

# Bubbles and steam electricity

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## Abstract

In 1840, Lord Armstrong was the first to study the electrical charge produced as steam escaped from boilers, the phenomenon called steam electricity. In 1969, interest in steam electricity was renewed because of explosions caused by the ignition of chemical vapors during the washing of ship tanks with steam jets. Steam electricity is proposed explained by the bubbles nucleated in the boiling of water droplets, the bubbles behaving like resonant quantum electrodynamic (QED) cavities. During bubble growth as the bubble cavity resonance coincides with vacuum ultraviolet frequencies, the water molecules on the bubble walls dissociate by cavity QED into hydronium  $\text{H}_3\text{O}^+$  and hydroxyl  $\text{OH}^-$  ions. After recombination, only about 20% of the ions are available for electrification, the ions called available ions to be distinguished from the hydronium and hydroxyl ions in the bubble walls described by the pH and pOH of water, called background ions. Boiler water having an acid pH is the result of acid-base equilibrium between dissolved carbon dioxide and carbonic acid, the concentration of background hydronium ions controlled by the buffering action by carbonate and bicarbonate ions. The chemistry may be described by the pH of the boiler water, and if acidic the bubble surface is charged positive by the abundance of background hydronium ions. Available hydronium ions are repulsed from the positive charged bubble surface and tend to the center of the bubble forming a positive charged vapor; whereas, the available hydroxyl ions are attracted to the bubble surface. Bursting of the bubbles at the surface of the droplet produces positive charge steam and negative charged droplets. Conversely, bubbles in boiling water having a basic pH produce a negative charged vapor and positive charged liquid droplets.

*Keywords:* bubbles, steam electricity, Leidenfrost, lightning, atmospheric electricity

## 1. Introduction

In the 1840's, steam boilers were commonplace in England. At Seghill, Newcastle on Tyne, steam happened to leak through a cement seal around the safety valve on a boiler. When a workman placed his hand in the steam while his other hand was on the lever of the valve, a spark discharge occurred and the workman received a electrical shock, the so called Seghill incident gaining much publicity. Lord William G. Armstrong [1] in a letter to Faraday reported the phenomenon of steam electricity. Faraday responded to Armstrong by letter [1] stating he investigated the Seghill incident and using an electrometer found the steam to be positive charged. Faraday determined the mine water used in the boiler was acidic because of the sulfate of lime deposit found on the inside surfaces of the boiler. But the steam was found not charged at another boiler using rainwater. Faraday at that time thought the steam electricity was caused by the nature of the water from which the steam was produced.

The Sedghill incident reported by Armstrong and Faraday was confirmed [2] by Pattinson. The review by Schafhaeutl [2] suggested the source of steam electricity was connected with the deposits on the boilerplates. Based on Faraday's suggestion that the nature of the water was somehow connected to the steam electricity, Armstrong [3] tested other boilers using the same mine water and found the same results. Shortly thereafter, Pattinson [4] found the length of sparks from the discharge of electrified steam to be proportional to boiler gage pressure.

In 1843, the notion of contact electrification by frictional charging was introduced to explain steam electricity. Armstrong [5] was of the belief that the source of electricity takes place at the point where the steam was subjected to friction but had great difficulty with the supposition that friction was the exclusive cause of the electricity. Faraday [6] was satisfied that steam electricity was not due to evaporation, or condensation, or a change of state based on the observation that the

charge of the steam could be changed by changing the material of the nozzle while the evaporation remained the same. About this time, Faraday changed his belief that the source of steam electricity was the nature of the water in favor of contact electrification - the contact electrification produced as particles of liquid water carried by the steam rub against the solid walls of the nozzle.

Faraday confirmed Armstrong's findings [6] that steam alone produced no electricity, but liquid water distilled from the boiler and added to the steam produced positive charged steam and a negative charged boiler. Positive charged steam ceased by adding small amounts of alkali to the distilled water. Replacing the distilled water with common London waters removed the steam charge. Ammonia added to distilled water produced charged steam, the steam able to redden turmeric paper, but the charge ceased after adding small amounts of sulfuric acid. Except for the latter, pH measurements of the steam were not reported in the Faraday experiments.

