. Charge separation occurs under the influence of the external electric field. Simple ion counters applied to the smoky air downstream of the fire reveal the presence of both positive and negative small and intermediate ions. Preliminary results from the investigation reported here were reported in (Latham, 1992). Vonnegut et al. (1995) (hereafter VLMH) presented the results of burning natural (tumbleweeds, pine boughs) and man-made (aspen excelsior) fuels on a large platform in the open under the influence of the fair-weather and artificially generated electric fields.

The larger question is why positive charges overhead are observed in wildland fires that generate pyrocumulus under fair weather electric fields, and negative charges in wind tunnel and outdoor controlled experiments. VMLH suggest that the release of negative charge by mechanisms given in this paper drives an influence (positive feedback) mechanism that, together with cloud airflow, separates charge in a direction opposite to the ‘normal’ thunderstorm, giving a positive lower charge center, and a preponderance of positive lightning flashes to ground. Calculations from measurements by Latham (1991) and observations by Schaefer (1957) seemed to indicate that the cloud is simply positively charged, like the dust clouds produced by volcanoes. Based on the values found in the experiments reported here, it seems that VLMH have it right; the charges from the fire may ‘seed’ a positive feedback mechanism in the cloud that provides the charge required for lightning strikes. The details of the influence generator remain a mystery.

2. Experimental background

The USDA Forest Service Intermountain Fire Sciences Laboratory has a large climate controlled wind tunnel for research work to establish parameters for fire behavior models and perform test fires for retardant materials. Ponderosa pine needles, arrays of small sticks, and Aspen excelsior packing materials are burned under controlled conditions of wood moisture content, packing ratio (the amount of fuel bed volume occupied by fuel per unit volume of bed), fuel bed depth, surface area-to-volume ratio of the fuel, and wind speed. The wind tunnel has a working section 3 m × 3 m × 15 m. Wind speed can be varied and held within the range of 0.44–2.6 m s⁻¹. During a fire, the tunnel is operated in a one-pass mode; outside air is drawn through the tunnel from a plenum and the smoky air returned to the great outdoors. Because there are screens at
the intake end of the working section, and turning vanes at the exhaust end, the working section is a Faraday cage.

In all, three series of charge release measurements were made, set up as shown in Fig. 1. For the first two series, a fuel bed 45.7 cm wide and 91.4 cm long was placed on insulating supports a distance of 2.3 m beneath a 3 m x 5 m fine mesh screen suspended within 10 cm of the top of the wind tunnel, generating an electric field terminating on the tunnel walls and floor, fuel bed, and flame. The geometry of the experiment gave a uniform field at the fuel bed surface. The insulated screen was connected to a variable voltage source of ±1200 V maximum. Total fuel bed weight was observed for the second series of experiments using an insulated weighing system. The fuel bed in the first and second series was connected to an ammeter consisting of an operational amplifier with a current-to-voltage feedback connection. The ammeter output was recorded on a strip-chart recorder for the first series of experiments and on a 12-bit digitizing data system for the second series. Data were taken at 20 sample s⁻¹ in the second series.

The third series of measurements had a grounded fuel bed, 0.92 m wide and 18 m long. Other data were taken for fire behavior experiments at the same time. The construction of the experiments was such that current measurements could not be made. For these experiments, a pair of concentric cylindrical (Gerdien) condensers, about 1 m downwind of the electric field mill, and vertically and horizontally centered in the working section of the tunnel, were used to measure air ions. Although these devices are used to measure atmospheric conductivity, they can also be used for ion concentration measurements (Tammet, 1967; Israel, 1970). Ions entering the condenser are driven to the center conductor by a local electric field, and the resulting current measured. Knowing the air flow rate then enables calculation of the volume density of singly-charged ions whose mobility is greater than a limiting value. The cylinders’ axes were perpendicular to the air flow, so flow through the cylinders was determined by their fans rather than the free stream wind. The voltage, air flow, and physical characteristics of the condensers give a theoretical limiting mobility (drift velocity in an applied electric field) of 0.014 cm s⁻¹ V⁻¹ cm⁻¹ for positive and 0.011 cm s⁻¹ V⁻¹ cm⁻¹ for negative singly charged ions.

![Wind Tunnel Measurement Arrangement: Side View (not to scale)](image_url)

Fig. 1. Schematic view of the experimental arrangement.
The downwind electric field meter and screen were used for series three measurements as for series one and two. Zero wind speed and zero applied electric field conditions were used to set zero values for the downwind electric field mill and the Gerdein condensers. The electric field at the field mill position due only to the screen potential was negligible because of the geometry. Data were taken at 12-bit resolution and 20 samples s\(^{-1}\). The first series of experiments were done prior to the field experiments of VLMH, where partial results were reported; the second and third series afterward.

