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Secker

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[45] **Apr. 4, 1972**

[54] FLOWING LIQUID ELECTROSTATIC GENERATORS

[72] Inventor: **Philip E. Secker,** Anglesey, North Wales, Great Britain

[73] Assignee: **KDI Corporation**

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[52] **U.S. Cl.** **310/10**
[51] **Int. Cl.** **H02n 3/00**
[58] **Field of Search** 310/10, 11; 417/50

[56] **References Cited**

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Primary Examiner—D. X. Sliney
Attorney—Sughrue, Rothwell, Mion, Zinn & Macpeak

[57] **ABSTRACT**

Radial charge migration in the field emitting injector/collector interspace region of flowing liquid electrostatic generators is significantly reduced by forming a sheath of uncharged liquid with a high axial velocity concentric with the charged liquid leaving the injector, thereby sweeping to the collector any charge carriers which undergo radial charge migration.

2 Claims, 4 Drawing Figures

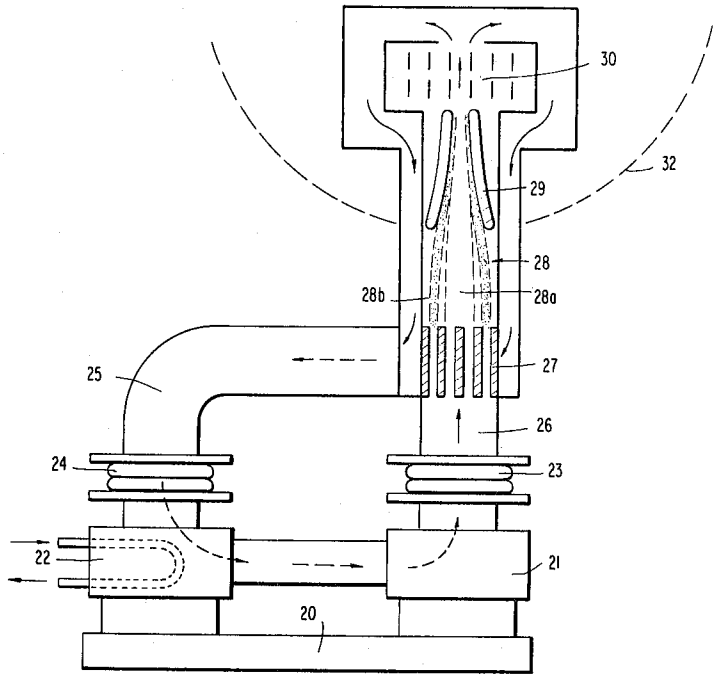


FIG. 1
PRIOR ART

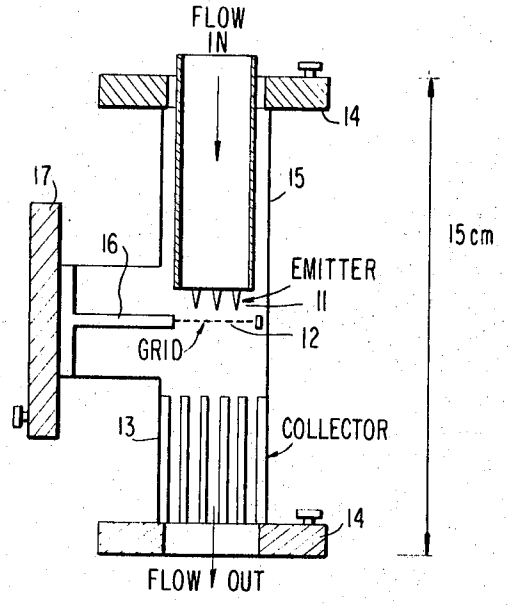
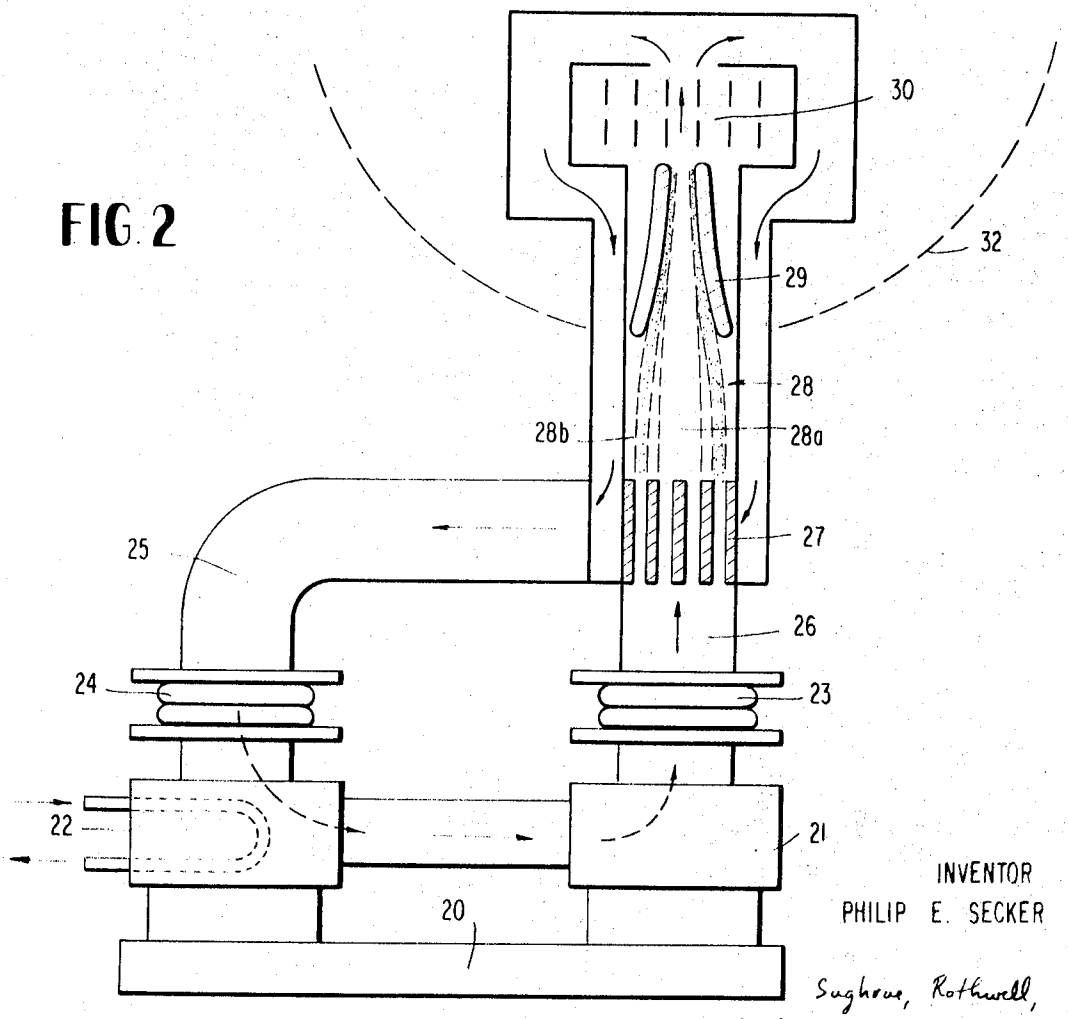