Negative charged steam was found by adding olive oil, and oils of laurel and turpentine to the distilled liquid water, but the charged steam ceased when the oils alone were present without the distilled water. If an alkali was added to the distilled water having olive oil, the steam lost charge, but not if added to distilled water having the oil of turpentine. Positive charged steam was found if sulfuric and camphor powder were added to distilled water. Faraday interpreted the pure distilled water droplets, the water globules coated with olive oil and oils of laurel and turpentine, and the powders of sulfuric and camphor as the rubbing agent and the nozzle as the rubbed surface, the sign of the steam charge sign depending on the tribo-electric series.

Faraday's hypothesis is tenable for oils and powders that are physically different from globules of water and suggest different frictional levels and attendant tribo-electrical charging. But small amounts of acids and alkalis soluble in water could not be expected to alter the contact potential from that of distilled water and produce different tribo-electrical charging. Contrarily, acids and alkalis were found to indeed alter the steam electrification, a finding supportive of Armstrong's contention that friction was not the exclusive cause of the steam electrification.

Faraday sought to eliminate steam altogether by working with compressed air. A container was pressurized with air from a syringe, the container providing a means to remove condensed moisture air before opening a valve to send the air against different materials. However, the procedure required extreme care to avoid oil contamination from the syringe. Both dry and common air were tested, the dry air obtained by leaving the compressed air in the container in contact with potassa fusa, a strong alkali for 10 - 15 minutes. Common air having moisture condensation was found to produce positive charge similar to steam; whereas, dry air failed to be electrified. Contrary to the contact electrification hypothesis, sulphur and silica powders in the compressed air experiments rubbing against wood and metal nozzles were found charged in opposition to their tribo-electrical order. Faraday expressed disappointment in not being able to explain why the tribo-electrical order was not found in the compressed air experiments

## **2. Scope, mechanisms, and purpose**

### *2.1 Scope*

In 1969, three large crude carriers were sunk or severely damaged by explosions that were thought to be caused by sparks from charge mist produced while their tanks were being washed with jets of hot and cold liquid water or steam ( see e.g. Jones and Bond, [7] ). Since Armstrong [1], steam has been known to be electrified, but because of the explosions during ship washing, wet steam was reaffirmed ( see e.g. Finke [8] ) as a source of highly charged mists. Hot and cold liquid water jets

also produce an electrified mist, but compared to wet steam do not pose a sparking hazard. On this basis, the scope of this paper is limited to electrification by wet steam.

## 2.2 Mechanisms

The interest of this paper is the mechanism by which the charge is produced in steam electrification, more commonly called spray charging. In 1972, Moore [9] discussed the prominent spray charging theories of Lenard [10] and Natanson [11].

In 1892, Lenard proposed the double layer theory as the explanation of waterfall electricity. The double layer is formed as the dipoles of water molecules orient on the surface of bubbles with the negative end pointing outward and the positive ends pointing inward. The positive inward dipole ends attracting negative ions in the liquid. If the water breaks up into a spray, the double layer and the attached negative ions form particles in the fine spray are likely to carry a negative charge, the positive charge remaining with the larger particles. In this way, Lenard explained how negative charged vapor was found away from a waterfall and a positive charge vapor remaining in liquid water particles near the splash.

In 1950, Natanson proposed the theory of ion fluctuations to explain spray charging. The liquid was considered to be composed of a large number of positive and negative charges. Breakup of the liquid into drops was assumed to produce drops having an excess of positive or negative charge that form in the volume of the drop because of ion fluctuations. In effect, Natanson related droplet charge to the ion density in the liquid. But the ions of interest were the cations and anions of soluble salts and not hydronium and hydroxyl ions. Small concentrations of salts in distilled water were found to increase the symmetrical ionization and decrease net charge; whereas, larger concentrations were required to reverse the sign of the net charge. In the ion fluctuation theory, charge separation is statistical and does not require any cause-effect charge separation mechanism.