3. Mechanisms of ion formation in flames

Before discussion of the results of the wind tunnel charge tests, we summarize some findings of investigations of ion formation in flames. Combustion of woody materials in free-burning fires occurs as diffusion, rather than premixed, flames. In premixed flames, such as the Bunsen burner, reaction takes place after the gases are mixed. The combustible gases in diffusion flames are released by pyrolysis of cellulose and lignin in the wood. The pyrolysates mix by diffusion at small scale with air, forming flamelets of reacting gases which are drawn out vertically by buoyant forces.

Two major mechanisms for generation of charged particles in flames have been identified: chemiionization, or chemical reactions that yield positive ions and electrons, and thermionization of carbon in high-temperature areas of the hot gases resulting from the burning, which also results in positive ions and electrons. These mechanisms occur in both premixed (Gerhardt and Homann, 1990a) and diffusion (Boothman et al., 1969) flames.

For either ionizing mechanism, there is strong evidence that large carbon particles in the smoke carry positive charge exclusively (Place and Weinberg, 1965, 1967; Boothman et al., 1969; Ball and Howard, 1971; Wersborg et al., 1974; Gerhardt and Homann, 1990a,b). The studies in premixed flames show that chemiionization reactions generally develop small positive ions (predominantly CH\(_2\)O\(^+\)) and electrons. The electrons then attach to molecule clumps to form small negative ions. Thermionization results in formation of a carbon particle–electron pair, with electrons forming small negative ions. This combination of ionization processes, along with secondary processes, results in multiply charged positive particles in excess of 300 amu (Gerhardt and Homann, 1990a) in size, and, finally, clumps of graphite particles up to 2.5 \(\mu\)m and larger, some of which have positive charges measuring up to \(2.6 \times 10^{-16}\) C (1630 electronic charges). According to these reports, negatively charged particles do not seem to grow to larger sizes. Data for these reports were taken close to the flames.

Boothman et al. (1969) studied ionization rates in both premixed and diffusion flames for several gases and burner configurations. Ionization rates were found by measuring the flame saturation current. The predominant form of ionization in the flames studied was chemiionization, especially in diffusion flames. Several differences were found between diffusion and premixed flames. First, diffusion flames are poor ion sources by comparison with premixed flames. Second, saturation currents of diffusion flames are
proportional to the fuel-flow rate (carbon issued) and insensitive to flame area, configuration, and burner type. Third, the rate of ion production is predictable. For woody fuels, as used in our experiments, the saturation current is about 33 $\mu$A $g^{-1}$ s$^{-1}$ of fuel burned ($33 \mu$C $g^{-1}$).

4. Results

The flame and the applied electric field act as a current generator, in that an excess of ions of one sign, depending on the applied field, appear in the smoke/hot air from the flame (Volta, 1782). The charge residing on these ions eventually finds its way back to 'ground' (the tunnel walls, for example), closing the circuit. A negative applied electric field, that is the screen voltage positive with respect to the tunnel and fuel bed, causes an excess of negatively charged particles in the smoke/hot air plume from the fire; likewise for a positive field and positive charges.

The peak current flowing from the flame to the air is displayed in Fig. 2 for the first series of experiments and in Fig. 3 for the second. Peak currents are used because the maximum amount of fuel is burning at peak current flow (by visual observation on series 1 and 2 and in the field experiments of VLMH). The electric field downwind of the flaming fuel is shown in Figs. 5 and 6 for series 1 and 2, respectively. Although the downwind field was measured, no calculation as to charge quantity can be made as the distribution of the charges in the tunnel is not known. These measurements are, however, qualitatively useful.

The effect of excess space charge buildup in the tunnel working section at no-wind condition is best seen in the data from the second series of measurements (Figs. 4, 6 and 7). The no-wind (0 m s$^{-1}$) current becomes nearly constant for applied electric fields greater (less) than about 200 ($-200$) V m$^{-1}$. The effective field seen by the flames is.
reduced by space charge; hence, the flame–air current is reduced as well. This effect is seen to a lesser extent in data from the first series (Fig. 2). In the downwind electric field sensor data of Fig. 5, the net charge in the tunnel working section gives an order of magnitude greater electric field for the no-wind case than for the cases for which charge is removed by airflow. There is no indication of reversal or oscillation in sign of current for the zero-wind cases.

