Title: APPARATUS AND METHOD FOR ENERGY PRODUCTION

Abstract: The present invention provides apparatuses and methods for producing energy from a fluid comprising solutes. In particular, negative enthalpy of solvation become stored potential energy. Some aspects of the invention provide methods and apparatuses to capture at least a portion of this stored potential energy using a plasma.
APPARATUS AND METHOD FOR ENERGY PRODUCTION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the priority benefit of U.S. Provisional Application No. 61/186,808, filed June 12, 2009, which is incorporated herein by reference in its entirety. Because June 12, 2010, is a Saturday and June 13, 2010, is a Sunday, filing of this non-provisional patent Application on June 14, 2010, is timely for claiming the priority benefit of the above-identified provisional patent application.

FIELD OF THE INVENTION

[0002] The present invention relates to apparatuses and methods for producing energy from a fluid comprising solutes. Some aspects of the invention relate to methods and apparatuses to capture at least a portion of this stored potential energy using a plasma arc.

BACKGROUND OF THE INVENTION

[0003] It is well known that water droplets from forced vaporization, atomization, and nebulization tend to be highly charged, especially if they contain dissolved electrolytes. Some of the original enthalpy of ionic hydration from dissolving an electrolyte in water becomes Coulombic potential energy shared among the excess ions on a given water droplet and Coulombic potential energy shared among the water droplets in the spray. There are several mechanisms by which these ions become released by the droplets into the surrounding air leading to exothermic plasma chemistry. The chemistry, ionic oxidation-reduction, ion-molecule reactions, and neutral reactions, require high temperature in order to overcome some activation barriers, even for exothermic reactions. The exothermic reactions increase the temperature of the plasma and increase its conductivity. The net result is the creation of heat over the Ohmic heating, $I^2R$, produced by the applied voltage and current in the electric arc. The total energy of the system, i.e., potential energy + kinetic energy, remains constant including the arc power and the power used in the atomization, which is a fraction of the surface energy of the water plus the hydraulic power loss in flowing the water through the atomizer nozzle. The First Law of thermodynamics: $\Delta U = Q-W$ is thus satisfied.
The highly polar water molecules in the liquid phase and its large dielectric constant break the strong ionic bonds of the solid electrolyte, e.g., NaCl which is also written Na⁺Cl⁻(s), separating the ions and restructuring itself into hydration shells around the ions. The solid binding energy is taken up as potential energy, i.e., the enthalpies of hydration of the Na⁺ and Cl⁻ ions. In addition, local rearrangement of the H₂O molecules from the average tetrahedral structure to the differently coordinated hydration shells occurs.

It is this hydration or solvation energy, i.e., stored potential energy, that can be recovered as heat from charged salt water droplets in a high temperature electric arc plasma as well as energy that is generated through the plasma chemistry of (1) air; (2) water molecules and their dissociation products; and (3) the atomic, ionic, and radical constituents of the salt.

Currently, no methods exist for recovering this stored potential energy. Capturing of at least some of this stored energy would allow a new energy production method that can satisfy at least some of the current energy demand.

Therefore, there is a need for methods and apparatuses for liberating, recovering, utilizing, and/or capturing this stored potential energy, e.g., heat of solvation, as well as other stored energy that may be generated from a plasma.

SUMMARY OF THE INVENTION

Some aspects of the invention provide methods for producing energy using a fluid comprising a solvated solute. In general, such methods capture, liberate, utilize, and/or recover the stored or potential energy of the solvated solute. The potential energy typically comprises enthalpy of solvation or solvation energy. Methods typically comprise:

- injecting the fluid into a plasma under conditions sufficient to exothermically recombine, neutralize, or associate solutes from the fluid, and to produce a net energy output that is greater than the amount of total energy used to produce the plasma.

In some embodiments, the fluid comprises a gas, vapor, mist, aerosol, liquid droplets, free ions, or a combination thereof.

In other embodiments, the solid comprises a compound having an ionic bond. Within these embodiments, in some instances, the solid comprises alkyl halide.
[0011] Typically, the net energy output (i.e., energy gain) is greater than the total energy used to produce the plasma. Typically, the net energy output is at least 15%, often at least 25%, more often at least 50% greater than the amount of total energy used to produce the plasma.

[0012] In other embodiments, the energy recovered from the process is at least 20% of the heat of solvation, typically at least 40% of the heat of solvation, often at least 50% of the heat of solvation, and more often at least 75% of the heat of solvation. It should be appreciated, however, the energy recovered need not come only from the heat of solvation. The amount of energy gain merely reflects the magnitude of energy recovered. It is possible the only a portion of the energy recovered is from recovery of heat of solvation. Other sources of recovered heat can be those described herein.

[0013] There are many materials that have a negative enthalpy of solvation. The scope of the invention includes any solid and the fluid combination that has a negative enthalpy of solvation. Often the fluid comprises liquid such as water. In general, the fluid comprises any solvent that produces an ionic solution when the solid is added to the fluid. Typically, the enthalpy of solvation is such that the overall energy recovery, production or capture is greater than the amount of energy used to produce the plasma. In some embodiments, enthalpy of solvation of the solid in the fluid is at least about -48 kJ/mol, typically at least about -96 kJ/mol, often at least about -192 kJ/mol and more often at least about -288 kJ/mol. In some embodiments, the fluid comprises a solvent that produces ionic solution from the solid.

[0014] Yet in other embodiments, the plasma is generated within a holraum. Such an apparatus allows one to more efficiently recover or capture the energy produced.

[0015] The plasma can be produced using any of the methods known to one skilled in the art. In some embodiments, the plasma is produced by an electric arc that is generated from a first electrode to a second electrode. The electric arc can be produced from an alternating current, direct current, rectified AC, or pulsed DC, typically over a frequency range of less than about 10 GHz.

[0016] Methods and apparatuses of the invention can produce the energy in a variety of forms such as thermal energy, radiation, heat, as well as various combinations thereof. In some embodiments, the produced energy comprises heat. Such energy can be captured, utilized, or
stored in any of the methods known to one skilled in the art. In some embodiments, the heat is
used to generate electric energy, for example, by generating steam and using the steam to
generate electric energy using a turbine. In other embodiments, the electric energy is produced
by a device comprising a heat engine, a generator, thermionic means, magnetohydrodynamic
(MHD) means, or a combination thereof. Still in other embodiments, heat is used to propel a
transportation device, such as an automobile, locomotive, boat, or a plane.

[0017] Other aspects of the invention provide energy producing apparatuses. In some
embodiments, such apparatuses comprise:

a chamber comprising:

an inlet adapted for introducing a fluid comprising a solvated solute into said
chamber,

an outlet, and

an energy capture device adapted for capturing energy that is produced within
said chamber; and

at least a pair of electrodes for producing a plasma within said chamber, wherein said
electrodes are positioned within said chamber such that the introduced fluid flows
through the plasma that is produced by said electrodes; and

an electric arc generating device operatively connected to said electrodes thereby
producing a plasma from an electric arc between said electrodes during operation
of said apparatus.

[0018] In some embodiments, such apparatuses comprise a means for feeding electrodes
into the apparatus. Typically, the electrodes erode during use; thus, in some embodiments, the
electrodes are automatically fed into the apparatus at some rate to maintain the arc production.
The rate of feeding (e.g., inserting) the electrode can be linked to a feedback mechanism, e.g., a
device that tracks the voltage and/or current required to produce the arc and adjusts the
electrodes to keep the voltage and/or current constant. Such devices are well known to one
skilled in the art.

[0019] Yet in other embodiments, the fluid is introduced using a Field Induced Droplet
Ionization (FIDI) or Electrospray Ionization (ESI) process. In some instances, the fluid which
comprises the solute is introduced into the arc as a steam, mist or aerosol. Mist or aerosol can be
generated, for example, via atomization, nebulization, or other means which increase the charge in the mist or aerosol using static electric fields; some devices use a radioactive isotopic source to add charge to the droplets. Apparatuses and methods of the invention can include producing ions from the fluid (e.g., salt water) by producing droplets and enhancing the ionization of the mist or aerosol.

[0020] Still in other embodiments, apparatuses of the invention can include the means and/or capability of feeding any gaseous and/or particulate emission into the arc and of adding droplets, etc. from an ionic solution.

[0021] Yet in other embodiments, the chamber is made from a material comprising ceramic, clay, glass, quartz, diamond coated material, or other materials known to one skilled in the art, or a combination thereof.

[0022] In other embodiments, the energy capture device comprises a heat exchanger. In some instances, the heat exchanger is made from a material comprising copper, stainless steel, or other materials known to one skilled in the art, or a combination thereof.

[0023] Generally, electrode can be made from any material can create an arc when a sufficient voltage is applied. Such suitable materials are well known to one skilled in the art. In some embodiments, the electrode is independently made from a material comprising tungsten, graphite, copper, platinum, alumina (Al₂O₃), oxides of copper, zinc, or nickel, other metal oxides, metals doped or alloyed with thorium or other rare-earth metals, or a combination thereof. Still in other embodiments, the electrode is doped or coated with a lower work function material. The electric arc can be generated using an alternating current, direct current, rectified AC or pulsed DC.

**BRIEF DESCRIPTION OF THE DRAWINGS**

[0024] Figure 1 is a graph showing heat or enthalpy of formation for the various states of Na, Cl, and NaCl.

[0025] Figure 2 graphs showing preference for mutual neutralization of Na⁺ + Cl⁻ rather than recombination at various conditions.

[0026] Figure 3 shows a curve crossing process of Na⁺ and Cl⁻.
Figure 4 shows graphs of the composition of dry air at temperatures up to 6000 °K as well as ion density as a function of NaCl molarity in water.

Figure 5 shows graphs of Na⁺ and Cl⁻ ionic thermal equilibrium.

Figure 6 is a graph of the Born-Haber cycle for sodium chloride.

Figure 7 is NaCl energetic in arithmetical form via Hess’ Law.

Figure 8 is a schematic representation of the Na⁺Cl⁻ solid crystalline lattice.

Figure 9 is a schematic illustration of the solvation process of NaCl salt by water.

Figure 10 shows thermochemistry of NaCl salt solvation by water.

Figure 11 is a schematic illustration of the dipole nature of H₂O molecule.

Figure 12 shows a schematic illustration of oriented polar H₂O molecules around Na⁺ and Cl⁻ ions.

Figure 13 illustrates concentration of Na⁺ and Cl⁻ near a water surface and the effects upon electrical conductivity.

Figure 14 shows evaporation and explosion scenario for charged droplets.

Figure 15 shows graphs of electrical and thermal conductivities of hot dry air and of plasma.

Figure 16 is a schematic diagram of one embodiment of the salt water burning (SWB) devices of the present invention with a control volume drawn in for calculating the thermodynamic power balance of the system.

Figure 17 is a schematic illustration of one particular embodiment of the SWB experiment setup of the present invention.

Figure 18 is a schematic illustration showing one particular embodiment of the vitrified clay pipe and aerogel insulation of the present invention.

Figures 19A and 19B show results of SWB experiment without any salt in water and with 3 M salt water, respectively.
Figure 20 shows the result of heating of water by pump and arc with and without salt water.

Figure 21 shows the details of the heating curves.

Figures 22 shows graphs of oscilloscope traces of the results of each SWB experiment.