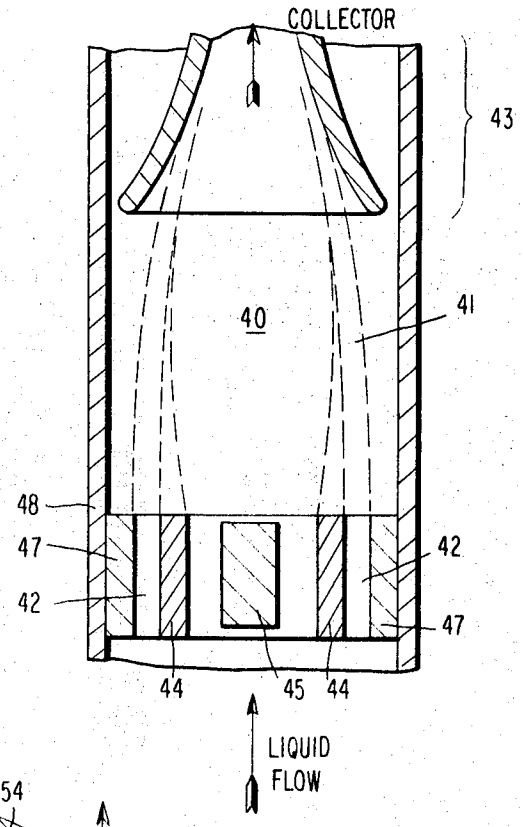
FIG. 2



INVENTOR
PHILIP E. SECKER

BY Sughrue, Rothwell, Mion, Zinn & Macpeak
ATTORNEYS

FIG. 3


COLLECTOR
43
41
40
48
47
42
42
47
44
45
44
LIQUID
FLOW

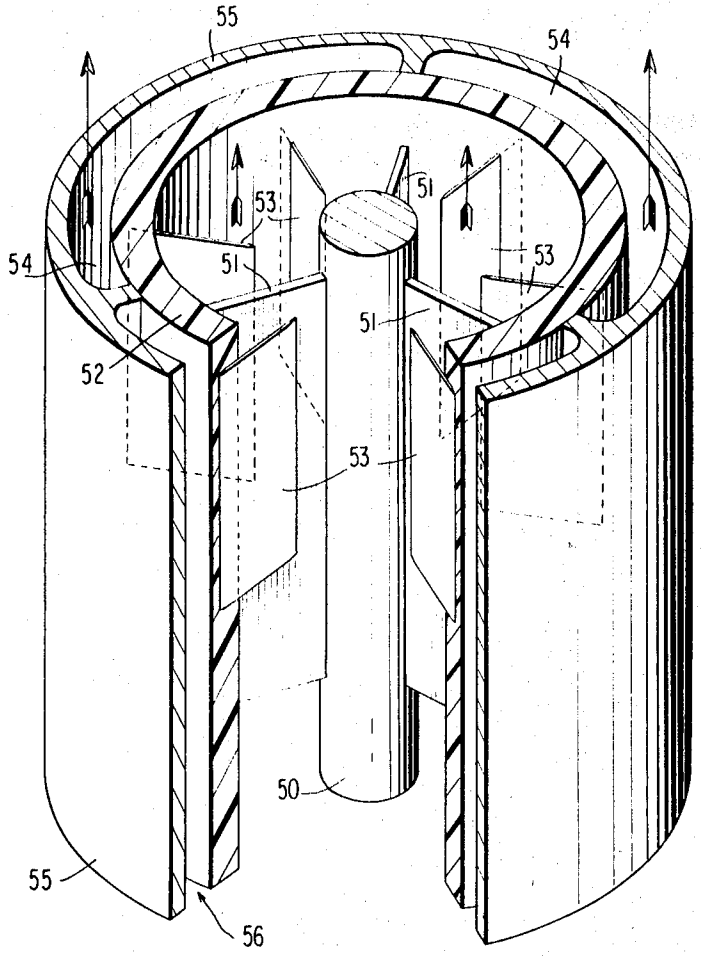

55
54
53
51
54
51
53
51
52
53
50
55
56

FIG. 4

FLOWING LIQUID ELECTROSTATIC GENERATORS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to improved flowing liquid electrostatic generators.

2. Description of the Prior Art

Recent developments have indicated that flowing liquid electrostatic generators can meet the need for electrostatic devices capable of producing voltages within the range 500 kV. to 2 MV. Such units could be used for E.H.V. electron microscopes and for use in semiconductor or integrated circuit ion implantation service.

The operation of flowing liquid electrohydrodynamic (EHD) devices is based upon the fact that it has been found to be possible to inject significant currents into dielectric liquids, e.g., hexane, in a non-destructive manner by using field-emitting electrodes. In its most basic form, the injection system consists of a razor blade mounted perpendicularly to a flat wire mesh grid which serves as a positively biased counter electrode. Application of a voltage of about 10 kV. to this diode provides, due to the intense field emission, a negative space-charge sheath around the razor edge. The electrons which are emitted from the metal surface of the razor are trapped by liquid molecules in the dielectric to form negative low mobility charge carriers. These charge carriers move towards the grid or counter electrode under the action of the electric field.

Collision between charge carriers and neutral molecules in the bulk liquid result in momentum transfer. Close to the grid, momentum transfer from the mechanically driven bulk liquid to the charge carriers sweeps some of the charge carriers beyond the grid wires and into a field-free region beyond the grid.

A simple EHD generator consists of a charge injector to produce charge carriers, a means for moving the liquid to enable the charge carriers to be driven into a field-free region, and a means for stripping the charge from the liquid.

FIG. 1 of the drawings illustrates a typical prior art EHD generator in simplified form. With reference to FIG. 1, the razor blades or injector is denoted by numeral **11**, a flat wire mesh grid or counter electrode by numeral **12**, the collector by numeral **13**, holding brackets by numeral **14**, a conduit for liquid flow by numeral **15**, the grid holder by numeral **16**, and a mounting bracket by numeral **17**.