There is a clearly linear relationship between the peak current from the fire and the applied electric field (Table 1, Figs. 3 and 4) when excess charge is removed by wind. This relationship was noted in the field experiments of VLMH. In fact, for series 1 and 2 of this paper, the relationship of peak current to applied electric field is remarkably constant at about 0.020 nA for each V m\(^{-1}\) of applied electric field, as seen in Table 1 (\(I/E\)). The measurements in series 1 were replicated 3 times, but the results were good enough that the series 2 experiments were done only once for each set of applied field
conditions. Since the peak current corresponded to flaming combustion of the entire fuel bed, the current per unit area of fuel bed was estimated at 0.048 nA m\(^{-2}\).

The second series of experiments was designed to relate the current to the weight loss rate of fuel during combustion (Fig. 6). Since the current can be expressed as C s\(^{-1}\), and the weight loss rate is expressed as g s\(^{-1}\), a relationship can be generated as a specific charge generation, net charge per mass of fuel burning (C g\(^{-1}\)). The linear regression to the values shown gives the relationship:

\[ Q = 0.034 + 0.0015E, \]  (1)

where \( Q \) is the excess charge in nC g\(^{-1}\) of fuel burning, and \( E \) is the applied electric field in V m\(^{-1}\). The constant represents charge emitted when no external fields were deliberately applied.

The effect of wind on the net space charge emitted is seen in Figs. 3 and 4. The data presented in Fig. 2 seem to indicate a dependence of current flow on wind speed, the data of Fig. 3, taken with the same equipment as in Fig. 2 except for the recording device, do not show this dependence. The same can be said for Figs. 5 and 6, respectively. The downwind field measurement, a space charge indicator, also shows very slightly greater space charge from higher wind speeds than from lower in the first series, but not in the second. Inclusion of wind in a multiple linear regression on the data of the first series gave \( R^2 \) of 0.5 and indicated that the wind had a very small influence.

<table>
<thead>
<tr>
<th>Series</th>
<th>Speed (m s(^{-1}))</th>
<th>( I/E ) (nA V(^{-1}) m(^{-1}))</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 med. exc.</td>
<td>0.89</td>
<td>0.020</td>
<td>0.97</td>
</tr>
<tr>
<td>1 med. exc.</td>
<td>1.8</td>
<td>0.025</td>
<td>0.99</td>
</tr>
<tr>
<td>1 pine needles</td>
<td>0.89</td>
<td>0.020</td>
<td>0.95</td>
</tr>
<tr>
<td>2 coarse exc.</td>
<td>1.34</td>
<td>0.021</td>
<td>0.99</td>
</tr>
<tr>
<td>2 coarse exc.</td>
<td>2.24</td>
<td>0.019</td>
<td>0.98</td>
</tr>
</tbody>
</table>
on the current. Because of the evidence in Figs. 4 and 6, regression on wind was not done. We have noticed in other experiments with fire that for low wind speeds, such as the 0.89 m s\(^{-1}\) speed shown in Figs. 2 and 5, there is a small reflux flow near the top of the wind tunnel. This means that a portion of the charge in the airflow can act as a shielding layer, reducing the effective electric field at the fire, hence the current. This explanation is borne out by the lack of wind effect in the second series, which was done at the higher windspeeds of 1.34 and 2.24 m s\(^{-1}\). We therefore neglected wind effects in our current vs. applied electric field regression.

![Specific charge (second series)](image)

**Fig. 6.** Charge generated per unit mass burned in the second measurement series.

![Ion Densities](image)

**Fig. 7.** Space charge measurements in the third measurement series.
Fig. 7 presents the results of the Gerdien condenser measurements of the third series of experiments. The diagonal line indicates equal concentration of sampled positive and negative ions. The numbers in parentheses are the wind speed and applied electric field, respectively. The position of the data points indicates the amount and sign of excess charge, calculated point-by-point from the measured data. Error bars indicate the high amount of noise in the data due to turbulence in the airflow downwind from the fire as well as smoke density variations and, perhaps, in the number of charges per particle. Even though all charged particles are not captured by the apparatus used, it is evident from the data that the net charge produced by induction due to the externally applied field is small compared to the amount available of both types generated by the flames, and that there is a large fluctuation in the amount and sign at any one measurement.

5. Discussion

The wind tunnel results support the field data of VLMH. The current flow from the flaming fuel to the air depends linearly on the applied electric field. The current per unit area in this study is estimated at 0.048 nA m\(^{-2}\), about one order of magnitude less than the free-burning platform values reported in VLMH, based on visual estimation of the flaming area. Estimates of flaming area in both cases are crude, however, so current density per area of fuel bed is not a well-defined quantity for either set of experiments. The specific charge (Fig. 6) appears to be far better defined. Flame structure was also different in these cases. Since, as noted previously, diffusion flames are the product of local fuel–air mixing and ignition, the amount of flame area present at any given time in a free-burning fire of this kind fluctuates wildly, as does the connection to ground of the high-conductivity flamelets. Customary estimates of ‘flame height’ or ‘flame area’ are biased by the inability of visual observation or standard video equipment to resolve phenomena at the flame time scale. Flames detaching from the body of a fire seem to behave like water drops or other particles separating from a conducting body in an applied electric field; they are charged by induction (a nice exposition is in Blanchard, 1967).