Figure 23 shows the instantaneous power in Watts for the two experiments averaged over each set of 6 scope traces. The graph shows the origins of the differences between the various power calculations.

Figure 24 shows the averaged current and normalized voltage waveforms for each experiment. In Figure 24, the I(t) and V(t) phase differences explain the P(t) = I(t) x V(t) power graph.

Figure 25 shows that the current waveforms between the two experiments are identical except for a small difference in magnitude.

Figure 26 is a graph showing consistency of V(t) from overlay of 6 scope traces for each experiment.

Figure 27 shows typical I(t) and V(t) arc waveforms. Wave forms of AC arc voltage and current.

Figure 28 is a Fourier frequency spectrum of V(t).

Figure 29 is a schematic illustration showing V(t) distortion due to the recovery voltage.

Figure 30 is a graph showing ideal AC arc V-I characteristic.

Figure 31 is an actual V-I characteristic measured.

Figure 32 shows a schematic of surface discharge experiment in an H₂O/ CaCl₂ solution and photos in time sequence of the initial arc followed by reaction chemistry leading to 10 cm diameter fireball.
Figure 33 is a graphic illustration showing the relationship among $\Delta H_{\text{att}}$, $\Delta H_{\text{hyd}}$, and $\Delta H_{\text{so}}$ for salt water.

Figure 34 shows several depictions of how salt dissolves in water.

Figure 35 is Born-Haber diagram for $\text{H}_2\text{O}$.

Figure 36 is a sine wave fit to arc power oscillation.

Figure 37 is a graph of thermal Data (70 g/L NaCl in water).

Figure 38 is a graph showing a numerical fit to $T(t)$ for heating by steam alone.

Figure 39 is a graph showing the temperature of the circulating water without any water spray and with steam.

Figure 40 is a graph showing the fluctuating arc power.

Figure 41 is a graph of temperature measurements of 75 g/L salt water solution.

Figure 42 is a graph of water temperature v. Time of 75 g/L salt water solution.

Figure 43 is a graph showing the time dependence of the arc power, current, and voltage over the course of the experiment using 75 g/L salt water solution.

Figure 44 is a graph showing the arc power, arc power going into heating the water, and the ratio of the two.

Figure 45 is a graph of integrated power ratio.

Figure 46 is graphs of temperatures $T(t)$ for the three phases or stages of the SWB experiment.

Figure 47 shows a schematic illustration of the pump, hoses, and container for circulating the water through the copper coil.

Figure 48 is a graph showing the time dependence of power dissipation, arc power, and the ratio based on smoothed data.

Figure 49 is a graph of average current, voltage, and power taken from scope traces at 14 times during stage #3 of the SWB experiment.
Figure 50 is microscope photos of the electrodes after SWB experiments.

Figure 51 is a graph of a Monte Carlo sampling of values of Q(R)/e from a Gaussian distribution.

Figure 52 is a graph showing the evaporation time as a function of droplet radius.

Figure 53 shows photos and physical depiction of Taylor cones.

Figure 54 is a schematic illustration of theoretical and computational model for ion ejection process.

**DETAILED DESCRIPTION OF THE INVENTION**

"Enthalpy of solvation," "heat of solvation," and "ΔH_{solv}" are used interchangeably herein and refer to the enthalpy change for the production of a solution of ions from one mole of gaseous ions, e.g. Na+(g) → Na+(aq); this is also known as the aqueous solvation free energy of an ion.

"Enthalpy of hydration," "heat of hydration" and "ΔH_{hyd}" are used interchangeably herein and refer to heat of solvation where the solvent is water.

"Enthalpy of vaporization," "heat of vaporization," and "ΔH_{vap}" are used interchangeably herein and refer to the energy required to evaporate solvent such as liquid water. For water ΔH_{vap} is 44 kJ/mole.

"Enthalpy of formation," "heat of formation," and "ΔH_f" are used interchangeably herein and refer to the heat generated or absorbed when a substance is formed from its constituent elements at atmospheric pressure and a specified temperature, usually 298 °K.

"Enthalpy of reaction," "heat of reaction," and "ΔH_r" are used interchangeably herein and refer to the amount of heat absorbed (endothermic, ΔH_r > 0) or produced (exothermic, ΔH_r < 0) when substances react at constant pressure where

\[ ΔH_r = \sum ΔH_f(\text{products}) - \sum ΔH_f(\text{reactants}) \]

It is the hydration or solvation energy, which is stored as potential energy, that can be recovered as heat from charged salt water droplets in a high temperature electric arc plasma through the plasma chemistry of air; water molecules and their dissociation products; and the atomic, ionic,
and radical constituents of the salt. Examples of the heats of hydration and formation are shown in the following table:

<table>
<thead>
<tr>
<th>Cation</th>
<th>$\Delta H_{\text{hyd}}$ (kJ/mole)</th>
<th>$\Delta H_{\text{f}}$</th>
<th>Anion</th>
<th>$\Delta H_{\text{hyd}}$</th>
<th>$\Delta H_{\text{f}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na$^+$</td>
<td>-424</td>
<td>+609</td>
<td>Cl$^-$</td>
<td>-359</td>
<td>-234</td>
</tr>
<tr>
<td>K$^+$</td>
<td>-340</td>
<td>+514</td>
<td>F$^-$</td>
<td>-504</td>
<td>-255</td>
</tr>
<tr>
<td>Mg$^{2+}$</td>
<td>-1963</td>
<td>+1450</td>
<td>ClO$_3^-$</td>
<td>-331</td>
<td>-185</td>
</tr>
<tr>
<td>Ca$^{2+}$</td>
<td>-1616</td>
<td>+1737</td>
<td>NO$_3^-$</td>
<td>-316</td>
<td>-311</td>
</tr>
<tr>
<td>Al$^{3+}$</td>
<td>-4741</td>
<td>+2881</td>
<td>OH$^-$</td>
<td>-519</td>
<td>-144</td>
</tr>
</tbody>
</table>

[0083] When ionically bound NaCl is dissolved in water, the Na$^+$Cl$^-$ binding energy in the crystalline solid becomes intermolecular potential energy in the water solution. When the salt water is vaporized and the salt water micro droplets that comprise the vapor evaporate liberating the Na$^+$ and Cl$^-$ ions in the arc plasma (without being bound by any theory, it is believed that they evaporate to a certain diameter and then undergo a Coulomb or Rayleigh explosion spreading the Na$^+$ and Cl$^-$ ions around in space), via any number of pathways, they neutralize each other and undergo other reactions that liberate lots of energy. Hess’ Law shows that this is independent of the pathways taken.

[0084] Thus, via the high temperature arc, apparatuses and methods of the invention convert the 783 kJ/mole of potential energy that the H$_2$O has stored in the process of dissolving crystalline NaCl into kinetic energy, i.e., heat, in the plasma. It is believed that this recovery of stored potential energy allows production of more thermal power out of the plasma then electric power that is used to generate the plasma.

[0085] One of the primary products of the Na$^+$, Cl$^-$, and other high temperature reactions is heat. It is kinetic energy that increases the temperature of already hot electric arc plasma, e.g., from about 4000 °K to about 8000 °K. At 8000 °K there is a great flux of infrared (IR), visible, and UV radiation created that is thermalized by the copper cylinder radiation cavity, or hohlraum, at the center of a reactor, thereby heating water circulating in the copper coils. The radiation cavity allows efficient capture of produced energy.

[0086] In contrast to the other known methods of processing water to produce hydrogen and oxygen, apparatuses and methods of the invention produce energy via a different mechanism. While it is possible that there is some H$_2$ created, it is believed that there is very little, if any, free oxygen created in methods and apparatuses of the present invention. It is
believed that most of the oxygen atoms form molecules other than $O_2$ when they react with the other products of the high temperature arc.

[0087] Apparatuses and methods of the invention allow generation or production of heat energy with very high efficiency. Figure 1 shows the temperature dependent enthalpies or heats of formation of sodium in various states, chlorine, and their ions. When the chemistry of sodium and chlorine in the vicinity of the high temperature arc is considered, the following reactions can initiate the heat generation process.

$$Na^+(g) + Cl^-(g) \rightarrow NaCl(g) + 556 \text{ kJ/mole} \quad (\text{eq. 1})$$

$$Na^+(g) + Cl(g) \rightarrow Na(g) + Cl(g) + 147 \text{ kJ/mole} \quad (\text{eq. 2})$$

$$Na(g) + Cl(g) \rightarrow NaCl(g) + 409 \text{ kJ/mole} \quad (\text{eq. 3})$$

The present inventors have discovered that reaction (2) typically predominates at high temperature. Such results are shown in Figure 2. These are ionic oxidation-reduction (redox) reactions. The $Cl^-$ ion is the reducing agent and is itself oxidized, i.e., it donates an electron. The $Na^+$ is the oxidizing agent and is itself reduced, i.e., it gains an electron.

[0088] The process at the molecular level is called a curve crossing process and is depicted in Figure 3. Equation (2) is not only exothermic but it leaves the Na(g) and Cl(g) free to react with the other species in the plasma.

[0089] Figure 4 shows the composition of dry air at temperatures up to 6000 °K. As the temperature of the gas increases, it is believed that $N_2$ dissociates as follows:

$$N_2 \rightarrow 2N$$

It is also believed that above about 3000 °K, any water molecules that are present also dissociate in the following manner:

$$H_2O \rightarrow H + OH$$

It is believed that by the time the temperature reaches 8000 °K the hydroxyl is also dissociated

$$OH \rightarrow O + H$$

Thus, it is believed that the salt water chemical composition within 8000 °K arc is mostly comprised of N, O, H, Cl, and Na.

[0090] Figure 4 also shows the electron and ion densities as functions of temperature in hot dry air. They are relatively small. The arc doesn't become what would be considered highly
ionized until quite high temperature. The presence of NaCl in the water increases the ion density. See Figure 4. The Na\(^+\) and Cl\(^-\) ion densities are proportional to the molarity of the solution. Strong electrolytes can greatly increase the ion density in plasma.

Depending on the amount of water vapor and NaCl that is being injected into the arc, it is believed that the sodium remains mostly ionized due to its very low, i.e., 5.14 eV, ionization potential. This equilibrium is described by Saha's and Boltzmann's equations and is represented in a graphic form in Figure 5. The Cl\(^-\) ion is mostly likely to be present as a neutral Cl at high temperatures where its electron has been stripped off due to collisions or photodetachment. It is believed that the chemistry is different in different parts of the arc flame, which may be 8000 °K at its core but only several thousand °K a few millimeters further out toward the flame-air boundary. The electrons from ionization of the Na(g) and of the Cl\(^-\)(g) increase the electrical conductivity, but do not significantly change its thermal conductivity, and help increase the temperature. This enhanced electrical conductivity due to the low Na(g) and Cl\(^-\)(g) ionization potentials can greatly increase the Ohmic heating of the plasma. In a high temperature arc inside the radiation cavity the power density of the thermal or black body or Planck radiation can be very large. The wavelength threshold for photodetachment of Cl\(^-\) is believed to be about 3600 Angstroms. The peak of the power versus wavelength curve for an 8000 °K blackbody radiation peaks at about that wavelength so that the lifetime of Cl\(^-\), which has a photodetachment cross section of about \(10^{-17}\) cm\(^2\) (very large), is expected to be short. Cl\(_2\), which has a photodissociation threshold at \(\lambda \approx 5200\) Angstroms and a cross that peaks at \(\lambda \approx 3500\) Angstroms is expected to have a short lifetime as well.

