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On the Kelvin electrostatic generator

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Abstract. The Kelvin generator is an amazing electrostatic device which poses many questions. Here we report the results of our investigations of this device under various controlled conditions with both non-polar and polar liquids and a sodium chloride aqueous solution. Further we have found that the generator works well even if the two liquid streams originate from different electrically insulated reservoirs. In addition we propose a model in which the electric charge results from the separation of the hydrogen and hydroxyl ions as the water droplets form.

Résumé. Le générateur électrostatique de Kelvin est une étonnante machine qui soulève de nombreuses questions. Nous présentons ici les résultats de nos expériences sous différentes conditions bien contrôlées avec des liquides non-polaires et polaires et une solution aqueuse de chlorure de sodium. De plus, nous avons trouvé que le générateur fonctionnait parfaitement bien si les deux filets de liquide étaient issus de deux réservoirs distincts électriquement isolés. Enfin, nous proposons un modèle dans lequel la charge électrique résulte de la séparation des ions hydrogènes et hydroxyles lorsque les gouttelettes d'eau se forment.

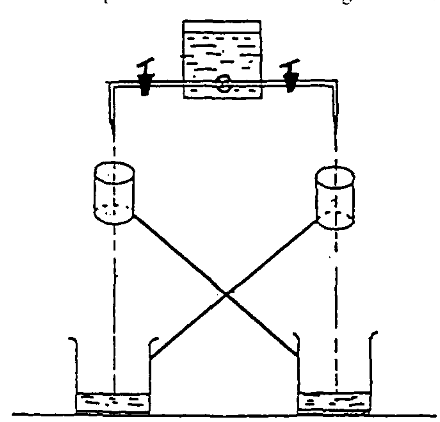
1. Introduction

More than 100 years ago, while he was working on atmospheric electricity, Lord Kelvin (Thomson 1872, Lloyd 1980) built an electrostatic machine—the Kelvin generator. Although not very well known, this electrostatic generator works and is very easy to build (Sutton 1938, Stong 1960, Evans and Stevens 1977, Blunk 1982, Sady 1984, Desmet 1987). Figure 1 shows a simple version of the Kelvin generator.

Two streams of water run down into two metallic collectors insulated from each other. The water passes through two metallic cans, electrically connected to the opposite collector, as shown in figure 1. We will call the two cans inductors,† as did Kelvin. If the two rods connecting the inductor and the collector are about 1 cm apart, a spark jumps between them, after a short time of perhaps 1 min. Thereafter the phenomenon repeats itself almost periodically. Hence, there must be a large electric field generated between the two rods, because the breakdown electric field in air under standard conditions for a 1 cm gap is 22.3 kV cm^{-1} (Aguet 1973).

Amazingly, it works! But many questions immediately come to mind (Blunk 1982). Under what conditions does the device work? Does the same can always acquire the same polarity? How does the initial charge imbalance occur? Where does the charge come from? Which parameters influence the

Figure 1. A simple version of the Kelvin generator.



† We realise that the word 'inductor' has a different meaning nowadays, but it is used here in its historical aspect and to indicate that the upper cans induce electric charge on the water.

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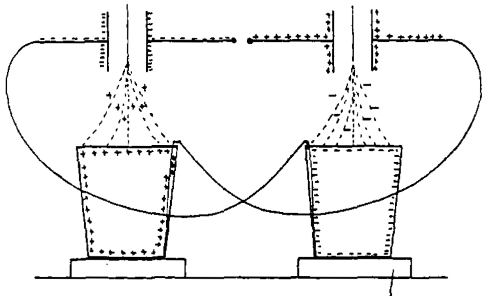


Figure 2. A schematic drawing of our Kelvin generator with one charge distribution.

charging process? What happens if two electrically insulated reservoirs are used to provide the water streams?

In order to answer some of these questions we built a generator which could easily be modified to change the inductors and to vary the height between the collectors and the inductors, the space between the rods and the water flow rate. Our version of the Kelvin generator is schematically represented in figure 2. More details about this apparatus are given elsewhere (Desmet 1987).