Both double layer and ion fluctuation spray charging theories provide plausible explanations of how water dipoles and ionic charges in the liquid are related to spray formation, but conservation of charge and mechanisms by which charge is separated during spray formation are not identified. Consistent with this view, Moore [9] makes the point that charges transferred from the liquid are to be conserved with the charges leaving with the spray. Neither double layer or ion fluctuation theory explicitly conserve the charge lost in the liquid with charge gained by the spray.

Loeb [12] discusses static electrification by electrolytic processes whereby small quantities of acids and bases may drastically change the pH of the water and the concentration of hydronium and hydroxyl ions, but pH as a parameter is absent both double layer and ion fluctuation theories. Consistent with Armstrong, the opinion here is that electrolytic processes underlying the nature of the water in steam electricity are important in spray charging.

## 2.3 Purpose

The purpose of this paper is to propose a theory for wet steam electrification based on the dissociation of water molecules in bubbles nucleated in water droplets by boiling.

## 3. Theory

In the steam electricity phenomenon, the boiling of water droplets produces pressurized steam in the boiler as shown in Fig. 1. Steam leaves the boiler through the nozzle, the liquid water droplets

breaking up as the jet exhausts the nozzle into the lower pressure surroundings. Bubbles are nucleated in the liquid droplets by boiling, but bubbles cannot be nucleated in a pure steam vapor. Hence, steam without liquid fraction can not be electrified by the present theory.

Water molecules on the bubble walls are proposed to dissociate into hydronium and hydroxyl ions by cavity QED as the resonant frequency of the bubble coincides with the dissociation frequency of the water molecule. After recombination, only about 20% of the ions are available for electrification, called *available* ions, in order to be distinguished from the hydronium and hydroxyl ions present in the boiler water, called *background* ions. The ionization of water is,



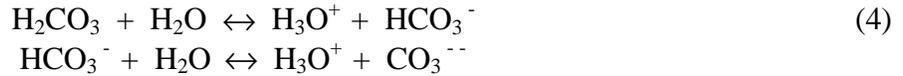
The concentrations of hydronium  $[\text{H}_3\text{O}^+]$  and hydroxyl  $[\text{OH}^-]$  ions are given by the ionization constant  $K_W$ ,

$$K_W = [\text{H}_3\text{O}^+][\text{OH}^-] \quad (2)$$

where,  $[\text{H}_3\text{O}^+] = [\text{H}_3\text{O}^+]_a + [\text{H}_3\text{O}^+]_b$ , and  $[\text{OH}^-] = [\text{OH}^-]_a + [\text{OH}^-]_b$ , the subscripts  $a$  and  $b$  denoting available and background ions. The common source of acidity in boiler water is atmospheric carbon dioxide  $\text{CO}_2$  that dissolves in water to form carbonic acid  $\text{H}_2\text{CO}_3$ ,



The kinetics of carbonic acid formation from carbon dioxide is relatively slow, on the order of seconds. Subsequent buffering action is fast, but nonetheless limited by the formation of carbon dioxide. Excess hydronium ions are converted to carbon dioxide through carbonic acid by buffering with carbonate  $\text{CO}_3^{--}$  and bicarbonate  $\text{HCO}_3^-$  ions.



In general, the boiler water may contain limestone, or calcium carbonate  $\text{CaCO}_3$  as found by Faraday [1]. Carbon dioxide dissolves limestone to form calcium and bicarbonate ions, the calcium carbonate competing with the formation of carbonic acid. Moreover, small amounts of  $\text{NaCl}$  in the boiler water can combine with the hydroxyl ions to form sodium hydroxide  $\text{NaOH}$ , a strong base. To avoid complicated acid-base chemistry, the charge separation mechanism is simplified in terms of the pH of the boiler water as shown in Fig. 2.