When the arc is not fully ionized, it is believed that neutral chemistry will occur throughout the flame. The table below is a list of some of the possible sodium-oxygen-hydrogen chemistry or reactions that are believed to occur in the flame. These reactions also have their ionic counterparts.

Table 1 Flame chemistry involving neutral sodium
Figure 6 is NaCl Born-Haber Cycle showing reference to the energetic of sodium chloride in its various states. As shown above, the standard enthalpy of formation of NaCl(s) relative to Na(s) and ½ Cl₂(g) is -411 kJ/mole, i.e., a little more than 4 eV and slightly less than 16 kcal/mole. Figure 7 shows the NaCl energetic in arithmetical form via Hess' Law.

As shown in Figure 8 the sodium chloride crystal is an ionically bound FCC (face centered cubic) lattice. The process of solvation of crystalline NaCl salt by water is schematically illustrated in Figure 9. And the thermochemistry is shown in Figure 10. The H₂O molecules are strong electric dipoles, as illustrated in Figure 11. When the Na⁺Cl⁻ molecules from the lattice are dissolved in water, the dielectric constant of the water, ε₉ ~ 80, reduces the interaction potential energy of the Na⁺- Cl⁻ ions by a factor of ε₉ and the Na⁺ and Cl⁻ form solvation shells. They are now only very weakly bound to each other. The ionic interaction that is Coulombic in the free state is now screened by the other ions and is described by variations of the Debye potential

\[ V_d(r) = e^2/r \rightarrow (e^2/r) \exp(-r/\lambda_D) \]

where \( \lambda_D \propto [T/N]^{1/2} \) is the Debye screening length.
The statistical structure of the water on a microscopic scale is depicted in Figure 12. Thus, Na\(^+\)Cl\(^-\) (aq) is dissociated into Na\(^+\) (aq) and Cl\(^-\) (aq). Thus, it is believed that the polar water molecules convert most of the NaCl lattice energy into potential energy. Apparatuses and methods of the invention recover this potential energy via exothermic reactions when a fluid comprising dissociated sodium chloride is injected into a high temperature arc.

It is believed that the water surface, whether liquid salt water in a test tube or droplets in the air, affects the overall efficiency and/or process. Figure 13 depicts the relative Na\(^+\) and Cl\(^-\) densities near the water-air interface.

The evaporation and Coulomb-Rayleigh explosion of charged droplets is depicted in Figure 14. These are some of the possible mechanisms for getting the Na\(^+\) and Cl\(^-\) ions from the salt water solutions into the arc.

**Plasma Arc**

Methods and apparatuses for producing electric arcs are well known to one skilled in the art. See, for example, Yu. P. Raizer, *Gas Discharge Physics* (Springer-Verlag, 1991) and J. D. Cobine, *Gaseous Conductors* (Dover, 1958). Many conventional works on arcs includes 2-D or 3-D computation fluid dynamics (CFD) calculations. These are useful for modeling complicated designs and deliver useful graphical images. They can be used in the design and development of various operational systems.

The equations for obtaining the arc temperature at its core and the radial distribution of temperature, and check for the consistency of temperature, electric field, and power dissipated, based on \(<P>_{ave}\) and \(<P>_{rms}\), which are integrals of the scope traces \(P(t) = I(t)V(t)\), are shown as follows:

\[
\text{(1)} \quad T_{max} = [(kl_0/8\pi\lambda(T))]^{1/2}
\]

\[
\text{(2)} \quad d^2T/dr^2 + r^{-1}dT/dr = -E^2F(T)/\lambda(T) - C[\Phi(T_{air})-\Phi(T)] \quad \text{with initial and boundary conditions} \quad T(r = 0) = T_o \quad \text{and} \quad dT/dr = 0 \quad @ \quad r = 0
\]

\[
\text{(3)} \quad W = 2\pi E^2\int_0^\infty \sigma(T(r)) r dr
\]

The conductivities, shown in Figure 15, are an important aspect of the physical properties of the arc and, thus, of its plasma chemistry properties as well.
Additional objects, advantages, and novel features of this invention will become apparent to those skilled in the art upon examination of the following examples thereof, which are not intended to be limiting. In the Examples, procedures that are constructively reduced to practice are described in the present tense, and procedures that have been carried out in the laboratory are set forth in the past tense.

**EXAMPLES**

**The Thermodynamics of the SWB**

Figure 16 is a schematic illustration of one particular embodiment of the apparatus of the invention. This device, herein sometimes called "The SWB", was used to determine the thermodynamic properties of the ion-redox processes.

One particular embodiment of an ion-redox apparatus comprises a 6 inch i.d. vitrified clay sewer pipe, a 3 inch copper pipe in the center that serves as the radiation cavity or hohlraum, and a double wrapping of 1/4 inch copper tubing carrying water (or alternatively ethylene glycol) to be heated by the exothermic ion reaction processes. A pair of 1/8 inch thoriated tungsten electrodes inserted through center bored aluminum cylinders, which are themselves inserted into alumina tubes, were used as electrodes.

Some of the modifications that can be made are (1) replacing the submerged water pump with an external pump that heats the flowing water to a much lesser extent and (2) inserting aerogel (Aspen Aerogels) between the copper coils and the inner surface of the clay cylinder. This latter greatly reduces the heat transfer to the clay pipe.

Experiments were run without spraying salt water into the electric arc and with the salt water spray. A 3 M NaCl aqueous solution was used.

**Results**

Two experiments were performed, one water spray without salt and one with a 3 Molar salt water solution being sprayed into the arc from two steam humidifiers. In the first experiment, the water without salt sprayed into the arc resulted in 52% - 59% of the 128-145 Watts of arc power being obtained in heating the circulating water. In the second experiment, the salt water sprayed into the arc resulted in about 109-198 Watts of heat being obtained in heating water and about 58-84 Watts being obtained in heating other elements. Because of the
106° phase difference between I(t) and V(t) the calculated average power is -16 Watts. In this case the appropriate power average to use was believed to be the average of \langle (P(t) > 0) \rangle or 72 Watts. Thus, a factor of possibly as much as 3 x power gain was obtained in these experiments.

**The SWB Setup**

[0107] Figure 17 is a schematic illustration of the experimental setup, which includes a Variac and the two matched microwave transformers immersed in a bath of transformer oil for cooling.

[0108] It was discovered that the transformers consume about \frac{1}{2} the power coming from the wall and convert it to heat. When the transformers were cooled by fans in the open air they reached temperatures in excess of 140 °C, in the oil bath convectively cooled by fans blown across the surface transformers appeared to stabilize at temperatures of 70 °C to 80 °C.

[0109] Figure 18 is a schematic representation of one particular embodiment of the ionic-redox device of the present invention viewed down into the SWB device. The aerogel insulation fits tightly between the copper coils and the clay pipe, the center copper radiation cavity, and the thoriated tungsten electrodes with their aluminum and ceramic sleeves. In this setup, because of the small diameter and length (about 70 feet) of the copper tubing, the external pump was pulling water through the coils at the rate of about 0.4 liters/minute. The temperature of 4 liters of water increased 6.3 °C over 30 minutes.

[0110] In the experiments, 4 liters of water were heated over about 30 minutes. So the flowing water was making three complete cycles through the coils. In that time, water temperature increased by 2.1 °C during each 10 minutes of residence time per cycle.

**The Arc Experiments**

[0111] The temperature measurements from the two SWB experiments are shown in Figures 19A and 19B. Some of the observations gleaned from these experiments are: (1) the temperature of transformer oil increased; (2) the clay pipe remained relatively cool, which is believed to be due to the presence of aerogels; and (3) the heating of the water by the pump is relatively slight. In Figures 19A and 19B, the two oil temperature readings are: (1) the low reading is from a thermocouple at the bottom of the bath; and (2) the high reading is from the IR radiometer, which measures the temperature of only the top 1 mm or so of the oil. In a separate
oil heating measurement it was found that they eventually come together at a temperature of 70 °C-80 °C.

[0112] Figure 20 shows details of the water temperature measurements including that due to the pump alone. Linear regression was performed on each curve and the slopes $\Delta T/\Delta t$ are shown on the graph. The pump and arc without salt water curves are relatively straight lines. As shown in Figure 21, the curve of $\Delta T/\Delta t$ for the salt water arc has several slopes. Irregularities seen in the changing $\Delta T/\Delta t$ slopes of the $T(t)$ curve are likely due to salt clogging the steam generators.

Power Into Heating Water

[0113] The power input that the slopes of Figures 20 and 21 represent are shown in the following table.

**TABLE: POWER GOING INTO HEATING WATER**

<table>
<thead>
<tr>
<th>Curve</th>
<th>$\Delta T/\Delta t({}^\circ C/\text{min})$</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump</td>
<td>0.19</td>
<td>52.9</td>
</tr>
<tr>
<td>No Salt Water</td>
<td>0.46</td>
<td>128.2</td>
</tr>
<tr>
<td>Minus Pump</td>
<td>0.27</td>
<td>75.3</td>
</tr>
<tr>
<td>3M Salt Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Regression Line</td>
<td>0.58</td>
<td>161.6</td>
</tr>
<tr>
<td>Minus Pump</td>
<td>0.39</td>
<td>108.7</td>
</tr>
<tr>
<td>1st 5 Minutes</td>
<td>0.90</td>
<td>250.8</td>
</tr>
<tr>
<td>Minus Pump</td>
<td>0.71</td>
<td>197.7</td>
</tr>
</tbody>
</table>

Arc Power

[0114] Table below is a list of the various power numbers obtained from the scope traces of the $I(t)$ and $V(t)$ waveforms. Graphs and discussions of these values for power are provided following the table.

Table: Electrical Power Dissipated By The Arc (Watts)

<table>
<thead>
<tr>
<th>Power Formulation</th>
<th>No NaCl</th>
<th>3M NaCl Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;P(t)\text{rms}&gt;$</td>
<td>211</td>
<td>185</td>
</tr>
<tr>
<td>$&lt;P(t)&gt;$</td>
<td>128</td>
<td>-16</td>
</tr>
<tr>
<td>$&lt;</td>
<td>P(t)</td>
<td>&gt;$</td>
</tr>
<tr>
<td>$&lt;[P(t) &lt; 0]&gt;$</td>
<td>-17.2</td>
<td>-87.4</td>
</tr>
<tr>
<td>$&lt;[P(t) &gt; 0]&gt;$</td>
<td>145</td>
<td>71.6</td>
</tr>
<tr>
<td>$&lt;P_{\text{max}}(t)&gt;$</td>
<td>466</td>
<td>367</td>
</tr>
<tr>
<td>$&lt;P_{\text{min}}(t)&gt;$</td>
<td>-141</td>
<td>-344</td>
</tr>
</tbody>
</table>
There are a number of different ways of calculating power and a very wide range of numerical values. Below is a discussion of the meanings of these in terms of the I(t) and V(t) waveforms given that, at any instant in time the peak power is defined by $P(t) \equiv I(t) \times V(t)$. Figure 22 shows, for reference, the overlaid I(t) and V(t) for each of the 6 oscilloscope traces taken on each experiment. Note the consistency in the 6 traces taken every 5 minutes over a 6 hour period. During each experiment the Variac was adjusted several times to keep the wall current in the 18A to 19A range, which gave a power reading of 900W to 100OW, respectively.