In such a system, the flowing liquid is returned to the emitter **11** after passage through the collector **13** by a return conduit not shown in FIG. 1. The return conduit may be formed of glass or a plastic, such as unplasticized polyvinyl chloride. A circulating pump to mechanically drive the liquid through the system is usually incorporated in the closed loop. For hexane, fluid velocities in the injector have been as high as 0.5 m/s. High fluid velocities significantly enhance the injector current. This is believed to be the result of space-charge removal from the emitting edges of the injecting device (razor blades).

In FIG. 1, three razor blade emitters **11** are shown having an edge length of 12 mm. and a tip radius of approximately 1,250 A. With a suitable potential difference between the emitters **11** and the grid **12**, field-controlled emission occurs into the dielectric. Rapid field divergence away from the emitter edge insures that liquid ionization and deterioration is small. Because of the small radius of the razor blade tips, an applied voltage of only a few kV. results in intense electric field and copius emission. This provides the high density of negative charge carriers required, and the region about the injector can be considered a quasi-virtual cathode. The space charge, due to the negative charge carriers in this region, reduces the field at the razor blade edges so that in the steady state emission is reduced to that level required to offset the charge loss by conduction from the virtual cathode region. Emitter **11** - grid **12** spacings in the prior art have typically been 1-2 mm, providing an emitter field of approximately 10^7 to 10^8V.cm.$^{-1}$.

The magnitude of current resulting from the application of an adequate voltage between the emitters **11** and the grid **12** is basically proportional to the product of the number of emitters and the total carrier velocity. If adequate separation between the razor blade emitters **11** is provided so that each emitter can operate in a space-charge limited mode, multiple blade arrays in excess of three can be used to provide substantial injector currents. For instance, the prior art obtained a maximum injector current of 550μA utilizing **43** blades with a tip-grid spacing of 1 mm. and an applied voltage of 9.5 kV. 10^{10}

The prior art has also used multiple-tipped corona emitters and sharp line emitters. For the latter system, ionization was increased by using an easily dissociable additive in N-octane. Chemical degradation of the liquid was encountered in such systems.

Turning now to the grid or counter electrode **12** shown in FIG. 1, the prior art has used a fine mesh grid of **30** lines per inch. The prior art has also used flat counter electrodes of plain or perforated aluminum, but these were found to be inferior to the use of a grid. The use of a grid permits the mechanically driven liquid to carry a significant proportion of the charge carriers through the openings in the grids, the charge carriers thereafter being conveyed to the collector **13** of the EHD generator. While bare metal grids permitted charge transmission in excess of 80 percent of the injected charge, the prior art has proposed that the use of insulation-coated electrodes might raise this figure to nearly 100 percent.

The collector **13**, as used by the prior art, consisted of a cylindrical brass plug 2 ½ centimeters in diameter, having 40, 1/16 inch diameter holes drilled therethrough. Typically, spacings of 3 centimeters from the grid were used. It was found necessary to use a collecting structure with an adequately large and clean surface area to permit efficient charge scavenging.

Once an EHD generator, as described, is in operation, the potential on the collector builds up relative to the injection system, which comprises the emitter and the grid or counter electrode. The associated electric field will exert a repelling effect on further charge carriers moving towards the collector. At some point, this repelling force on the charge carriers reaches a degree where the charge carriers become stalled between the injector and the collector due to the collector repelling field nearly balancing out the momentum transfer effect of the flowing liquid. At this point, where axial carrier motion becomes greatly reduced, charge carriers which are essentially stationary are prone to radial diffusion as a result of their mutually repulsive field. This effect, which is exaggerated at higher collector voltages, results in serious charging of any insulating walls bounding the conversion space. This can lead to disruptive flashover to any grounded surface. Furthermore, device efficiency is seriously lowered since charge carriers are effectively lost from the collector. The present invention solves both of these problems.