Flame structure and soot production can be affected by externally applied electric fields (Place and Weinberg, 1965, 1967; Xie et al., 1992), but the fields in this experiment are too small by several orders of magnitude to have such an effect. So, fluctuation in flame effective area, as indicated by the error bars in Fig. 7, does not depend on the applied electric field; the electrically effective flame area depends only on the structure of the flame as determined by combustion.

We have only the field observations of Latham (1991) and Vonnegut et al. (1995) to compare to the wind tunnel experimental values. The first of these reports gives, based on the total positive charge brought to ground by positive lightning flashes, a figure of 53 C. The assumption for that calculation was that all the charge originated from the fire; no in-cloud electrification mechanism was invoked. The fine fuel loading, which contributes to the flaming phase of wildland fires, was 10\(^{-3}\) g m\(^{-2}\). That loading, according to (1) above with a measured fair-weather electric field of \(-100\) V m\(^{-1}\), gives a charge of \(-0.07\) C for the total fire, assuming that all the fine fuels burned in
the same way as in the wind tunnel. This is not only far too small to generate the 53 C needed, it is also the wrong sign. Even if the negatively charged plume was bent over some portion of the fire, generating positive charges from the fire underneath, electric fields could not get large enough to provide all the charge necessary for the lightning to ground.

The electric field–fire charge generation and separation mechanism measured in this paper and in the field experiments of VLMH is not a positive feedback, or influence, mechanism, but rather a straightforward Le Chatelier, or negative feedback mechanism. Assume a fire with an applied electric field as in the no-wind conditions of this paper. Charge is generated and separated in such a way as to oppose the originating electric field. The charge on the smoke thus reduces the electric field seen by the fire, reducing the production of excess charge. Eventually, the fire will see no electric field, and no more excess charge is produced. Of course, the excess charges, on the smoke, will be attracted to the field-generating electrode if we are in a nice environment with a screen, as in the wind tunnel. But even if they are, a stable current flow will be set up, depending on the mobility of the charges on the smoke. The sign of the charge emitted by the fire will not reverse.

Now suppose that the excess charge on the smoke is removed by wind. In that case, somewhere downwind, the electric field, as seen by the flame, is reduced. The same sign of charge as from the upwind fire is generated and separated, only not as much because the field is smaller downwind than it is upwind due to the charge blowing in from upwind. So the downwind fire is still producing charge of the same sign as the upwind fire.

Now, by magic, allow the charge from the upwind fire to accumulate over the downwind fire (say in a vertical column). At some time, the electric field over the downwind fire is reduced to zero at the fire by the accumulating charge. Shortly thereafter, there is a field reversal at the downwind fire. Charge of the opposite sign is produced so as to neutralize the accumulated charge from the upwind fire. Clearly, this oppositely signed charge cannot exceed the excess charge of the first sign, else the electric field would again reverse. Thus, there is always an excess of charge of the original sign, and a positive feedback mechanism cannot be constructed.

Based on the limited data on plumes and charging for natural fires, it seems that the pyrocumulus was seeded by charge from the fire-generated plume in the same way that clouds described by Vonnegut et al. (1962) were seeded by corona discharge, and that the charge generation and separation mechanism in the cloud, rather than that connected to the fire, was responsible for the resulting anomalous behavior of the lightning. Based on the ability of free-burning fires in the presence of an external electric field to generate and separate charge, the cloud charging must depend on a positive feedback mechanism. The positive charge overhead noted by Schaefer (1957) may have been due to a dipole structure with a positive lower charge.

6. Conclusion

We have described the results of some smoke charging experiments conducted on fires in our wind tunnel facility. Certainly, smoke can provide a current flow from a fire
to the atmosphere, the sign and amount of the charges comprising the current depending linearly on the applied electric field and the fuel consumption rate, although there may be different consumption rate dependencies for different fuel arrangements. The charge is carried on all sizes of particles, as predicted by other laboratory studies on both premixed and diffusion flames. The fire-generated charge is not only not sufficient in magnitude to account for the lightning generated by a fire-driven plume that becomes a cumulus cloud, but is the wrong sign as well. It does, however, seem to provide a seed for charge generation/separation in the cloud. We intend to continue experiments in the field with prescribed burns and wildfires, concentrating on large fires and pyrocumulus.

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References