Figure 23 shows the instantaneous power in Watts for the two experiments averaged over each set of 6 scope traces. The graph shows the origins of the differences between the various power calculations shown in the above Table.

Figure 24 shows the averaged current and normalized voltage waveforms for each experiment. In Figure24, the I(t) and V(t) phase differences explain the $P(t) = I(t) \times V(t)$ power graph. Figure 25 shows that the current waveforms between the two experiments are identical except for a small difference in magnitude. But the difference in phase and somewhat in shape of the voltage waveforms is clear.

The consistency of the voltage waveforms can be seen in Figure26, which represents an overlay of each of the 6 scope traces for each experiment. Regarding the calculated powers, note that, in all power calculations, the arc dissipated power was less for the salt water solution than for no salt water even though the rate of heating of water in the copper coils was greater. Without being bound by any theory, it is believed that the power dissipation in the salt water free experiment lies in the range:

$$\langle P(t) \rangle \text{ to } \langle P(t) \rangle_{0} = 128-145 \text{ Watts}$$

For the experiment where salt water vapor is steamed into the arc, it appears $\langle P(t) > 0 \rangle = 71.6$ Watts. It is believed that the phase differences are an issue in interpreting I(t), V(t), and P(t) measurements. Table below summarizes various quantities:

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating Water, no salt water in arc</td>
<td>75.3</td>
</tr>
<tr>
<td>Heating Water, 3M</td>
<td>108.7 − 197.7</td>
</tr>
</tbody>
</table>
salt water into arc

Arc power, no salt water 128 - 145

Arc power, 3 M salt water 71.6

It is believed that heat flows into other materials besides the water flowing in the copper tubing. Estimates of these heat losses are given in Table below.

<table>
<thead>
<tr>
<th>Heat Sink</th>
<th>Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay pipe</td>
<td>6</td>
</tr>
<tr>
<td>Slate tile on top</td>
<td>15-20</td>
</tr>
<tr>
<td>Cu tubing coil</td>
<td>18</td>
</tr>
<tr>
<td>Internal moist air</td>
<td>20-40</td>
</tr>
<tr>
<td>(Internal dry air)</td>
<td>(2-6)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>58 – 84 Watts</strong></td>
</tr>
</tbody>
</table>

For the experiment where salt water vapor was not introduced into the arc it is believed that about 52% - 59% of the power was used to heat the circulating water. This correlates with the estimated heat loss listed in the above Table.

[0119] Looking at the power breakdown for the salt water experiment, it is clear that methods and devices of the invention results in more heat production than electrical power put into the arc by a factor of between two and three. Even if the \( <P(t)>_{\text{rms}} \) value is used for the arc, the net heat production is greater than the amount power used to generate the arc.

**The Voltage Waveform**

[0120] Figure 27 shows typical arc current and voltage waveforms. The waveforms that were obtained at frequencies greater than 60 Hz also looked similar to these. Typically, the \( I(t) \) current waveforms were regular but not sinusoidal. They appear more like triangular functions. Lots of large amplitude harmonics in the Fourier spectrum of \( V(t) \) were observed as shown in Figure 28. It is believed that some of voltage pulse distortion comes from the characteristics of the microwave transformers, as does some of the phase shift. Some of it is also believed to come from plasma oscillations and electrode effects. However, it is believed that the major factor in pulse distortion is due to the recovery voltage, as shown in Figure 29. When the current goes through zero there is, briefly, no power delivered to the arc, so the voltage must spike in order to
restart the discharge. While this may be less important at higher frequencies, it is believed to be important at 60 Hz. The expected V(t) vs. I(t) volt-ampere characteristic for an arc is shown in Figure 30. By way of comparison, the actual V-I characteristic measured is shown in Figure 31. It is believed that much of what is observed is due to a combination of the microwave transformers themselves and the very large phase shifts that are observed in V(t) compared to I(t).

**SWB Experiments**

[0121] Burning salt water in an electric arc on the surface of an alumina (Al₂O₃) tube showed that the surface processes on the electrolyte are involved in the SWB. The experiment is shown in Figure 32. The present inventors have discovered the involvement of the salt water droplets produced by the explosive heating of the liquid surface. Theory and modeling studies of the surface arc experiment indicate that the temperature can get quite high. In some instances, even to the point of pyrolyzing water. At high temperatures the recombination processes involving hydrogen, oxygen, nitrogen, and electrolyte ions are capable of producing great net exothermicity.

[0122] It is believed that a high electric current in the top few molecular "layers" of the salt water, which is highly conductive as shown in Figure 13, heated and exploded the salt-water surface into small, salty droplets. The heat, charged droplets, which appeared to act as small spherical corona discharges, and the high electric field near the electrodes initiated a high temperature arc. In the high temperature environment, sodium and chlorine ions can neutralize each other or recombine to release the considerable heat or enthalpy or Gibbs' free energy of hydration, \( \Delta G_{\text{hyd}} = \Delta H_{\text{hyd}} - T \Delta S_{\text{hyd}} \) that the liquid water had provided during the process of dissolving the crystalline NaCl. Some aspects of the invention recover this stored potential energy to provide a net energy generation that is higher than the net energy input for generating the arc. Without being bound by any theory, it is believed that (1) extraction of energy from salt water is a surface process, not a volume process; (2) the presence of charged salt water droplets allow achievement of the high temperature discharge by shedding ions into the environment; and (3) highly exothermic neutralization or recombination of the ions is responsible for the net energy production. These points were true for surface arc discharge as well as radio frequency (RF) salt water experiments.
[0123] It is believed that when ionically bound NaCl is dissolved in water, the Na\(^+\)-Cl\(^-\) binding energy in the crystalline solid becomes intermolecular potential energy in the water solution. When the salt water is vaporized and the salt water micro droplets that comprise the vapor evaporate liberating the Na\(^+\) and Cl\(^-\) ions in the arc plasma via any number of pathways, they neutralize each other and undergo other reactions that liberate lots of energy. Hess’ Law provides that this is independent of the pathways taken.

[0124] In some embodiments, via the high temperature arc, the 556 kJ/mole of potential energy that the H\(_2\)O has stored in the process of dissolving crystalline NaCl is converted into kinetic energy, i.e. heat, in the plasma. Thus, in some embodiments, methods and devices of the invention converts potential energy into kinetic energy.

**Thermodynamic Potential and State Functions**

[0125] The internal energy of a particle or system is usually denoted by the letter U. It’s a state function or thermodynamic potential in that the difference in internal energy between two states is independent of the pathway taken between the two states:

\[
\Delta U = U_B - U_A
\]

This is the foundation for Hess’ Law. It should be noted that methods of the invention do not violate the First Law of Thermodynamics, i.e. conservation of energy,

\[
\Delta U = Q - W
\]

where Q is heat or energy flowing into the system (Q > 0) and W is work being performed by the system (W > 0).

[0126] There are other thermodynamic state functions or potentials that are used in the discussions of the thermochemistry of methods of the present invention. For example, enthalpy, denoted by H, is used:

\[
H = U + PV
\]

H also represents the available thermal energy at constant pressure. It is not necessary to work at constant pressure, but any open air process is running at local atmospheric pressure.

[0127] In addition, the Gibbs free energy, denoted by G, is used:

\[
G = H - TS = U + PV - TS
\]
where S is entropy. Gibb's free energy is used for transformations under constant pressure. The term "free" means that only the portion (U-TS) is free to perform work.

[0128] In thermochemistry the words "energy", and "heat" are often used interchangeably, for example, energy of evaporation or vaporization is referred to as heat of vaporization or enthalpy of vaporization. The universal symbol for enthalpy is the letter "H". The enthalpy of vaporization, which is the energy required to evaporate a mole of liquid is written $\Delta H_v = H_{\text{vapor}} - H_{\text{liquid}}$ and has units of kcal/mole or kJ/mole where $\text{leal} = 4.18$ J.

[0129] In addition to the enthalpy of vaporization, the other enthalpies or energy changes used herein are: (1) enthalpy of formation, $\Delta H_f$: the enthalpy change with a mole of a compound is formed from its elements; (2) lattice energy or enthalpy $\Delta H_x$ or $\Delta H_s$ or $\Delta H_{\text{lat}}$: the enthalpy change when a mole of ionic solid in its crystalline phase is formed from its constituent ions in their gas phase; (3) enthalpy of hydration, $\Delta H_{\text{hyd}}$: the energy change when a mole of gaseous ions is "dissolved" - or accommodated - in a large volume of water, e.g., at the limit of infinite dilution; and (4) enthalpy of solvation, $\Delta H_{\text{sol},v}$: the change of enthalpy when a mole of solute is dissolved in a solvent.

[0130] An important relationship among these different energies is: $\Delta H_{\text{sol},v} = \Delta H_{\text{lat}} + \Delta H_{\text{hyd}}$, which is illustrated in Figure 9.

The Thermochemistry of Salt and Water

[0131] Figure 9 is accurate in depicting the initial lattice state and the final hydrated state but this isn't necessarily the path that the system takes. Because the enthalpy is a state function, the path doesn't matter; only the initial and final enthalpies matter. This property allowed the development to the Born-Haber cycle approach to calculating enthalpy changes using states for which the enthalpies are well known. An example of this is shown in Figure 6.

[0132] In the SWB are plasma and in the post plasma region, known as the afterglow in gas discharge physics, all of these states may exist in one region of temperature and density (T, p) or another. The heats of formation are zero for the "building block" elements and molecules in their standard states at $T = 298.15 \text{ } ^{\circ}K$ and atmospheric pressure. So $\Delta H_f \equiv 0$ for the common homonuclear diatomic gases such as $\text{H}_2$, $\text{N}_2$, $\text{O}_2$, and $\text{Cl}_2$. It is zero for elemental solid sodium at the reference temperature and pressure.
[0133] The Born-Haber diagram showing the energetics of the dissolution of solid salt in water is shown Figure 33. The actual path taken is:

\[ \text{Na}^+\text{Cl}^- (s) + \text{H}_2\text{O}(aq) + 3 \text{kJ/mole} \rightarrow \text{Na}^+(aq) + \text{Cl}^-(aq) + \text{H}_2\text{O}(aq) \]

The water, in rearranging its molecules to accommodate the \( \text{Na}^+ \) and \( \text{Cl}^- \) ions, take in from the environment net \(-3 \) kJ/mole of salt dissolved. For a 1 Molar NaCl solution in water this amounts to lowering the temperature of the water by about 1.2°C.