As will be appreciated by one skilled in the art, the theory and practice of EHD generators is well documented, and the applicant accordingly wishes to incorporate, by reference, the following publications which discuss the operation of EHD generators:

"Liquid-Filled Electrostatic Generator," *Electronic Letters*, Vol. 2, No. 5, May 1966, J. F. Hughes and P. E. Secker;

"High-Current Injection Into Liquid Hexane Using Field Emitters," *Brit. J. Appl. Phys.*, Vol. 17, pp. 885–890, 1966, G. Coe, J. F. Hughes and P. E. Secker;

"Collection of Charge From a Moving Stream of Liquid Dielectric," *Brit. J. Appl. Phys.* (J. Phys. D.), Ser. 2, Vol. 2, 1969, J. F. Hughes and P. E. Secker;

"Liquid-Filled EHD High-Voltage Generator," *Proc. I.E.E.*, Vol. 116, pp. 1785–88, Oct. 1969, P. E. Secker and J. F. Hughes.

SUMMARY OF THE INVENTION

In flowing liquid electrostatic generators, radial charge migration in the injector/collector interspace region is minimized by the present invention.

In the improved method and apparatus of this invention, a modified injector system, typically of circular cross section, is surrounded by a duct, in a preferred embodiment an annular duct, so that charge liquid leaving the injector is enclosed in a fast-flowing sheath of uncharged liquid. Carriers radially diffusing from the "charge" core migrate into the neutral sheath and are mechanically swept by the flowing neutral sheath liquid into the collector electrode.

It is thus one object of the present invention to provide an improved EHD generator.

It is another object of the present invention to prevent substantial radial charge migration in the injector/collector interspace region of flowing liquid EHD generators.

It is yet another object of the present invention to provide means for preventing internal "flashover" of a flowing liquid EHD generator system to ground.

It is a final object of this invention to increase the efficiency of flowing liquid EHD generators.

These and other objects of the present invention will become clear upon a review of the drawings taken in conjunction with the detailed description of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic cross-sectional view of a typical prior art flowing liquid EHD generator.

FIG. 2 is a schematic cross-sectional view of the novel injector electrode of this invention used in an overall EHD generator.

FIG. 3 is a detailed schematic cross-sectional view of the novel injector assembly of this invention in operation.

FIG. 4 is a cross-sectional perspective view of the novel injector assembly of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The broad theory of EHD generators has been heretofore outlined in the description of the prior art. The following discussion is offered to set the context of the present invention in systems which have proven most efficient. It will be appreciated by one skilled in the art that the practice of the present invention can find application in systems as the prior art has utilized, and in systems which will vary from those described in the specification. In the preferred embodiment of this invention, hexane is utilized as the liquid dielectric material. Other materials, such as freon, etc., could be used. It is of primary importance that the following criteria be met for the liquid dielectric, rather than any one special dielectric be selected. Specifically, the dielectric must have good insulating properties. Hexane, when purified, has a dielectric strength exceeding 10^6 V./cm. The liquid dielectric must further have a low negative carrier mobility, a low viscosity and preferably be non-flammable. Typical viscosity values are equal to or less than 0.5 centistokes. Any liquid with the above criteria could be used in the EHD generator of this invention.

The negative charge carrier mobility for hexane is only 1.5×10^{-4} cm.^{2}/V/sec. Negative charge carrier mobilities of this magnitude serve excellently in an EHD generator. With typical injector designs, the unipolar charge current density in the conversion space with hexane will be approximately 1.5μA/cm. It is possible that the prior art dielectrics, such as gaseous, gaseous-solid systems and the like could be used in this present invention. For instance, the prior art utilized dust particles, aerosols, glass beads, water droplets in a gas, and metal or gas bubbles in the dielectric liquid. Problems were encountered with the use of such carriers, such as accumulation of the charge carriers in regions of high electric field resulting in electrical breakdown.

Turning now to FIG. 2, wherein purified hexane is used as the dielectric liquid, numeral **20** represents the base assembly of the EHD generator. Numeral **21** represents a mechanical pump utilized, as heretofore indicated, to flush the charge carriers out of the counter electrode region.

Numeral **22** represents a heat exchanger. The inventors of the invention described herein have found that during operation, it is advisable to permit the process to occur under a slight temperature rise, approximately 10° C., so that a pressure of about 7—8 p.s.i. develops in the system. This inhibits bubble formation in areas where drastic changes in cross sectional flow area occur, such as at the outlet from the injector. A further advantage of operation at elevated temperature is that moisture condensation under various parts of the system is minimized. Any state of the art system can be used to maintain temperature/pressure constant, and it will be appreciated that the above temperature/pressure values are only preferred and not limiting on the operation of this invention.

Numerals **23** and **24** designate teflon bellows which prevent vibration from pump **21** being transmitted into the active EHD generation region. Such bellows are not essential, and merely form a preferred embodiment.