Charge separation in acidic boiler water having  $\text{pH} < 7$  presumes the available ions created on the bubble surface by cavity QED having already undergone recombination do not undergo further recombination with background ions. However, the hydronium and hydroxyl ions are not in equilibrium,

$$[\text{H}_3\text{O}^+]_b [\text{OH}^-]_b \neq \{ [\text{H}_3\text{O}^+]_a + [\text{H}_3\text{O}^+]_b \} \{ [\text{OH}^-]_a + [\text{OH}^-]_b \} \quad (5)$$

To satisfy Eqn. 5, the background  $[\text{H}_3\text{O}^+]_b$  ions may be reduced to compensate for the available  $[\text{H}_3\text{O}^+]_a$  and  $[\text{OH}^-]_a$  ions by buffering with bicarbonate ions to produce carbon dioxide. But the carbon dioxide formation time is long compared to the time for a bubble after nucleation to burst at the droplet surface. Hence, *local* equilibrium of hydronium and hydroxyl ions cannot be satisfied in

the liquid phase, and therefore to satisfy equilibrium both  $[H_3O^+]_a$  and  $[OH^-]_a$  ions already on the bubble surface move to the vapor phase of the bubble. Since acid pH carries an abundance of background hydronium ions compared to hydroxyl ions, the *local* bubble surface is charged positive. Available ions separate in the vapor phase; the  $[H_3O^+]_a$  ions are repulsed from the bubble surface and move to the center of the bubble, while the  $[OH^-]_a$  ions are attracted and attach to the bubble surface. Thus, bubble bursting at the droplet surface carries positive charge steam of hydronium  $[H_3O^+]_a$  ions leaving behind the droplet charged negative with hydroxyl  $[OH^-]_a$  ions.

Chemistry for basic boiler water having  $pH > 7$  again presumes the available ions already having undergone recombination do not recombine further with background ions. But to satisfy equilibrium in the liquid state,  $[H_3O^+]_b$  ions still have to be reduced to accommodate the available  $[H_3O^+]_a$  and  $[OH^-]_a$  ions. Basic pH differs from acid pH only by buffering with carbonate instead of bicarbonate ions, but the formation time of carbon dioxide is still long compared to the time for a bubble to burst in droplets. Local equilibrium on the bubble surface is satisfied only by both available  $[H_3O^+]_a$  and  $[OH^-]_a$  ions moving to the vapor phase of the bubble. Since basic pH carries an abundance of background hydroxyl ions compared to hydronium ions, the bubble surface is charged negative. Available ions separate in the vapor phase; the  $[H_3O^+]_a$  ions are attracted and attach to the bubble surface, while the  $[OH^-]_a$  ions are repulsed from the bubble surface and move to the center of the bubble. Thus, bubble burst at the droplet surface carries a negative charge steam of hydroxyl  $[OH^-]_a$  ions leaving behind positive charged droplets of hydronium  $[H_3O^+]_a$  ions.

The average charge carried by the steam in the bubbles depends on the charge of the bubble wall given by the background concentrations of hydronium and hydroxyl ions in the droplet. The probability ( $P^+$ ,  $P^-$ ) of the bubble wall being positive or negative is,

$$P^+ = \frac{[H_3O^+]_b}{[H_3O^+]_b + [OH^-]_b} \quad \text{and} \quad P^- = \frac{[OH^-]_b}{[H_3O^+]_b + [OH^-]_b} \quad (6)$$

A normal statistical distribution of charged particles about the mean or net charge is suggested based on data on the distribution of charged droplets by Pounder [13,14].

### 3.1 Background

Steam electrification caused by the separation of hydronium and hydroxyl ions in bubbles is common to many historical applications in atmospheric electricity including lightning and thundercloud electrification, and the Leidenfrost phenomenon.

Lightning based on thundercloud electrification [15] may be described by the hydronium and hydroxyl ions produced from the dissociation of the water molecules as moisture carried to high altitudes condenses and supercools to form graupel, a liquid-ice mixture. Bubbles nucleate in the supercooled water because of the large volume expansion that accompanies freezing. Initial freezing of the graupel skin places the graupel interior into compression, the compression tending to force the bubble vapors through the skin into the surroundings. Charge separation occurs within the bubbles as water molecules on the bubble walls dissociate by cavity QED into hydronium and hydroxyl ions as shown for steam electrification. Typically, the moisture in the updraft has an acid pH, and therefore the liquid wall of the bubbles in the graupel carries a positive charge because of the abundance of hydronium ions in the moisture. The available hydronium ions leave the graupel as positive charged vapor, the companion hydroxyl ions remaining to give the graupel a negative charge. Ice crystal particles are formed by the vapor deposition of hydronium ions from the bubble,

the clouds of particles forming positive charged ice crystal clouds. Cloud-to-cloud lightning in the upper atmosphere occurs between graupel and ice crystal clouds, while cloud-to-ground lightning takes place as graupel clouds that escaped discharge as cloud-to-cloud lightning fall to the lower atmosphere and discharge with the positive charge earth's surface.