[0134] Figure 34 depicts the dynamics of the dissolution process. In the Born-Haber diagram for salt water, it can be seen that dissolving \( \text{Na}^+ (g) + \text{Cl}^- (g) \) in water would give up 771 kJ/mole to the water. The enthalpies in the previous Born-Haber diagram can be used to calculate the energetic of a scenario such as solid sodium and \( \text{Cl}_2 \) gas in water. Looking at the reverse process:

\[ \text{Na}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{Na}^+(g) + \text{Cl}^- (g) \]

requires 771 kJ/mole or approximately 8 eV per molecule. An electric arc or RF driven arc at, for example, 8000 °C cannot provide this kind of energy in order to make use of the \( \text{Na}^+(g) \) and \( \text{Cl}^- (g) \) ions in a viable process. But when the Born-Haber diagram for water in Figure 35 is analyzed, it shows that evaporation of water takes far less energy. The enthalpy of vaporization is 44 kJ/mole. The salt concentration has a little effect on this. A 1 Molar NaCl solution is 1 mole of NaCl in 55 moles of \( \text{H}_2\text{O}(aq) \). Accurate analysis is complex but beneficial to the understanding of the thermochemistry of SWB. Typically, enthalpies of hydration, such as the 771 kJ/mole for NaCl, are determined in the limit of infinitely dilute solution. The energetic of much more concentrated solutions are different.

[0135] The vaporization process, in which the formation of salt water droplets occurs, is:

\[ \text{H}_2\text{O}(l) + \text{Na}^+(aq) + \text{Cl}^-(aq) \rightarrow \text{H}_2\text{O}(g) + \text{Na}^+(g) + \text{Cl}^- (g) \]

having an associated endothermic heat of vaporization. The formation of droplets is believed to be not this process, but this is a potential, but not very effective, process for generating \( \text{Na}^+ \) and \( \text{Cl}^- \) ions in the gas phase.

[0136] The exothermicity in the SWB comes from, at least in part, the following sodium and chlorine reactions and additional branches involving \( \text{N}_2, \text{N}, \text{O}_2, \text{O}, \text{NO}, \text{H}_2, \text{H}, \) and \( \text{OH} \) and their positive and negative ions:

\[ \text{Na}^+(g) + \text{Cl}^- (g) \rightarrow \text{Na}(g) + \text{Cl}(g) + \Delta H_{\text{exut}} \]
\[
\begin{align*}
\text{Na}^+_{(g)} + \text{Cl}^{-}_{(g)} & \rightarrow \text{NaCl}_{(g)} + \Delta H_{\text{rec}} \\
\text{Na}_{(g)} + \text{Cl}_{(g)} & \rightarrow \text{NaCl}_{(g)} + \Delta H_{\text{ass}} \\
\text{NaCl}_{(g)} & \rightarrow \text{NaCl}_{(g)} + \Delta H_{\text{recy}}
\end{align*}
\]

These are all exothermic where

\[
\begin{align*}
\Delta H_{\text{neut}} & = \text{enthalpy of ionic mutual neutralization} = 133 \text{ kcal/mol} = 577 \text{ kJ/mol} \\
\Delta H_{\text{rec}} & = \text{enthalpy of ionic recombination} = 35 \text{ kcal/mol} = 147 \text{ kJ/mol} \\
\Delta H_{\text{ass}} & = \text{enthalpy of neutral association} = 98 \text{ kcal/mol} = 410 \text{ kJ/mol} \\
\Delta H_{\text{recy}} & = \text{enthalpy of recrystalization}
\end{align*}
\]

[0137] As shown in Figure 2, the first reaction is likely to be the preferred channel at high temperature. For KCl the second reaction is likely to be the preferred channel. Sodium flame chemistry has been studied and is somewhat well understood. The plasma chemistry of the SWB is complex. Of the species likely to be found in the plasma, which varies in temperature from, perhaps, 8000 °C in the core to about 500 °C at the "edge", Na, Cl⁻, and O²⁻ have a relatively low ionization potentials of the atomic species and NO of the molecular species. O²⁻ and Cl⁻ are expected to be short lived in a very hot plasma due to photo dissociation or neutralization with Na⁺. Na⁺ is expected to be the only significant positive ion because all others charge transfer with Na. Thus, it is expected that there will be lots of the Na(3p) resonant state atoms. The 2.1 eV photons from Na(3p) are trapped, effectively containing heat within the plasma.

[0138] In some experiments, a 50 Amp Variac was used. At the input to the four microwave oven transformer, the voltage and current waveforms were nearly 90° out of phase; therefore, there was a lot of wasted power that was used in heating the transformer oil. In one particular experiment, Th/W electrodes were changed and plain water (via 2 humidifiers) was used in the arc. The average arc power oscillated sinusoidally over a period of about 22 minutes. Its average power was 107 Watts. It put 47 Watts into heating the circulating water. Another experiment was performed using the arc with a 75 g/liter of salt water solution. The arc voltage and power rose over time, but early on about 80 Watts of power was used to heat the water at an arc power of 55 Watts. There was a net gain for about \( \frac{1}{2} \) hour.
Another experiment was performed without flowing water or salt water vapor through the arc. Measurable temperature rise in the circulating water was observed. Three oscilloscope traces were recorded and the averaged power for each was calculated using the following equation:

\[ <P(t)> = T^{-1} \int I(t) V(t) \, dt \]

The results of the calculation are summarized below, where the \( I(t) \) and \( V(t) \) are peak-to-peak values:

<table>
<thead>
<tr>
<th>Trace #</th>
<th>( I(t) )</th>
<th>( V(t) )</th>
<th>( &lt;P(t)&gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.48 Amps</td>
<td>680 Volts</td>
<td>75 Watts</td>
</tr>
<tr>
<td>2</td>
<td>4.64 A</td>
<td>1.12 kV</td>
<td>73 W</td>
</tr>
<tr>
<td>3</td>
<td>4.32 A</td>
<td>1.12 kV</td>
<td>97 W</td>
</tr>
</tbody>
</table>

It is believed that changes in phase account for the power differences. In these experiments, the electrodes were pure tungsten.

Another experiment was performed using 70 mg/ liter of salt water in the misters and the waveforms from the eight scope traces were recorded along with a comparison the voltage readings that was used to calculate current from inductive doughnut and the new Fluke. The first is Channel #1 and the Fluke is Channel #2. Channel #1 shows 8.4 Amps and #2 shows 8.6 Amps, which is very good given the fluctuations. The arc powers associated with the other seven waveforms are:

<table>
<thead>
<tr>
<th>Trace #</th>
<th>( &lt;P(t)&gt; )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>108 Watts</td>
</tr>
<tr>
<td>2</td>
<td>123 W</td>
</tr>
<tr>
<td>3</td>
<td>87 W</td>
</tr>
<tr>
<td>4</td>
<td>116 W</td>
</tr>
<tr>
<td>5</td>
<td>76 W</td>
</tr>
<tr>
<td>6</td>
<td>118 W</td>
</tr>
<tr>
<td>7</td>
<td>82 W</td>
</tr>
</tbody>
</table>

A sine wave fit to the power data was performed and is shown in Figure 36. The average power was calculated to be 102 Watts and the time constant \( \tau = 1/v \) where \( v \) is the oscillation frequency was calculated to be 11.5 minutes. The thermal data are shown in Figure 37. The SWB with arc was performed with the salt water mist and got the results shown in Figure 37. After awhile, the experiment was stopped because the transformer oil began to boil.

In another experiment, the temperature of the 4 liters of water circulating through the copper coil with only the humidifiers on was measured. As shown in Figure 37, this
experiment was conducted for nearly \( Wi \) hours until \( T(t) \) had substantially leveled off. The temperature of the steam coming out the top of the pipe leveled off at about 55 °C, which is similar to the temperature of the mist coming from the humidifiers into the bottom of the pipe.

Figure 38 shows a numerical fit to \( T(t) \) for heating by steam alone. In order to perform an experiment where the difference between the power delivered by the arc and that put into the circulating water by the pump plus the steam can be distinctly seen, the arc is started after the pump+steam curve has leveled off.

Another experiment was conducted by operating the pump alone for 2 \( Vi \) hours until the temperature of the circulating water had about leveled off, after which the steam was introduced for about 2 hours until the temperature curve leveled off again. These results are shown in Figure 39. It appears this procedure gave a more accurate reading because not only did the water heat at a faster rate after the arc is lighted but the pump temperature then begins to follow the water temperature. The corresponding scope traces were recorded and the current, voltage, and power figures are shown in table below:

<table>
<thead>
<tr>
<th>Trace #</th>
<th>I</th>
<th>V</th>
<th>&lt;P&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.2 A</td>
<td>1.18 kV</td>
<td>93 W</td>
</tr>
<tr>
<td>2</td>
<td>8.0 A</td>
<td>1.16 kV</td>
<td>86 W</td>
</tr>
<tr>
<td>3</td>
<td>7.2 A</td>
<td>1.30 kV</td>
<td>128 W</td>
</tr>
<tr>
<td>4</td>
<td>7.2 A</td>
<td>1.44 kV</td>
<td>121 W</td>
</tr>
<tr>
<td>5</td>
<td>7.0 A</td>
<td>1.46 kV</td>
<td>86 W</td>
</tr>
</tbody>
</table>

Even though the peak-to-peak current and voltage don’t fluctuate by much, the power fluctuates by 50%. Figure 40 shows the fluctuating arc power. The time constant, \( \tau = 1/v \), for this sinusoid is 21.6 minutes.

The following table shows calculated power balance:

<table>
<thead>
<tr>
<th>Power In (Watts)</th>
<th>Power Dissipated (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &lt;P_{arc}&gt; = 107 )</td>
<td>Heating H(_2)O</td>
</tr>
<tr>
<td>(</td>
<td>P_{min} = 86, P_{max} = 126 )</td>
</tr>
<tr>
<td></td>
<td>Cu tubing</td>
</tr>
<tr>
<td></td>
<td>Pipe – top</td>
</tr>
<tr>
<td></td>
<td>Pipe – bottom</td>
</tr>
<tr>
<td></td>
<td>Slate</td>
</tr>
</tbody>
</table>

\( Total\ In = 107 \)        \( Total\ Out = 110 \)
Another experiment was performed as follows. The pump was operated until the water temperature reached steady state and ran the humidifiers (i.e., source of water droplet or mist injection into the art) until the water reached a steady state. The arc was then ignited. The water temperature measurements are summarized in Figure 41. The three temperature stages: pump alone, pump and steam, and pump/steam/arc are all clear. There are two periods in the second stage when the temperature decreased. These occurred when one of the two humidifiers clogged up. In the end, the arc experiment was conducted with only one source of salt water mist. The arc was located 3" above the bottom of the clay pipe and 7" down from the top. So the bottom had higher temperature.