Numeral **26** designates that portion of the loop or conduit which carries the liquid hexane into the injector/collector region. Conduit **26** must be a good insulator and is preferably glass or a plastic, such as unplasticized polyvinyl chloride.

Numeral **27** designates the novel emitter/counter electrode assembly of this invention. Typically, the operating voltage of the injector will vary from 15—20 kV., although this range is only preferred and other ranges are operable. The injector assembly **27** is represented in detail in FIG. 4 of the drawings, and will be explained at a later point in the specification.

Numeral **28** is used to generically represent the injector/collector interspace region of the present invention. As heretofore indicated, it is in this region where stalling of the charge carriers can occur, leading to reduced device efficiency and disruptive flashover to ground. At this portion, the inner "core" of charge carriers is shown by numeral **28***a*, and the outer "sheath" of uncharged liquid is shown by numeral **28***b*.

Numeral **29** represents a variation of the present invention wherein a collector extension **29** is used. The collector electrode was extended down the loop **26** which contains the injector, the loop functioning as a support column, terminating in a copper pipe having a flared inlet spaced a distance from the injector. The liquid is thus pumped through the injector, across the conversion space and up the collector extension **29** before entering the collector 30 per se.

The inventor has found that **100** percent charge scavenging is only possible when the collector **30** has a very large surface area. A plurality of collector electrodes are represented by numeral **30** in FIG. 2. Most preferably, the electrodes are chemically etched prior to immersion in the hexane liquid, for instance, in dilute hydrochloric acid. Thus, in a subsidiary aspect of this invention, the inventors have found that efficient charge stripping does not take place at the collector of the prior art which merely consists of a block of metal through which a large number of holes have been drilled. It will be understood that in the context of the present invention, the term collector and collector/electrodes are used interchangeably, a plurality of electrodes forming the collector.

Numeral **31** represents an exterior return loop or conduit which is formed of glass, as in a preferred embodiment, is the loop or conduit **26**.

In this embodiment, though it will be obvious any closed loop variation can be used, the closed loop is formed by the hexane inflow conduit **26** which is surrounded by the hexane outflow conduit **31**. After the hexane has contacted the collector **30**, it flows out of the top of the collector and in an annular region formed around the conduit **26** by the conduit **31**. The hexane then passes through the horizontal exchange loop **25** into the heat exchanger **22** and the pump **21**. It will be appreciated that the heat exchanger and pump can be reversed in position, and the present description merely represents a preferred embodiment.

Numeral 32 of FIG. 2 represents a stress distributing sphere. Since potentials approaching 1 MV. are approached, it is necessary to have a suitable external stress-distributing sphere and adequate clearance from earth. This was achieved by mounting the main part of the collector 30 on top of the two coaxial glass conduits 26 and 31.

To summarize the processing sequence of the EHD generator shown in simplest terminology, the hexane may be viewed as initially passing through the heat exchanger 22, through the mechanical pump 21, up conduit 26 where it passes through the injector assembly where it is "charged," passing through the injector/collector interspace 28 and into the flared collector extension 29, and then entering the collector 30 where charge is scavenged from the flowing hexane. Thereafter, the liquid exits from the collector 30 into the conduit 31 and is returned via loop or conduit 25 for repetition of the above cycle.

Having thus described a typical cycle of the present invention, the following discussion will be directed primarily to the improved injector assembly of this invention.

As heretofore indicated, in the injector/collector interspace 28, charge carriers, due to the repulsive effect of the potential build up on the collector 30, tend to become semi-stalled, undergo radial diffusion and lead to lower device efficiency and disruptive flashover to ground.

With specific reference to FIG. 3, applicant has solved the above problem by enclosing the central core of charged liquid 40 with a sheath of uncharged liquid 41 between the injector and the collector, which will begin above the collector flared inlet 43. With reference to FIG. 3, this is done, in the preferred embodiment, by forming an annular bypass channel 42 around the emitter electrodes which are generically shown at 44 (though it will be understood that 44 represents, in effect, the razor blades in their support which will form the inner wall of the bypass channel) of the injector and the central counter electrode 45. In FIG. 3, the annular bypass channel 42 is formed by the interspace between the injector comprising the emitters per se, which are razor blades in their support, and the exterior members 47, which are formed of an insulating material such as Perspex. Of course, though shown individually, it will be appreciated that the outer members 47, which function to form the bypass channel 42, can be integrally molded and a part of the insulating walls 48.