The Leidenfrost phenomenon [16] describes the electrification of a drop of boiling water supported from a hot surface by a film of its own vapor and is quite similar to that of steam electrification. The temperature of the hot surface is above 400 °C and heats the underside of the drop to the 100 °C boiling point of water. After cavity QED dissociation of water molecules, the available ions are separated in the bubble as for steam electrification. If the drop has an acid pH, bubbles nucleated in boiling leave the drop from its underside as a positive charged steam of hydronium ions, the drop charged negative by hydroxyl ions. Conversely, if the pH of the drop is basic, the steam vapor is charged negative and the drop positive.

### 3.2 Sonoluminescence and the dissociation of water molecules

How steam electrification is related to the dissociation of the water molecule in bubbles finds basis in the phenomenon of sonoluminescence (SL). SL was first observed [17] by Frenzel and Schultz in 1934 and is usually described as the production of visible light during the cavitation of water, but is also known [18] to produce hydroxyl ions. Many SL theories have been proposed [19].

The Planck theory of SL [20] differs from other SL theories because the source for producing SL photons is the Planck energy of the stimulated emission from the bubble wall molecules as the bubble resonant frequency during bubble collapse coincides with the dissociation frequency of the water molecules. The bubble resonant frequency continuously increases during bubble collapse, the significance of which is that the discrete dissociation frequencies of the water molecule can always be stimulated, i.e., the bubble acts as a continuously variable vacuum ultraviolet to soft X-ray laser. The Planck energy  $E$  is,

$$E = h\nu = \frac{hc}{\lambda} \quad (7)$$

where,  $h$  is Planck's constant,  $\nu = c / \lambda$  is the bubble resonant frequency,  $c$  is the speed of light, and  $\lambda$  is the wavelength of the bubble resonance. In a spherical bubble of radius  $R$ , the bubble resonance may be considered as a wave of wavelength  $\lambda \sim 4R$  and frequency  $\nu \sim c / 4R$ , where  $c$  is the velocity of light.

Liquid water is highly absorptive over the frequency range from the vacuum ultraviolet to soft X-rays. Provided the bubble geometry collapses to dimensions corresponding to this frequency range, QED resonance always produces hydronium and hydroxyl ions. The bubbles at the time the water molecules dissociate are not visible because vacuum ultraviolet frequencies have wavelengths less than 160 nm, the corresponding bubble radius less than 40 nm.

Charge separation is not of importance in bubble collapse because the bubble walls collide. Excited OH\* hydroxyl radicals are also produced, the excited radicals combining with Ar atoms in the air dissolved in the water bubble walls under the high stagnation pressures developed as the bubble walls collide. The high pressures produce Ar\*OH excimers, the visible photons produced as the excimers decompose in the pressure relief of the rarefaction shock.

Of interest here is the dissociation of the water molecule during bubble nucleation and growth, rather than visible photons during bubble collapse. Nucleation is collapse in reverse. Bubbles are nucleated at dimensions on the order of the spacing between water molecules, the bubble

dimensions corresponding to soft X-ray frequencies, the water molecules dissociating as the bubble grows to dimensions corresponding to frequencies in the vacuum ultraviolet. SL photons are not produced as bubbles nucleate and grow because the bubble walls do not collide to form the Ar\*OH excimers, but water molecules dissociate in both bubble growth and collapse.