2. General considerations

In order to make the generator work two essential requirements must be fulfilled. First, the collectors must be well insulated from each other and from the electrical ground to prevent any leakage. Second, the device must be carefully adjusted, so that the streams become turbulent and break into droplets within the inductors. This last condition can be achieved either by adjusting the water flow rate and/or the position of the inductors. It is thus easier to use cylindrical inductors a few centimetres high rather than rings. The turbulent character of the water flow is observed visually. We estimated the water velocities near the centre of the inductor. We found that the water flow rates range from 1.8 to 2.8 ml s^{-1}, which correspond to a Reynolds number of between 2000 and 3000. The atmospheric conditions were measured during the experiments. The relative humidity varied from 45 to 65%, the air pressure from 738 to 780 Torr and the temperature from 8 to 25 °C. These conditions did not seem to have any influence on the charging process.

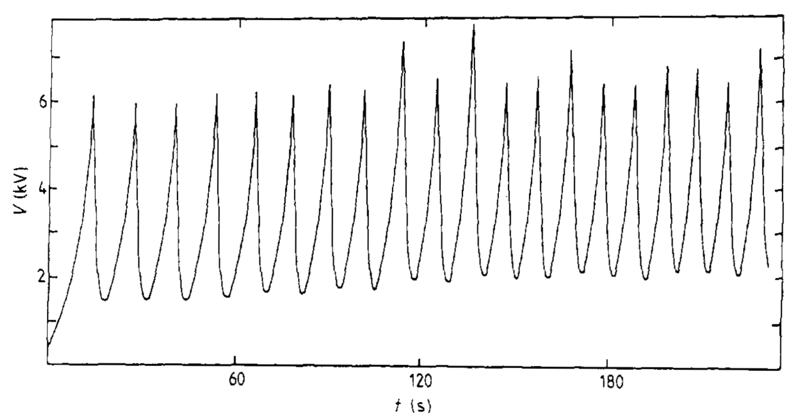
As the electric charge builds up in the generator, the water streams acquire a trumpet shape as a result of electric forces. Very quickly the working area becomes wet and the resulting collected moisture stops the generator because of electric leakage. To avoid this leakage, one can reduce the separation between the inductors and collectors, use collectors of larger diameter or increase the flow rate of the liquid.

We were unable to make the generator work with the water dripping instead of flowing, or with a water stream diameter larger than 2 mm, or with only one stream. In these cases we could not meet the second requirement, i.e. turbulent flow within the inductors.

3. Investigations on the charge distribution

When the generator is working the electrical charges are distributed as shown in figure 2. It is impossible to anticipate which collector–inductor will be positive and which will be negative. The initial sign of the charge on one collector–inductor is totally random, but as soon as one collector–inductor acquires a particular polarity, the other acquires the opposite polarity. The potentials between each inductor–collector and ground have the same absolute value, within experimental error, but are of opposite sign. Once the charging process has begun, different parts of the generator always have the same polarity

Figure 3. The potential difference between ground and one collector as a function of time.



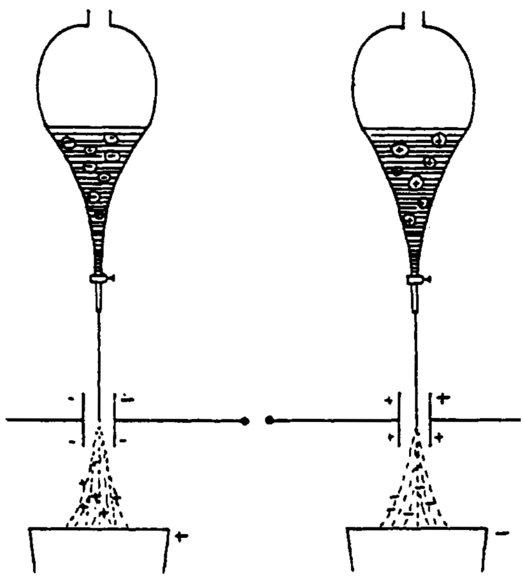


Figure 4. One possible charge distribution when two electrically insulated metallic reservoirs are used.

because each electric breakdown does not completely discharge the collectors. The charge/discharge process is close to periodic as illustrated in figure 3, where each peak represents a breakdown observed as a spark between the two rods separated by 5 mm. By increasing the distance between the two rods in order to prevent the electrical breakdown, we measured potential differences of up to 24 kV between the collectors. In most of our experiments with the Kelvin generator, the two streams originated from the same reservoir. The use of two reservoirs, whether electrically insulated or not, did not change the operation of the generator. Hence, the hypothesis of a continuous conductor (Sutton 1938) must be rejected. By using two well insulated metallic reservoirs, we found that each reservoir has the polarity of the inductor beneath it, as shown in figure 4.