It will further be appreciated that with reference to FIG. 3, that this is merely a schematic embodiment of the preferred bypass injector assembly of this invention, FIG. 4 providing a detailed perspective view of this embodiment.

It will further be obvious to one skilled in the art that though a circular bypass channel is provided in FIG. 3, this is merely because of the circular orientation of the conduit or insulating walls 48. Other shapes are possible, but since a circular bypass channel provides highly laminar flow, which is most desirable in the sheath of uncharged liquid 41, this has been found to be most preferred.

Reference should now be made to FIG. 4 which should be read in conjunction with the following description of the bypass injector. As heretofore indicated, the prior art used a flat grid spaced from the emitters per se. The present inventor, in a further subsidiary aspect of this invention, have found that not only is it feasible to use a flat grid, but further significant advantages can be obtained upon the utilization of a central counter electrode, which serves the same purpose as the grid of the prior art. In FIG. 4, this is represented by numeral 50. The central counter electrode 50 is supported by members 51 from the outer casing of the injector or emitter holder 52. In this instance, the emitter holder 52 is formed of Teflon. Disposed radially inward towards the counter electrode 50 and held by the emitter holder 52 are the emitters per se 53 which are razor blades. In the following discussion, the term emitter and razor blades will be used interchangeably, it being appreciated that the plurality of emitters comprise the active injector.

Hexane, of course, which will form the charge carrier "core," will flow through the circular region containing the counter electrode 50 and the razor blades 53, which is formed by the emitter, or blade holder 52.

Formed around the blade holder 52 is, of course, the bypass channel 54. In this instance, the bypass channel 54 is formed by the annular region between the blade holder 52 and the outer casing 55. Most preferably, the outer casing, formed of Perspex or plastic for easy fabrication, actually forms an intermediate portion of the loop 26, being joined to the glass tubing 26 at both ends of the casing 55. It is preferred that the outer casing 55 be joined to the glass loop or conduit 26 rather than be formed as a separate complete extension mounted therefrom. This will provide laminar flow to be obtained with less eddy obstructions in the path of the hexane.

Numeral 56 in FIG. 4 is used to represent the bottom portion of the inner space wherein hexane will enter to thereby form the sheath of uncharged liquid issuing from the bypass channel 54.

In FIG. 4, the razor blades 53 are of course mounted with their emitting edges parallel to and coaxially distributed around the central counter electrode 50 whose axis is aligned parallel to the direction of liquid flow. It has been found that greater emitting edge lengths per unit area normal to the direction of liquid hexane flow yields a much more satisfactory current density in the conversion space than appreciated by the prior art. It will be obvious that this greater emitting edge length per unit area is provided, in part, by the fact that the liquid which is to be charged is restricted in total volume of flow by the combination of the blade holder 52, the counter electrode 50 and the support members 51.

The resultant high velocity of the liquid flow in the injection region is very important. This provides the charge carriers the necessary axial velocity to prevent the carriers being captured by the central counter electrode 50. FIG. 4, in its entirety, represents a six blade, coaxially oriented injector assembly.

Summarizing then the function of the bypass channel of the present invention, uncharged liquid hexane will initially enter the emitter/counter electrode assembly of FIG. 4 and pass the bottommost portion of the outer casing 55. The central portion of the hexane then passes through the central "tubular" section defined by the emitter holder 52, flows rapidly past the emitters or razor blades 53, which are operating in the field emission mode, and whereby the charge carriers heretofore referred to in the hexane are formed.

A certain portion of the hexane, however, the outermost portion, will pass into interspace 56 which is the beginning of the bypass channel 54 formed by the outer surface of the emitter holder 52 and the inner surface of the outer casing 55. This will form the outer sheath of uncharged liquid. As the inner charged core exits from the central tubular area defined by the emitter holder 52, it will thereafter be surrounded by the flowing sheath of uncharged liquid issuing from the bypass channel 54, and thereby be insulated by the sheath of uncharged liquid from the walls of conduit 26.

The charge core and neutral sheath will thereafter be pumped to the collector. It is believed that reference to FIG. 3 at this point will aptly illustrate the relationship of the charged liquid core and the sheath of uncharged liquid between the emitter/counter electrode and the collectors.

By using the above flowing liquid sheath of uncharged liquid, radial charge transfer from the central charge core in the injector/collector interspace is minimized. It will be apparent from FIG. 3 that the charged liquid and the neutral sheath liquid are in direct physical contact with each other. There is no separating solid wall or the like.