In order to slow down the heating of the transformer oil, which reached boiling temperature within \( \frac{7}{6} \) hour on some instances, steel pans were set atop the transformers and filled them with ice. The oil was stirred to keep the temperature uniform throughout the volume. The arc was run at 7+ Amps for \( \frac{W_2}{2} \) hours before the oil got too hot. Total of 3\( \frac{7}{6} \) large bags of ice was used in this experiment. A schematic illustration is shown in Figure 17. Figure 42 shows the detail of the water temperature. The regression line is a quadratic,

\[
T_{\text{H}_2\text{O}}(t) = -337.8 + 1.443 t - 1.318 \times 10^{-3} t^2
\]

Oscilloscope traces were taken during the arc stage of the experiment. The arc ran very smoothly at about 7 Amps for most of the experiment. The voltage increased over time. Figure 43 shows the time dependence of the arc power, current, and voltage over the course of the experiment. Points (1), (2), and (3) are times when the electrodes were moved closer together due to the arc flickering, or going out or, in one case, tripping the 50 Amp circuit breaker. It is believed that the increase in voltage is due to erosion of the electrodes so that they become farther apart and, possibly, the electrodes getting coated with CuCl, which would increase their resistance. The linear fit to \( P(t) \) is:

\[
P_{\text{arc}}(t) = -400.9 + 1.003 t
\]

Figure 44 is a graph showing the arc power, arc power going into heating the water, and the ratio of the two. The arc was ignited at 435 minutes and the first scope trace was saved 9 minutes later. The graph shows that for nearly the first \( \frac{7}{6} \) hour more power was going into heating the water circulating in the copper tubing than the arc was producing. The energy ratio is shown in Figure 45. The ratio is:
\[
J \frac{PH_2 \theta(t) \, dt}{J \text{Parc}(t) \, dt}
\]

These ratios are not the complete power/energy ratios. They only include the arc power going into heating the water. The full analysis below will include the other losses, which make the ratio even more favorable. The details of the temperatures \( T(t) \) for the three phases or stages of the experiment are shown in the graphs on Figure 46.

[0149] Power balance analyses were performed on stages 1 and 3. Stage 2 was made more difficult because sometimes one humidifier working and sometimes two. So it's not clear what the steady state would have been in stage 2. The energy transfer rate or power is calculated from:

\[
P(\Delta T) = VpC_p \Delta T / \Delta t
\]

Written as a differential equation the power balance is

\[
V_{H_2} \rho_{H_2} C_p (H_2O) \frac{dT_{H_2O}}{dt} = P_{in} - P_{diss}
\]

In the experiment, the input power is from the arc after \( T_{H_2O} \) reached a steady state before igniting the arc. The dissipated power is that heating the copper coil, which is proportional to \( dT_{H_2O}/dt \); the power heating the sewer pipe and top slate; the power heating the pump, if \( T_{H_2O} > T_{\text{pump}} \); the power heating the air and water vapor in the cylinder; the power heating the hoses and water container (see Figure 47); and the power lost to the environment. The last consists mostly of conduction and thermal radiation to the surrounding air from the sewer pipe due to its large area. The conduction of heat for a surface to the air is described by Langmuir's empirical form of Newton's cooling law:

\[
Q_L(W/cm^2) = 9.3[\phi_l(T) - \phi_l(T_{\text{air}})]
\]

where \( T > T_{\text{air}} \). Thermal or blackbody radiation loss is:

\[
P_{BB}(W/cm^2) = \varepsilon \sigma T^4 - \sigma T_{\text{air}}^4
\]

where \( \varepsilon \) is the relative emissivity \( 0 < \varepsilon < 1 \) and \( \sigma = 5.67 \times 10^{-12} \) W/cm\(^2\)K\(^4\).

[0150] Although aerogel insulation was used between the copper coils and the inner wall of the clay pipe, heat does get through over time. The heat capacity is significant because of the large volume of the pipe. That the pipe temperature is increasing implies that:

\[
V_p \rho_{Cp}(\text{pipe}) dT_p \rho / dT > 0
\]

and that

\[
P_{in}(\text{pipe}) > Q_L(\text{pipe}) + P_{BB}(\text{pipe})
\]
In the arc stage of the experiment the water temperature was beginning to level off at some steady state toward the end of the experiment. Steady state means that as much heat is flowing out of the water as is flowing into it so that the net heat into the water approaches zero. About 9 minutes into the experiment, before the arc voltage and power had increased, the following power input and output was observed:

<table>
<thead>
<tr>
<th>Power Input (Watts)</th>
<th>Power Dissipation (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{arc} = 55 Watts</td>
<td>Water 80 Watts</td>
</tr>
<tr>
<td></td>
<td>Pump 1.5 W</td>
</tr>
<tr>
<td></td>
<td>Pipe 3.5 W</td>
</tr>
<tr>
<td></td>
<td>Slate 7 W</td>
</tr>
<tr>
<td></td>
<td>Cu Coil 5 W</td>
</tr>
<tr>
<td></td>
<td>Thermal radiation 7 W</td>
</tr>
<tr>
<td></td>
<td>Conduction 0.5 W</td>
</tr>
</tbody>
</table>

Total In = 55 W \hspace{1cm} Total Out = 104.5 W

The graph on Figure 48 shows the time dependence based on smoothed data. There is power lost to heating the salt water + air mixture but it's difficult to establish just what that is because the system was "closed". It is believed that at least some of the hot air and water vapor escaped between the top of the pipe and the slate, from the gap around the ceramic electrode holders, and from other small gaps in the piping.

[0151] Some of the nominal 10 ml/ min of water had leaked as liquid from the connections to the humidifiers. So the exact amount of salt water going up the cylinder is not clear. But, from the power out, it appears some ions were introduced into the arc as a power efficiency problem can be seen during the experiment. The arc itself only occupies a small part of the cross sectional area of the Cu radiation cavity, so lots of salt water droplets and water vapor probably make it by without participating in the chemistry. These experiments show that there is a net power gain from the SWB.

[0152] Another experiment was conducted as follows: after letting the SWB experiment go through its several hour thermal equilibration phase the arc was lit in an attempt to obtain good measurements using both steamers and then try out the airbrush mister. An electric mixer was used to circulate the transformer oil in the hotter of the two baths in order to keep the temperature more uniform. This is schematically illustrated in Figure 17. Typically, it was found that the top few millimeters of oil can get extremely hot while the bulk of the oil below
that remains relatively cool. After igniting the arc voltage waveform was recorded. The scope trace appeared to indicate a problem with the transformer. It was observed during the scope tracing, the oil above one of the transformers in the bath bubbled furiously. The problem was attributed to one of the four transformers burning out.

The Arc Voltage

The graph of average current, voltage, and power taken from scope traces at 14 times during stage #3 is shown in Figure 49. It is believed that the principal reason for the steady increase in arc voltage is the erosion of the electrodes, which increases the length of the gap. The current is:

$$ I = (\pi d^2/4)n_e \mu E $$

where $n_e$ is the electron density, $e$ is the electronic charge ($1.6 \times 10^{-19}$ Coulombs), $\mu$ is the electron mobility, and $E$ is the electric field.

$$ V \approx \frac{E}{L} $$

where $L$ is the electrode separation. It is known based on arc theory and measurements that:

$$ I = \text{constant} \times (IE)^2 \alpha^3 $$

where $0.04 < \alpha < 0.25$ for various arc measurements. This range of $\alpha$ was obtained from a number of arc heat transfer experiments. Thus,

$$ E = \text{constant}/ I^n $$

where $n = (2-3 \alpha)/(2+3 \alpha)$. This can be written as:

$$ V \propto \frac{L}{I^n} $$

Since the arc experiments were run at constant average current, it is believed that the voltage increases as the electrode separation increases due to erosion. As shown in Figure 50 microscope photos, the electrodes become covered with a hard crystalline substance that is not soluble in water. The substance is greenish in color. It is believed that the substance is cuprous chloride, CuCl. Cu(I)Cl is insoluble in water and has melting and boiling temperatures of $T_m = 426$ °C and $T_b = 1490$ °C. The tips of the electrodes can be clearly seen. Therefore, the electrode separation can be measured this way and adjust the separation while watching the oscilloscope trace to try to maintain a constant voltage. A higher voltage means higher power but the experiment is limited by what the Variac + 4 transformers can draw through the 50 Amp circuit breaker.
As can be seen, the oil temperature should be kept well below 160 °C, especially the temperature in the top couple of millimeters.

**The Properties of Transformer Oil**

Transformer oil has the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value in metric unit</th>
<th>Value in US unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density at 60°F (15.6°C)</td>
<td>800 × 10^-3 kg/m^3</td>
<td>54.9 lb/ft^3</td>
</tr>
<tr>
<td>Kinematic viscosity at 68°F (20°C)</td>
<td>2 cSt</td>
<td>72 cSt</td>
</tr>
<tr>
<td>Kinematic viscosity at 212°F (100°C)</td>
<td>2.6 cSt</td>
<td>2.3 cSt</td>
</tr>
<tr>
<td>Fire point</td>
<td>170 °C</td>
<td>338 °F</td>
</tr>
<tr>
<td>Pour Point</td>
<td>150 °C</td>
<td>158 °F</td>
</tr>
<tr>
<td>Flash point</td>
<td>160 °C</td>
<td>320 °F</td>
</tr>
<tr>
<td>Autoignition point</td>
<td>250 °C</td>
<td>516 °F</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>1860 J/(kg*K)</td>
<td>0.444 Btu/(lbm*°F)</td>
</tr>
<tr>
<td>Thermal conductivity at 20°C (68°F)</td>
<td>0.126 W/(m*K)</td>
<td>0.085 Btu/(ft*°F)</td>
</tr>
<tr>
<td>Thermal expansion at 20°C (68°F)</td>
<td>7.5 × 10^-3 °C/mol</td>
<td>4.2 × 10^-3 mK/mol</td>
</tr>
<tr>
<td>Breakdown strength</td>
<td>min 70 kV</td>
<td>min. 70 kV</td>
</tr>
<tr>
<td>Dielectric dissipation factor at 90°C (194°F)</td>
<td>max 0.002</td>
<td>max 0.002</td>
</tr>
<tr>
<td>Permittivity at 20°C (68°F)</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

**The Role of Water Droplets in the Physics of the SWB**

It’s generally accepted as common knowledge that, if salt water is made to boil, pure H₂O evaporates and salt is left behind. This is only true when the water is boiled quiescently. For a vigorous boil where droplets are spewed into the air, the droplets are also salt water. In the same manner, waves on the ocean, white caps especially, propel droplets of salt water into the air. Such droplets play a role in the SWB because they tend to be highly charged. The charging is a statistical phenomenon known about since the mid-1800s. It was first investigated by Rayleigh in the 1880s and it has been the subject of intensive study since the 1970s. The study of the formation of droplets, droplet evaporation, charging, breakup, evaporation, and collisions has a long history. The applications are diverse including cloud and aerosol microphysics, ocean spray, lighting, combustion in engines, carburation and fuel injection, spray painting, electrospray, ink jet printing, and fire fighting (see publications such as

There are a number of ways by which charged water droplets shed their excess ions into the surrounding air including: evaporation of the water droplet; coronal loss of charge; ion evaporation; Rayleigh or Coulomb explosions; Taylor cones; Droplet collisions; H₂O molecules from the surrounding vapor condensing on a droplet and releasing the enthalpy of condensation as enough heat to eject an ion; FIDI; and ESI.

These processes provide the Na⁺ and Cl⁻ ions needed for the power gain in the SWB.

**Statistical Charging of Droplets**

A commonly accepted process for drop charging is statistical. Although the average numbers of Na⁺ and Cl⁻ ions in a volume, say 1 µm in radius, of salt water are equal, they do fluctuate about the mean values,

\[
<\text{[Na}^+]> = <\text{[Cl}^+]> \sim 6 \times 10^{20} \text{ M ions/ cm}^3
\]

where M is the molarity of the solution. If you extract a large number of 1 µm radius volumes from a container of salt water and average the number of ions in all the volumes one will get the correct average values (this is called an ensemble average). Any given droplet of 1 µm radius, however, is very unlikely to have exactly the same number of Na⁺ and Cl⁻ ions. There will be a relatively small excess of one or the other. The relative excess may be very small, approximately \(\sqrt{N/ N}\), but the number of excess or net charges can be quite large. This is statistical charging.