4. Experiments with different liquids

We operated the generator with the different liquids listed in table 1. This table also gives the polar character and the relative permittivity of each liquid and whether the generator produced an electric discharge. Unfortunately, when we change the liquid we modify many parameters, such as the viscosity, the ionic strength, the electrical conductivity and the surface tension. Hence, no detailed conclusions about the polar liquids can be reached. However, it appears that non-polar liquids fail to produce the expected discharge.

In order to investigate the role of some of the above parameters, we have measured the time required for one collector to increase its potential from 2 to 4 kV under different experimental conditions. As shown in table 2 the charging time is increased by adding Agepon, a surface-active agent, to the water, or by adding polyvinyl pyrrolidone to increase the viscosity of the water or by adding dioxane, a non-polar non-dissociable ether.

5. The electrification process

Once the whole process has begun, i.e. when a slight potential difference between the two inductors has developed, it is easy to understand how the generator works. Let us consider the stream passing through the positive inductor shown on the right in figure 2. The autohydrolysis constant for pure water at 24 °C is 1.0×10^{-14} and yields 1.0×10^{-7} moles per litre each, or 6.1×10^{16} ions per litre, of aqueous hydrogen ions and hydroxyl ions. Each of these ions will then experience an electric force as shown in figure 5. In the cylindrical inductors the electric field is axial and largest at the edges of the cylinder, as indicated by the bold arrow in figure 5. In the centre of the cylinder the electric field is zero. Therefore, the ions experience electric forces which depend on their position inside the cylinder. But, overall, the positive ions are repelled upwards by the positive inductor and the negative ions pulled downwards. Hence the droplets, which are formed within the inductor, carry an excess of negative hydroxyl ions

Table 1. Experiments with different liquids.

Liquid	Polarity Y/N	Relative permittivity	Working Y/N
Tap water	Y	80	Y
Distilled water (non-deionised)	Y	80	Y
Saturated solution of NaCl	Y	—	Y
Acetone (CH_3COCH_3)	Y	21	Y†
Carbon tetrachloride (CCl_4)	N	2.24	N
Dioxane ($C_4H_8O_2$)	N	2.24	N

† Difficult because of its high volatility, not dried.

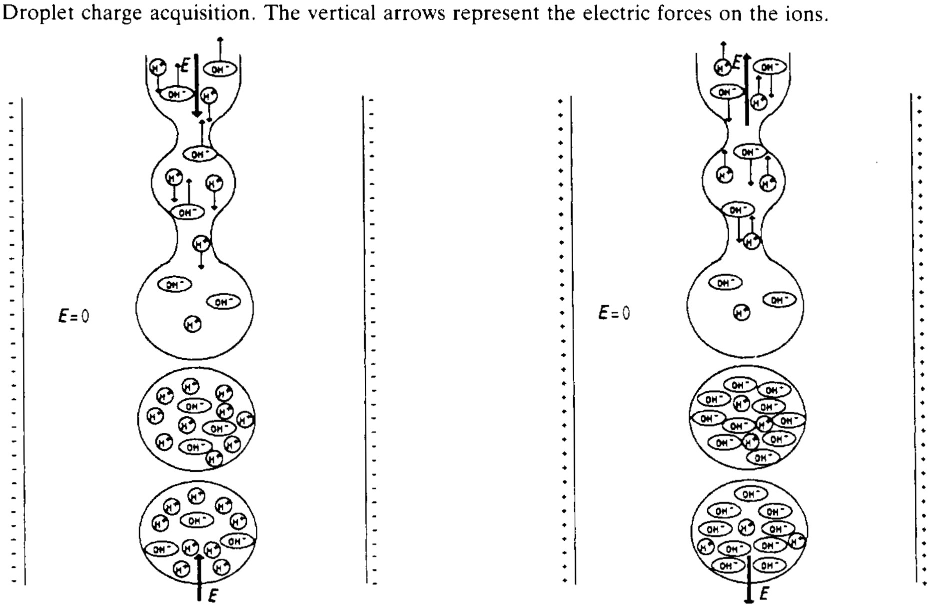
Table 2. Influence of Agepon, polyvinyl pyrrolidone and dioxane on the charging time.