The Planck theory of SL based on the emission produced as the bubble resonance coincides with the dissociation frequency of the bubble wall water molecules is consistent with the zero-point energy field. An arbitrary cavity may be considered to contain zero point energy having field modes with frequencies quantized by its dimensions, the lowest of which is the bubble resonant frequency of cavity QED. Zero point energy considers the cavity to contain a continuum of frequencies greater than resonance that has been interpreted to imply a cavity contains an infinite source of Planck energy. In this regard, the Planck theory of SL differs in that only cavity field modes having frequencies greater than resonance and which are contained in the absorption ( and emission ) spectrum of the cavity wall are allowable, thereby limiting the Planck energy in the cavity to be finite.

In the Planck theory of SL, the emission is not in equilibrium with the temperature of the bubble wall. Stimulation of bubble wall water molecules at vacuum ultraviolet frequencies may be considered caused by zero point energy even though the bubble wall is at ambient temperature. This means zero point energy  $E = \frac{1}{2} h\nu$  is always available to stimulate any bubble wall water molecule providing the absorption ( and emission ) spectrum exists at that frequency. For a Planckian photon produced by a pair of diametrically opposite bubble wall molecules in resonance with the bubble cavity, the Planck energy  $E = h\nu$  is the sum of the zero point energy of the respective water molecules. Hence, the Planck theory of SL is consistent with the general form of Planck's blackbody spectrum in which the spectrum density  $\rho(\nu, T)$  includes the zero point energy,

$$\rho(\nu, T) = \frac{4\nu^2}{c^3} \left[ \frac{h\nu}{\exp(h\nu/kT) - 1} + \frac{1}{2} h\nu \right] \quad (8)$$

where,  $k$  is Boltzmann's constant, and  $T$  is absolute temperature.

The general form of Planck's blackbody spectrum is consistent with that of random electrodynamics proposed [21] by Boyer in 1969. However, both Planck and Boyer formulations differ [22] from that by Einstein who excluded the zero point energy. In this regard, Planck [23] commented that the zero point energy provided an explanation of atomic vibrations that are independent of temperature, e.g., electrons liberated by the photoelectric effect that are independent of the temperature of the metal and the intensity of the exciting radiation. This is consistent with the Planck theory of SL that asserts the water molecules dissociate on the bubble walls at ambient temperature by cavity QED resonance in the same way they would dissociate if irradiated by an external laser. In contrast, the Einstein formulation [22] of black body radiation would require for the dissociation of the water molecules at a Planck energy in the vacuum ultraviolet, say 10 eV, to have an unrealistic temperature of about 100,000 K.

The Planck theory of SL was formulated to explain the SL in collapsing bubbles, but is consistent with the dissociation of water molecules during the nucleation of bubbles as applied to waterfall electricity in the Lenard effect. Indeed, Prevenslik [24] reported a maximum of about  $2 \times 10^5$  water molecules dissociate in every bubble nucleated in a waterfall splash, the number consistent with the number of SL photons from a collapsing air bubble in water, called the standard unit of SL, the number determined [25] experimentally. A maximum 80 % recombination leaves from  $4 \times 10^4$  to  $2 \times 10^5$  hydronium and hydroxyl ions in each bubble for electrification.

## 4. Discussion

### 4.1 Historical review

Lenard's explanation [10] of negative charged vapor away from waterfalls and a positive charge remaining in the splash is consistent with the proposed theory for water having a basic pH common to limestone riverbeds in mountains,  $P^- > P^+$ .

Faraday's investigation of the Seghill incident [1] showing the steam to be charged positive is consistent with an acid pH common to mine water and the sulfate of lime residue found in the boiler,  $P^+ > P^-$ . Rainwater dissolves carbon dioxide from the air and produces carbonic acid having a pH  $\sim 5.8$ , but in a boiler the carbon dioxide is removed to produce a neutral pH  $\sim 7$ . Hence the report the boiler using rainwater did not produce charge is consistent with water having balanced positive and negative charge, or a net neutral charge,  $P^+ \sim P^-$ .

Faraday's finding [6] that positive charged steam ceased by adding small amounts of alkali to the distilled water may be explained by the distilled water already acidic by dissolved carbon dioxide, being neutralized by the alkali,  $P^+ \sim P^-$ . Loss of positive charge found by replacing the distilled water with common London waters is a similar in that dissolved carbon dioxide in the alkaline water from River Thames is known to produce neutral pH. The reddening of turmeric paper, today known as curcumin, in negative charged steam produced by adding ammonia to distilled water means the boiler water was basic having a pH  $> 8.6$ ,  $P^- > P^+$ . After adding small amounts of sulfuric acid, the steam charge was reduced to neutrality,  $P^- \sim P^+$ .