In 1946, Leontovich derived a theory of such fluctuations that gives the RMS number of excess charges of either sign in a sphere of radius R as:

\[
[<N^2>]^{1/2} = \left(4\pi R^2 N_i / \kappa \right)^{1/2}
\]

where \(N_i\) is the total ion density and \(\kappa = 1/\lambda_D\), i.e. the inverse of the Debye Length. If the probability distribution is a Gaussian or normal distribution (i.e., the bell curve), \([<N^2>]^{1/2}\) is its standard deviation. Leontovich's result was made use of by Iribarne and Thomson (1976) in their widely cited work on charged droplets.

The approximation here is the use of Debye-Huckel theory, which is valid for very low electrolyte concentrations. Brush and Wensrich (1961) pointed out this limitation to Leontovich's result and stated that it is only valid for an electrolyte ion density
\[ N_1 \simeq \frac{(ekT)^3}{8\pi e^6} \]

This amounts to a molarity:
\[ M \simeq 10^{-3} \text{ Moles/liter} \]
or a Debye length \( \lambda_0 \approx 100 \text{ Angstroms} \).

[0160] The present experiments (e.g., SWB works), used strong electrolytes, i.e. molarities in excess of unity. A result for strong electrolytes can be derived using binomial probability and combinatorial theory that yields
\[ [\langle N^2 \rangle]^{1/2} = \left( (6 \times 10^2 M)(4\pi / 3)R^3 \right)^{1/2}/2 \]

[0161] Figure 51 shows the results of a Monte Carlo sampling of values of \( Q(R)/e \) from a Gaussian distribution with standard deviation:
\[ \sigma_Q = [\langle N^2 \rangle]^{1/2} \]

This calculation was performed for a 5 molar 1-1 electrolyte solution.

**Liberation of Ions From Droplets**

[0162] A number of possible processes for liberation of ions from droplets are listed above.

**Water Droplet Evaporation**

[0163] The rate of mass loss by small droplets due to evaporation is given by:
\[ \frac{dm}{dt} = -4\pi(DM/RT)(p_v - p_{air}) \]

Written in terms of rate of change of the droplet radius due to evaporation the equation is:
\[ \frac{dr}{dt} = -(DM/RT)p_v/p_r \]

where \( D \) is the diffusion coefficient for H\(_2\)O molecules through the saturated vapor at pressure \( p_v \) at the surface of the drop into the surrounding air at pressure \( p_{air} \) and relative humidity \( \phi \). \( M \) is the H\(_2\)O molecular mass. The graph on Figure 52 shows the evaporation time as a function of droplet radius. Note the temperature at the surface of the water is 100 °C but that the temperature of the surrounding air is 500 °C. If the air temperature is 100°C a 1 µm radius droplet can take more than a second to evaporate where as at 500 °C the time is about \( 1/8 \) second. The difference is in the temperature dependence of the diffusion coefficient:
\[ D(T) \propto T^{2.3} \]
Nevertheless, other processes described below are more effective at releasing ions than merely evaporating the water from around the ions. The temperature in the lower part of the SWB copper cylinder is believed to be somewhere between 100°C and 500°C.

**Loss of Charge by Coronal Discharge**

A charged sphere creates an electric field at its surface given by:

\[ E(R) = \left(\frac{Q}{4\pi\varepsilon_0}\right) \frac{1}{R^2} \]

The ambient air has a breakdown electric field of about: \( E_b \geq 30 \text{ kV/cm} \). If the sphere, or charged spherical water drop in our case, has \( Q \) and \( R \) such that \( E(R) \geq E_b \), then a coronal plasma will be formed around it and it will shed excess charge. The maximum charge for a given radius \( R \) is \( Q_{\text{breakdown}} = 4\pi\varepsilon_0 R^2 E_b \) or the maximum number of excess ions allowed is \( N_{\text{breakdown}} = (4\pi\varepsilon_0/e)R^2 E_b \).

The coronal discharge limit is shown in Figure 53. If the droplet, say when it is formed, has excess charge greater than this limit, the charge will be shed or neutralized in a corona discharge in the surrounding air.

**Ion Evaporation**

Iribarne and Thomson (1976) proposed a theory of ion evaporation from the surface of droplets, which is now widely accepted. The idea is that a large number of excess ions on or near the surface of a droplet reduce the energy barrier to evaporation. As a droplet is evaporating, the radius \( R \) decreases, but the charge remains the same until some limit is reached where the droplet sheds charge. The ion evaporation criterion is: \( N \varepsilon^2/R_\varepsilon^2 - \Delta \varepsilon^2 \), where \( \Delta \varepsilon \) is Gibb's free energy of solvation and \( R_\varepsilon \) is then the critical radius. If \( N \) is very large the Rayleigh instability occurs first (see the next section). The criterion for this not to occur is that: \( R_\varepsilon > 4N^{2/3} \) Angstroms.

**Rayleigh or Coulomb Explosions**

If a droplet has a charge \( Q \) and is evaporating so that its radius is decreasing, at some radius the repulsive Coulombic forces of the excess ions in the droplet will overcome the surface tension (\( \gamma \)) forces holding the drop together and it will fly to pieces. The relationship between the Rayleigh critical radius and charge is: \( Q_{\text{Rayleigh}} = 8\pi\varepsilon_0 \varepsilon R^3 \). It should be noted that \( Q_{\text{Rayleigh}}(R) \) and \( Q_{\text{breakdown}}(R) \) have different \( R \) dependencies.
Taylor Cones

Under conditions of large applied electric fields, such as a water drop between two parallel plates with a voltage applied across them, the droplets can become distorted forming conical ends, two for uncharged droplets and one for charged droplets, from which a stream of ions may be emitted. These are Taylor Cones. See Figure 53. The electric field at the tips of the Taylor cones is strong enough that they emit a stream of ions.

Droplet Collisions

Khain, et al. (2004) studied extensively collisions of charged droplets with applications to fogs and rain clouds. A figure of merit in that area of meteorology is the collision efficiency, which is defined by the ratio of the actual collision cross section to the geometrical cross section. For two droplets of radii $R_1$ and $R_2$ the collision efficiency is: $\varepsilon_c = \sigma / \pi(R_1 + R_2)^2$.

For collisions of a charged and a neutral droplet with radii in the 10-20 $\mu$m range and the maximum possible charge on the droplet they found $\varepsilon_c$ in the range 20-30. For two charged droplets, one with maximum charge of one sign and the other with 5% maximum charge of the opposite sign, the found $\varepsilon_c$ as large as 2500. With a better knowledge of our droplet sizes and densities, i.e., the number of droplets per cm$^3$, the importance of collisions can be better assessed. It is believed that such collisions would cause enough disruption to effect the release of ions.

Ion Emission from Enthalpy of H$_2$O Condensation

It has been shown that ion formation from charged droplets was enhanced when they were in bath of the vapor of the polar molecular solvent. In short, an H$_2$O molecule can condense on a salt water droplet and the release of its enthalpy of condensation may be enough to free an ion from the surface. The present inventors have studied this process both theoretically and computationally using the model shown in Figure 54. The model treats the Na$^+$ ion bound to the water molecule as a quantum Morse oscillator and the water droplet as a stochastic thermal bath having a known thermal conductivity. The colliding H$_2$O molecule releases its enthalpy of condensation as well as its kinetic energy. The heat wave is described by the heat equation. There is also the direct ion-dipole interaction with the Na$^+$ ion. The whole process is simulated in the context of the Monte Carlo method. It is believed that this process is a significant source of ions in the experimental systems described herein because of the high
temperature in copper radiation cavity and because of the high electrolyte molarity that we use. This process is enhanced by the droplet distortions and surface oscillations that occur on liquid spheres.

**FIDI: Field Induced Droplet Ionization**

[0172] An electric field between two parallel plates can pull excess ions off of water droplets via the formation of Taylor Cones. In the present SWB application use of a high voltage AC electric field between planar or possibly cylindrical electrodes is contemplated to provide more ions from the water droplets going into the arc.

**ESI: Electrospray Ionization**

[0173] Electrospray Ionization process is well known to one skilled in the art. There are many such devices available including paint sprayers for metallic objects such as automobiles. This technique produces a spray of ionized droplets.

[0174] The foregoing discussion of the invention has been presented for purposes of illustration and description. The foregoing is not intended to limit the invention to the form or forms disclosed herein. Although the description of the invention has included description of one or more embodiments and certain variations and modifications, other variations and modifications are within the scope of the invention, e.g., as may be within the skill and knowledge of those in the art, after understanding the present disclosure. It is intended to obtain rights which include alternative embodiments to the extent permitted, including alternate, interchangeable and/or equivalent structures, functions, ranges or steps to those claimed, whether or not such alternate, interchangeable and/or equivalent structures, functions, ranges or steps are disclosed herein, and without intending to publicly dedicate any patentable subject matter.
What is Claimed is:

1. A method for producing energy using a fluid comprising a solvated solute, said method comprising:
   - injecting the fluid into a plasma under conditions sufficient to exothermically recombine, neutralize, or associate solutes from the fluid, and to produce a net energy output that is greater than the amount of total energy used to produce the plasma, wherein the fluid comprising the solvated solute is produced by dissolving a solid having a negative enthalpy of solvation in the fluid.

2. The method of Claim 1, wherein the fluid comprises a gas, vapor, mist, aerosol, liquid droplets, free ions, or a combination thereof.

3. The method of Claim 1, wherein the solid comprises a compound having an ionic bond.

4. The method of Claim 3, wherein the solid comprises alkyl halide.

5. The method of Claim 1, wherein the net energy output is at least fifteen percent greater than the amount of total energy used to produce the plasma.

6. The method of Claim 1, wherein the enthalpy of solvation of the solid in the fluid is at least -96 kJ/mol.

7. The method of Claim 1, wherein the fluid comprises a solvent that produces an ionic solution from the solid.

8. The method of Claim 7, wherein the fluid comprises water, ammonium hydroxide, other polar solvent, or a combination thereof.

9. The method of Claim 1, wherein the plasma is produced by an electric arc that is generated from a first electrode to a second electrode.

10. The method of Claim 1, wherein the plasma is produced by an electric arc that is generated from an alternating current, rectified AC, radio frequency, microwave frequency, or a combination thereof.
11. The method of Claim 1, wherein the plasma is produced by an electric arc that is generated from a direct current (DC), pulsed DC, or a combination thereof.

12. The method of Claim 1, wherein the produced energy comprises heat energy.

13. The method of Claim 12, wherein the heat energy is used to generate electric energy.

14. The method of Claim 13, wherein the electric energy is produced by a turbine.

15. The method of Claim 13, wherein the electric energy is produced by a device comprising a heat engine, a generator, thermionic means, magnetohydrodynamic (MHD) means, or a combination thereof.