Important parameters to consider in the design of the bypass channel to form the uncharged sheath are only that a sufficient amount of uncharged liquid be provided to stop any substantial radial diffusion from occurring. Obviously, by shaping the collector inlet appropriately, as shown by numeral 43 in FIG. 3, for instance in the shape of an outwardly diverging cone, the uncharged liquid cylinder can more or less carry the charged liquid directly into the collector per se.

In the heretofore discussed example, the emitters per se were standard razor blades as used in the prior art, having a length of approximately 12 mm. and a tip radius of approximately 1,250 A. However, it must be reiterated that the injector/collector configuration illustrated in FIG. 4 offers an improvement over the prior art in that a greater emitting edge length per unit area normal to the direction of liquid flow is provided by a combination of the emitters **53** parallel to and coaxially distributed around the central counter electrode **50**.

It will further be appreciated by one skilled in the art that although razor blades have been delineated as the emitters per se, any comparable means can be used so long as each emitter operates in the space-charge-limited mode, and no ionization of the liquid occurs.

In a specific example, the bypass assembly shown in FIG. 4 was used in conjunction with the overall generator assembly of FIG. 2. A six blade, coaxially oriented injector assembly was used. The dielectric material used was purified normal hexane. This had a flow rate of 2 meters per second in the system other than in the immediate injector region. A voltage of 15 kV. was applied to the injector, resulting in an output voltage of 500 kV. on open circuit and 30μA. on short circuit. Operation was under a pressure of 7—8 p.s.i. at a temperature of 30° C. Without pressurized operation, a voltage of only 200 kV. (open circuit) and a current of 14μA (with the collector shorted to ground) was realized before discharging was observed inside the generator in the conversion space. The axial flow velocity in the injector region per se was 10 meters per second, and the overall system liquid velocity was 2 meters per second. The glass carrier loop **26** utilized had an inner diameter of 5 centimeters. The collector was spaced approximately 5 centimeters from the closest edge of the injector assembly. The spacing between the edges of the blades **53** and the centrally disposed counter electrode **50** was 0.2 centimeters.

With the dimensions heretofore shown, the uncharged liquid sheath is about 5 mm. thick resulting from a corresponding lateral spacing of the bypass channel **54**. This is not critical, and almost any thickness for the liquid sheath is sufficient as long as the sheath effectively inhibits radial diffusion. The "core" liquid was 3 cm. in diameter at the injector outlet, and this was effectively contained by the sheath of neutral flowing liquid having a diameter of 5 cm. for the apparatus shown.

In generators requiring a large current output, it should be possible to operate in parallel a number of injector/collector arrangements of the type shown in FIG. 4. Each individually charged liquid core would be enveloped in its own fast flowing neutral liquid sheath thereby isolating it from neighboring charged cores, or one neutral sheath enveloping all the charged "cores."

It will be appreciated that the central concepts of the present invention are applicable for apparatus and dimensions which will greatly vary from those shown in the specification, the specification merely providing one preferred embodiment of this invention.

What is claimed is:

1. In a flowing liquid electrostatic generator comprising a liquid carrying conduit for transporting a charged liquid in combination with an injector electrode assembly and a collector electrode assembly, the improvement which comprises:

an injector electrode assembly having means to form a flowing layer of substantially uncharged liquid substantially completely surrounding the flowing charged liquid, whereby said flowing charged liquid is insulated from said liquid carrying conduit by said flowing uncharged liquid,

said injector assembly comprising means for supporting a plurality of emitting electrodes which have a long axis and a short axis, said long axis being arranged parallel to the direction of flow of said flowing liquid and said emitting electrodes being carried in a support means which comprises a cylindrical outer support member, and a cylindrical member substantially completely enclosing said cylindrical support member at a distance therefrom, whereby a channel is formed which permits the passage of a portion of said liquid flowing in said liquid carrying conduit, said channel dividing said flowing liquid stream into at least two portions, a central portion which is charged by electron injection from said injector electrode assembly, an outer concentric portion which is not charged but which insulates said central flowing portion from said liquid carrying conduit and,

said emitting electrodes bein inwardly disposed in a radial manner in said means for supporting a plurality of said emitting electrodes.

2. The flowing liquid electrostatic generator of claim **1** further comprising a counter electrode centrally disposed within said inwardly disposed emitting electrodes.

* * * * *