With regard to contact friction, the opinion here is consistent with that of Armstrong who had difficulty with the supposition that contact friction was the exclusive cause of steam electrification. In 1840, the nature of the water was thought to be the cause of electrification, the nature of the water known today by electrolytic processes. Later in 1843, Faraday instead proposed contact friction to explain steam electrification. But Faraday's inability to explain the compressed air experiments by contact charging only underscores the importance of electrolytic processes.

Lack of pH measurements of the steam makes it difficult to fully compare Faraday's results with the present theory that is based on pH. Certainly, the contact friction hypothesis is tenable for oils and powders that are physically different from globules of water, but Faraday's experiments show contact friction may be overwhelmed by electrolytic processes requiring small quantities of acids and alkalis, or the oils and powders themselves.

#### *Spray electrification and charge conservation*

Spray electrification as explained by the double layer [10] and ion fluctuation [11] theories lacks explicit conservation of charge between liquid and vapor. In contrast, the proposed theory requires changes in the concentration of hydronium and hydroxyl ions obey ionic equilibrium as spray leaving the liquid is electrified.

In spray charging, a continuous supply of water is available so that the loss of capacity to produce charge is not noticed. But to illustrate the importance of charge conservation, consider the spray charge produced as bubbles are continuously being nucleated in a flask of boiling water and burst at the liquid surface. Unlike the jet, the volume of water in the flask is finite. Assume the water is distilled and has been boiled to remove dissolved carbon dioxide and carbonic acid leaving a neutral pH. Because of the orientation of water molecules on the bubble surface, the bubble vapor

in the double layer theory carries away negative ions to the surroundings leaving the liquid with an excess of positive charge and eventually producing an acidic water solution. In the distilled water, ion fluctuations of dissolved salts are insignificant so as to negate the applicability of the ion fluctuation theory altogether. Neither theory answers the question how boiling is related to subsequent loss of charge to the surroundings.

In contrast, the proposed theory does not produce an acid or a base, but always produces water of neutral pH. Boiling of pure distilled water instantly produces a neutral steam, but if the neutrality is perturbed to be acidic by some reason, the bubble spray is first charged positive by hydronium ions, the hydroxyl ions increasing the pH of the water. Boiling next produces a negative charged spray leaving the water with a reduced pH. Upon continued boiling, the pH converges to neutrality.

### 4.3 Steam electrification

In 1840, Pattinson [4] found the length  $\Lambda$  of the spark discharge from steam electrification to be proportional to the pressure  $P$  of the steam,  $\Lambda \propto P$ . In the proposed theory, the steam is electrified as bubbles nucleate in boiling drops, every bubble producing at least  $4 \times 10^4$  hydronium and hydroxyl ions to electrify the steam. Hence, it may be argued that the spark length  $\Lambda$  is proportional to the number  $N$  of bubbles nucleated in the droplets,  $\Lambda \propto N$ . The number  $N$  of bubbles is not known, but should vary inversely with the heat of vaporization  $h_{fv} = h_v - h_f$ , where  $h_v$  and  $h_f$  are the enthalpy of the vapor and the fluid. The inverse relation is expected because for the same amount of heat supplied to the boiler, a lower heat of vaporization enables more bubbles to be nucleated to electrify the steam,  $N \propto h_{fv}^{-1}$ . Hence,  $\Lambda \propto h_{fv}^{-1}$ . Indeed, the liquid-vapor phase region of water is characterized by the lowering of the heat of vaporization  $h_{fv}$  as the pressure  $P$  is raised. Fig. 3 shows Pattinson's spark length  $\Lambda$  data to be proportional to  $h_{fv}^{-1}$  confirming the proportionality of electrification by the number of bubbles produced in boiling.