16. The method of Claim 13, wherein the heat energy is used to propel a transportation device.

17. An energy producing apparatus comprising:
   a chamber comprising:
      an inlet adapted for introducing a fluid comprising a solvated solute into said chamber,
      an outlet, and
      an energy capture device adapted for capturing energy that is produced within said chamber; and
   at least a pair of electrodes for producing a plasma within said chamber, wherein said electrodes are positioned within said chamber such that the introduced fluid flows through the plasma that is produced by said electrodes; and
   an electric arc generating device operatively connected to said electrodes thereby producing a plasma from an electric arc between said electrodes during operation of said apparatus.

18. The energy producing apparatus of Claim 17, wherein said chamber is made from a material comprising ceramic, clay, glass, quartz, diamond coated material, or a combination thereof.
19. The energy producing apparatus of Claim 17, wherein the energy capture device comprises a heat exchanger.

20. The energy producing apparatus of Claim 17, wherein said heat exchanger is made from a material comprising copper, stainless steel, or a combination thereof.

21. The energy producing apparatus of Claim 17, wherein each of said electrode is independently made from a material comprising tungsten, graphite, copper, platinum, alumina ($\text{Al}_2\text{O}_3$), oxides of copper, zinc, or nickel, other metal oxides, metals doped or alloyed with thorium or other rare-earth metals, or a combination thereof.

22. The energy producing apparatus of Claim 17, wherein said electrode is doped or coated with a lower work function material.

23. The energy producing apparatus of Claim 17, wherein said electric arc generating device comprises an alternating current supply device, a rectified AC device, a radio frequency generator, a microwave frequency generator device, or a combination thereof.

24. The energy producing apparatus of Claim 18, wherein said electric arc generating device comprises a direct current supply device, a pulsed DC device or a combination thereof.
Figure 1. Heats or enthalpies of formation for the various states of Na, Cl, and NaCl
Ionic recombination rate coefficient versus pressure (temperature = 1820 K). ▲, three-body recombination for NaCl; △, mutual neutralisation for NaCl; ◆, three-body recombination for KCl ($\eta = 1.73 \times 10^{-13}$ au); ■, three-body recombination for KCl ($\eta = 2 \times 10^{-7}$ au); □, mutual neutralisation for KCl ($\eta = 2 \times 10^{-7}$ au).

Ionic recombination of sodium chloride (atmospheric pressure $\eta = 5.8 \times 10^{-6}$ au). ○, this work; ◇, Hayhurst and Sugden (1967); △, Burdett and Hayhurst (1979). Open symbols refer to mutual neutralisation, full symbols to three-body recombination.

Figure 2. Preference for mutual neutralization of Na$^+$ + Cl$^-$ rather than recombination.
Figure 3. Na\(^+\) + Cl\(^-\) → Na + Cl

Ion Densities in Dry Air at Thermal Equilibrium at Temperature T
\[ \rho_n = 1.2931 \times 10^{-7} \text{ g/m}^3 \]

Ion Density as a Function of NaCl Molarity in Water

Equilibrium Population Fractions in Dry Air at High Temperature

Figure 4
Figure 5  Na\(^+\) and Cl\(^-\) ionic thermal equilibrium

Figure 6  The Born-Haber cycle for sodium chloride showing the relationships between the energetics of all states. The units are kJ/mole.
Na(s) + ½ Cl₂(g) → NaCl(s)  Enthalpy of formation, -411 kJ

1. Na(s) → Na(g)  \[ \Delta H_1 = \Delta H_{\text{sublimation}} = +107 \text{ kJ} \]
2. ½ Cl₂(g) → Cl(g)  \[ \Delta H_2 = ½ \text{ Cl} \cdots \text{ Cl bond energy} = +122 \text{ kJ} \]
3. Na(g) → Na⁺(g) + e⁻  \[ \Delta H_3 = 1\text{st ioniz. energy} = +496 \text{ kJ} \]
4. Cl(g) + e⁻ → Cl⁻(g)  \[ \Delta H_4 = \text{ electron affinity of Cl} = -349 \text{ kJ} \]
5. Na⁺(g) + Cl⁻(g) → NaCl(s)  \[ \Delta H_5 = \text{lattice energy of NaCl} = ? \]

overall:  
\[ \text{Na(s) + ½ Cl}_2(g) \rightarrow \text{NaCl(s)} \]
\[ \Delta H_{\text{overall}} = -411 \text{ kJ} = \Delta H_1 + \Delta H_2 + \Delta H_4 + \Delta H_5 \]
\[ -411 \text{ kJ} = 107 \text{ kJ} + 122 \text{ kJ} + 496 \text{ kJ} - 349 \text{ kJ} + \Delta H_5 \]
\[ \Delta H_5 = \text{lattice energy} = (-411 - 107 - 122 - 496 + 349) \text{ kJ} = -787 \text{ kJ} \]

**Figure 7.** NaCl energetics, as shown in Figure 6, and Hess' Law

![NaCl lattice diagram](image)  

**Figure 8** The Na⁺-Cl⁻ solid crystalline lattice. It is bound by 784 kJ/mole relative to Na⁺(g) + Cl⁻(g). This is about 8 eV.
**Enthalpy of Solution for NaCl**

\[ \text{NaCl (s)} \xrightarrow{\text{H}_2\text{O}} \text{Na}^+(\text{aq}) + \text{Cl}^-(\text{aq}) \quad \Delta H_{\text{soln}} \]

\[ \text{NaCl (s)} \rightarrow \text{Na}^+(\text{g}) + \text{Cl}^-(\text{g}) \quad \Delta H_1 = \text{lattice energy of NaCl} = 787\text{kJ/mol} > 0 \]

\[ \text{Na}^+(\text{g}) \xrightarrow{\text{H}_2\text{O}} \text{Na}^+(\text{aq}) \quad \Delta H_2 = \text{hydration energy of Na}^+ = -444\text{kJ/mol} < 0 \]

\[ \text{Cl}^- (\text{g}) \xrightarrow{\text{H}_2\text{O}} \text{Cl}^-(\text{aq}) \quad \Delta H_3 = \text{hydration energy of Cl}^- = -340\text{kJ/mol} < 0 \]

\[ \Delta H_{\text{soln}} = \Delta H_1 + (\Delta H_2 + \Delta H_3) = 787 \text{kJ/mol} - 784 \text{kJ/mol} = 3 \text{kJ/mol} \]

- Lattice
- Enthalpy
- Enthalpy
- Hydrolysis
- Enthalpy of solution

**Figure 10**
Structure of water molecule

Figure 11. The dipole nature of H$_2$O molecules

Charged molecules (here ions) interact with the dipole of water molecules forming hydration shells with oriented water molecules.

Figure 12. Oriented polar H$_2$O molecules around Na$^+$ and Cl$^-$ ions
Figure 13. Concentration of Na⁺ and Cl⁻ near a water surface and the effects upon electrical conductivity.

Gaetane Haut "Charged-residue model" (CR). Offspring droplets resulting from a first Rayleigh instability continue to evaporate solvent until they become too small and undergo a second Rayleigh instability and explode. Following a sequence of evaporation-explosion, very small droplets only containing a single solute molecule are produced. Bottom. In the "ion evaporation model" (IEM), before ultimate droplets are formed, the electric field at the droplet surface becomes large enough to expel solute ions Drost. Implosion of a glycerol droplet investigated by ultra fast microscopy. In the moment of instability, the deformed droplets have a spindle-like shape from which two highly-charged liquid jets are emitted. The great versatility of electrospray allows to combine two ESI sources for producing ions of both signs and studying ionion reactions.

Figure 14. Evaporation and explosion scenario for charged droplets
Figure 15. Electrical and thermal conductivities of hot dry air and of plasma

Figure 16. A diagram of the SWB with a control volume drawn in for calculating the thermodynamic power balance of the system
Figure 17. SWB experiment setup

Figure 18. The vitrified clay pipe and aerogel insulation
Figure 19A had water with no salt spray and Figure 19B experiment used a 3 M salt water solution spray.

Figure 20. Heating of water by pump and arc with and without salt water.
Figure 21. Details of the heating curves

Figure 22. Each graph is an overlay of 6 scope traces. Note that the currents should be multiplied x 10.
Instantaneous Power vs. Time
Experiments of 031209 & 031309

Figure 23

I(t) & V(t) for Arc w/o Salt Water

I(t) & V(t) 65.7 degrees out of phase

Figure 24

I(t) & V(t) for Arc with 3M Salt Water Solution

I(t) & V(t) 105.8 degrees out of phase
Figure 25. Comparison of Currents and Normalized Voltages

Figure 26. Consistency of $V(t)$ from overlay of 6 scope traces for each experiment
Figure 27. Typical I(t) and V(t) arc waveforms. Wave forms of AC arc voltage and current. (a) Limitation of current by Inductance. (b) Limitation of current by resistance. (Carbon electrodes, 9 amp., 60 cycles/sec)

Figure 28. Fourier frequency spectrum of V(t).
Figure 29. Schematic of V(t) distortion due to the recovery voltage.

Figure 30. AC arc V-I characteristic.
Figure 31

Figure 32. Schematic of surface discharge experiment in an H₂O/ CaCl₂ solution and photos in time sequence of the initial arc followed by reaction chemistry leading to 10 cm diameter fireball.
Figure 33. The relationship among $\Delta H_{\text{mut}}$, $\Delta H_{\text{hyd}}$, and $\Delta H_{\text{soln}}$ for salt water.
Ionic solvation in water has a dual entropy effect. The entropy is increased by the additional space occupied by the salt ions, e.g., Na\(^+\) and Cl\(^-\), and the entropy is decreased by the orientation of the water molecules about the ions.

Na\(^+\) and Cl\(^-\) ions are solvated by water molecules.

The force is ion-dipole interaction.

The Dissolving Power of Water

As solid sodium chloride dissolves, the positive and negative ions are attracted to the positive and negative ends of the polar water molecules.

Figure 34. Several depictions of how salt dissolves in water.
Figure 35. Born-Haber diagram for H₂O.

Sinusoidal Oscillations in Arc Power

Figure 36. Sine wave fit to arc power oscillation.
Figure 37. Thermal Data (70 g/L NaCl in water)

Figure 38. T(t) and dT/ dt for heating by steam alone.
Figure 39

Figure 40. Oscillating Arc power. The average arc power is 107 Watts.
Figure 41. Temperature measurements (75 g/L salt water solution).

Figure 42. Water temperature v. Time (75 g/L salt water).
Figure 43. Arc power, current & voltage (75 g/L salt water).

Figure 44. Power and water heating efficiency (75 g/L salt water)
Plot\left[\frac{100}{60 \int_{-400.9 + 1.033x}^{t_{\min}} \{x, t_{\min}, t\}} / \text{EH2Oall}(t, t_{\min}), \{t, t_{\min} + 1, 533\}, \text{PlotRange} \to (0, 150)\right]

Energy Ratio = E(\text{H2O})/E(\text{arc})

Figure 45. Integrated power ratio.

Stage #1 Temperatures

Stage #2 Temperatures

Stage #3 Temperatures

Figure 46
Figure 47. The pump, hoses, and container for circulating the water through the copper coil.

Figure 48
Figure 49

Figure 50. Electrode tips.
Figure 51

Droplet Evaporation as a Function of Time

\[
\frac{dR}{dt} = -(D \frac{M}{kT}) \rho_v \rho_R
\]

Figure 52
Figure 53. Photos and physical depiction of Taylor cones.
Figure 54. Theoretical and computational model for ion ejection process.