	t(1.9 kV→3.9 kV) (s)	
H_2O	2.8 ± 0.6	
H_2O + Agepon (15 ml per l)	5.3 ± 1.7	
Amount of polyvinyl pyrrolidone (%)	**Viscosity η (cp)**	**t(1.9 kV→3.9 kV) (s)**
0	1.011	2.65 ± 0.26
5	2.354	3.23 ± 0.29
10	4.673	5.25 ± 0.31
15	9.025	6.06 ± 0.14
Amount of dioxane (%)	**Relative dielectric constant**	**t(1.1 kV→2.7 kV) (s)**
0	80.38	1.96 ± 0.82
20	63.50	2.75 ± 0.46
40	45.96	4.74 ± 1.36
60	28.09	5.00 ± 1.24
80	12.19	7.72 ± 1.13
100	2.24	∞

and are thus negatively charged. The forces experienced by the ions on leaving the inductor are irrelevant, because they cannot alter the charge on any droplet. The collector in which the droplets fall and the other electrically connected inductor become progressively more and more negative. Simultaneously, the left inductor induces charge separation in the stream, where the droplets are positively charged and increase the positive charge on the left collector and the right inductor. It is a self-amplifying process.

The explanation given above is compatible with all our experimental results and explains why the streams must become turbulent and divide into droplets within the inductors in order to ensure that, in the stream, the presence of a discontinuity will prevent charge neutralisation. The model also explains why the generator does not work with carbon tetrachloride and dioxane, the molecules of which do not dissociate into ions. We believe that the operation of the generator with acetone is due to

Figure 5. Droplet charge acquisition. The vertical arrows represent the electric forces on the ions.



the fact that the acetone was not dried beforehand. The water molecule electric dipole moments and the possible existence of an electric double layer at the water surfaces were first taken into account but quickly rejected as being responsible for the net appearance charge. According to Harper (1957) an outer layer about two molecules thick at the surface of the water is ill defined because of thermal agitation. A second layer of water molecules partially orientated positive outwards is a few molecules thick. The potential difference arising from this double layer is about 0.25 V. A third layer about 100 Å thick is depleted of ions, below which the concentration increases similarly for hydrogen and hydroxyl ions. The existence of the double layer and the value of the potential difference are questioned by several authors (Butler 1951, Harper 1957). Furthermore, the double layer is so thin that it could not be split during the formation of the droplets because films of water thinner than 100 Å were never observed (Harper 1957). Moreover, the unstable character of the liquid streams does not favour the formation of an electric double layer. Hence, we conclude that the net appearance of charge is not due to the breaking of the electric double layer at the surface of water. Another possibility is the preferential adsorption of some ions present in air, which leads to a predicted sign of the droplets opposite to the observed sign.

It is much more difficult to identify among the numerous possible causes (Thomson 1872, Stong 1960, Sutton 1938, Walker 1973) that responsible for the appearance of the initial charge imbalance. Indeed, Sutton (1938) proposes ionised air draft and Walker (1973) suggests natural radioactivity and cosmic rays. It is obvious that all these causes are external to the generator and involve random natural processes. In order to eliminate as a possible cause any geometric difference between the left and the right side of the generator, we have run the generator several times under the same conditions. Between the different runs the generator was completely discharged, taken apart, dried and put back together without interchanging the left and right parts. Over 30 runs the left collector was, consecutively, 11 times positive, 3 times negative, 1 time positive, 3 times negative, 1 time positive, 7 times negative and 4 times positive; or, at the end, 17 times negative and 13 times positive. We thus suggest two causes for the initial charge imbalance: the random natural occurrence of ionising radiation in the vicinity of one of the inductors or collectors; or the random natural occurrence of a charge inhomogeneity in the water stream.

6. Conclusions

Our experiments have answered some of the questions mentioned in the Introduction. First, as explained in §2, we have clearly determined the conditions under which the device works. Second, we have shown that, after the generator starts working, the same inductor–collector always acquires the same polarity, but it is impossible to anticipate which polarity. Third, we have found that many parameters, such as viscosity, surface tension and ionic strength, influence the operation of the generator. Finally, we have demonstrated that the generator works perfectly well when two insulated reservoirs provide the two water streams.

We explain the accumulation of charge in the Kelvin generator with a model in which the charges arise from the ions naturally present in water. Unfortunately, our experiments do not indicate how the first charge imbalance occurs. While it is easy to force, for instance, the right collector (figure 2) to become negative, it is more difficult to investigate the random spontaneous initial charge imbalance. In order to evaluate our model further, more experiments on the influence of the liquid flow rate, its ionic strength in water and its acidity will be carried out. It will prove particularly interesting to observe the operation of the generator with a polar liquid in one stream and a non-polar liquid in the other, or with liquids of different pH in the two streams.

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