In 1989, Finke [8] repeated the Faraday experiment [6] on steam electricity. Like Faraday, Finke measured the current  $J_o$  from the nozzle to ground. Similar to the length  $\Lambda$  of spark, the current  $J_o$  is expected to vary inversely with the heat of vaporization, i.e.,  $J_o \propto h_{fv}^{-1}$ . But Finke's data ( Fig. 2 of Ref. [8] ) shows sporadic charge reversals at the nozzle. Fig. 3 shows the current  $J_o \propto h_{fv}^{-1}$  that excludes the sporadic charge reversal to be consistent with the number of bubbles carrying charge. The charge reversals observed at the nozzle were likely caused by chemical contamination, as there is no reason to believe steam electrification would be sporadic.

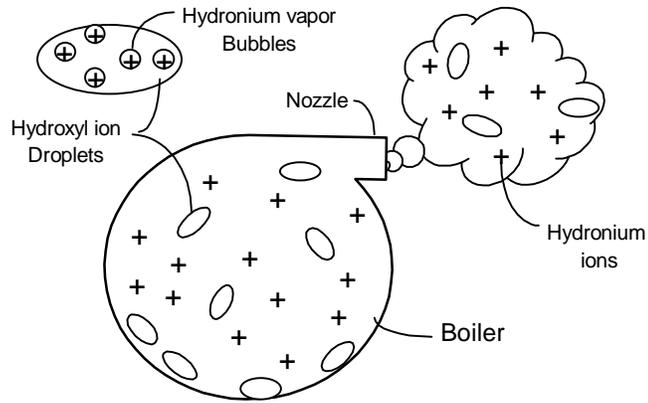
## 5. Conclusion

Steam electrification is proposed to find origin in the nucleation of bubbles in boiling, the electrification occurring as water molecules on the bubble walls dissociate by cavity QED into hydronium and hydroxyl ions. Separation of ionic charges takes place by the repulsion and attraction to the bubble wall, the wall charge depending on the pH of the boiling water.

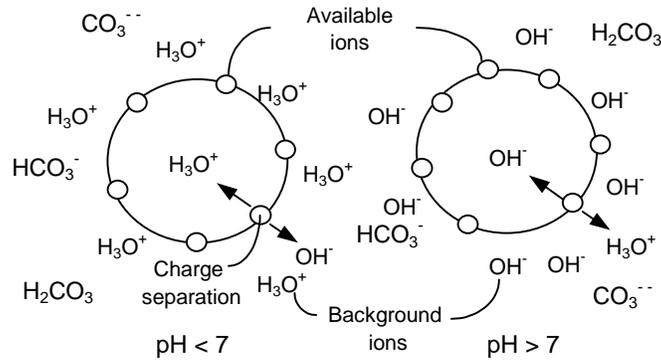
The present theory for steam electrification may also be applied to electrified mist from hot and cold liquid jets. Before liquid water breaks up into spray droplets, bubbles nucleate in the liquid by the rapid decompression in leaving the nozzle. But the number of bubbles would be small compared to the far greater number if the water were to boil. Hence, the mist from hot and cold liquid jets is electrified, but far less than for wet steam.

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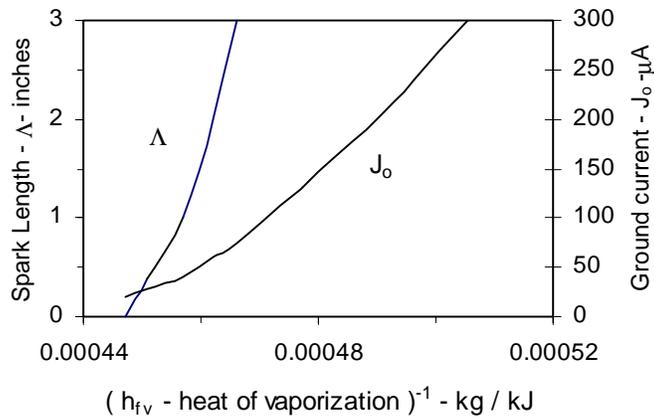
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**Fig. 1.** Steam electricity - pH < 7



**Fig. 2.** Charge separation



**Fig. 3** Steam electricity

Inverse proportionality of spark length and ground current to heat of vaporization