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(54) **ELECTROHYDRODYNAMIC ATOMIZATION NOZZLE EMITTING A LIQUID SHEET**

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B05B 1/06	(2006.01)

(52) **U.S. Cl.**

CPC ***B05B 5/0533*** (2013.01); ***B01J 2/04*** (2013.01); ***B05B 1/044*** (2013.01); ***B05B 7/065*** (2013.01); ***B05B 7/061*** (2013.01); ***B05B 1/06*** (2013.01); ***B05B 5/0255*** (2013.01)

(57) **ABSTRACT**

Embodiments for producing un-agglomerated, monodisperse droplets using a liquid sheet are provided. Nozzles with exit slit openings shape a spray liquid into a thin liquid sheet as the spray liquid exits from the slit opening. Stable multi-jet operation is achieved by including notches along the edge of the slit. The notches separate the liquid sheet into multiple jets to provide anchoring and stable multi-jet operation. In some embodiments, the liquid sheet electrospray techniques and nozzles described herein provide high mass throughput and versatile multiplexing spray systems while reducing the engineering effort and high manufacturing cost

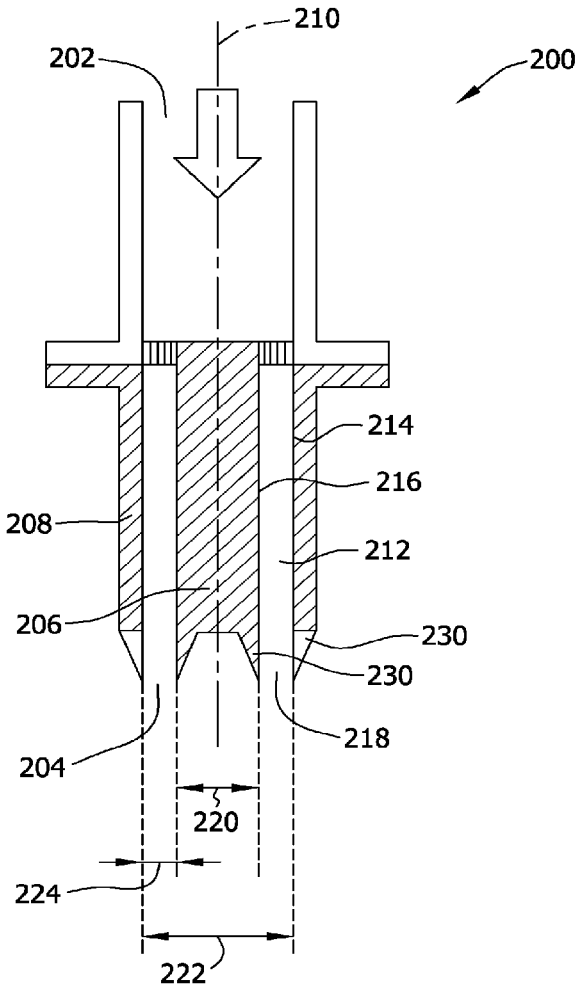


Figure 1

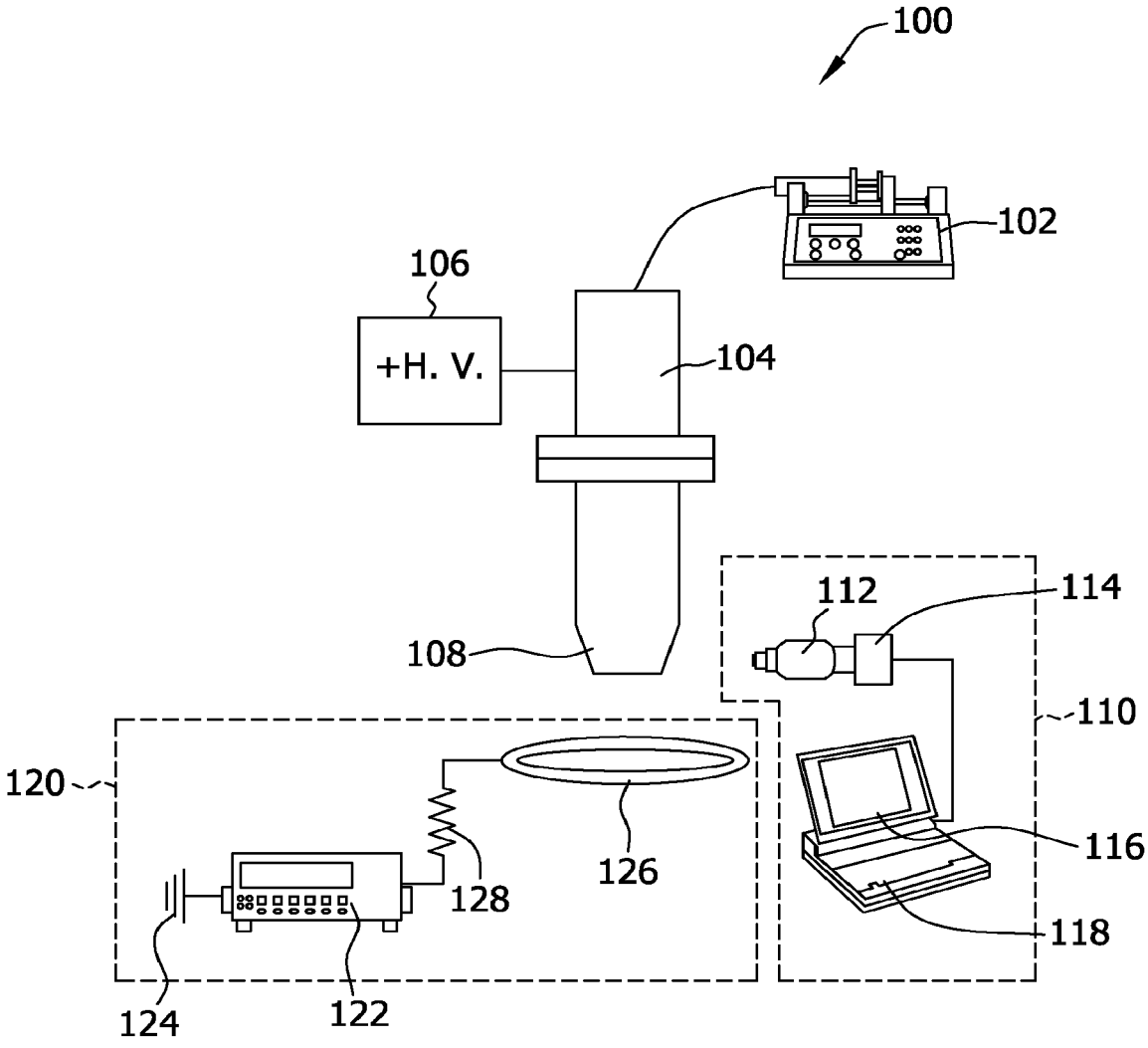


Figure 2

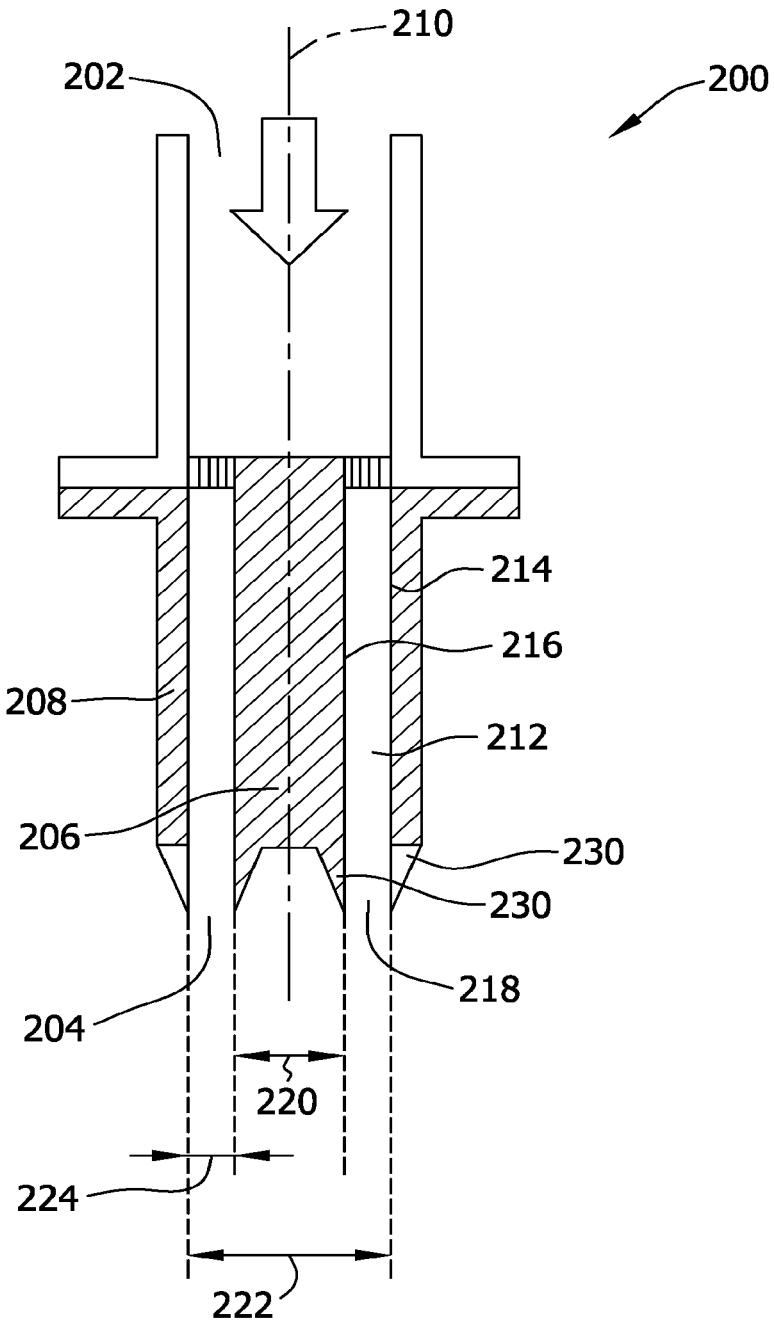


Figure 3A

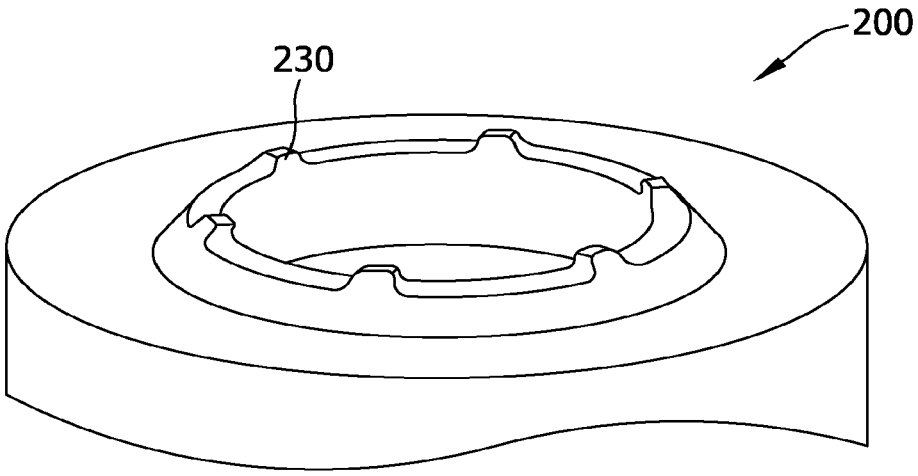


Figure 3B

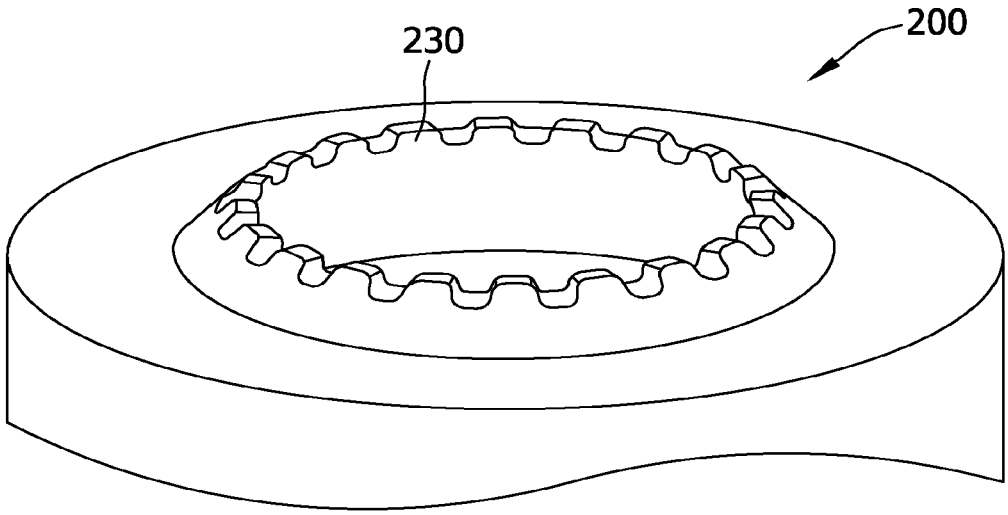


Figure 4A

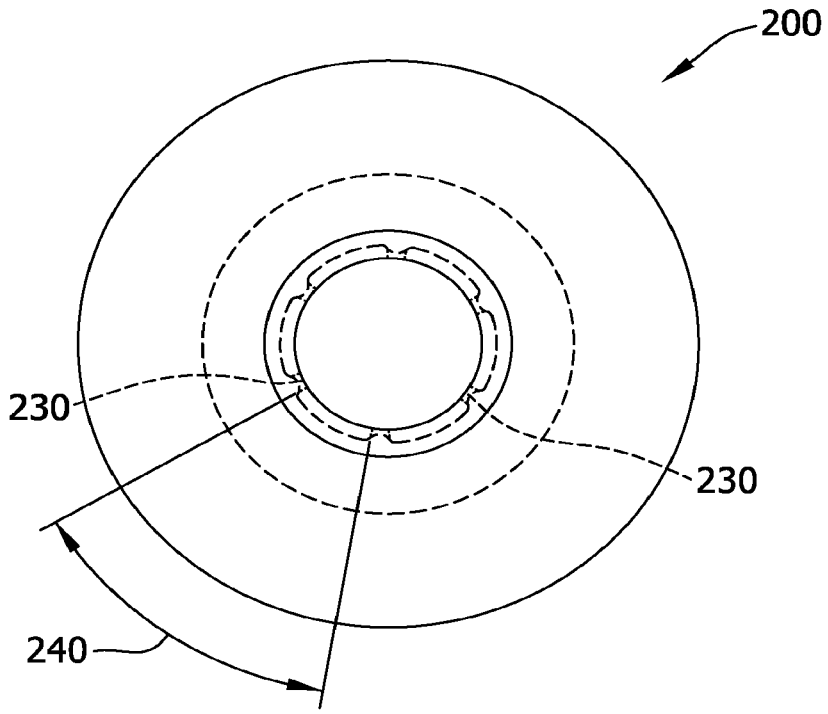


Figure 4B

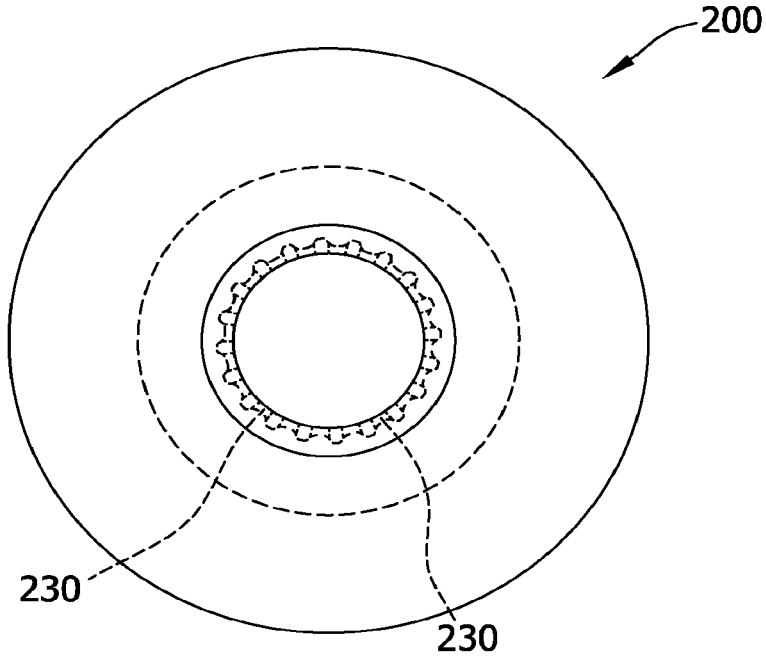


Figure 5A

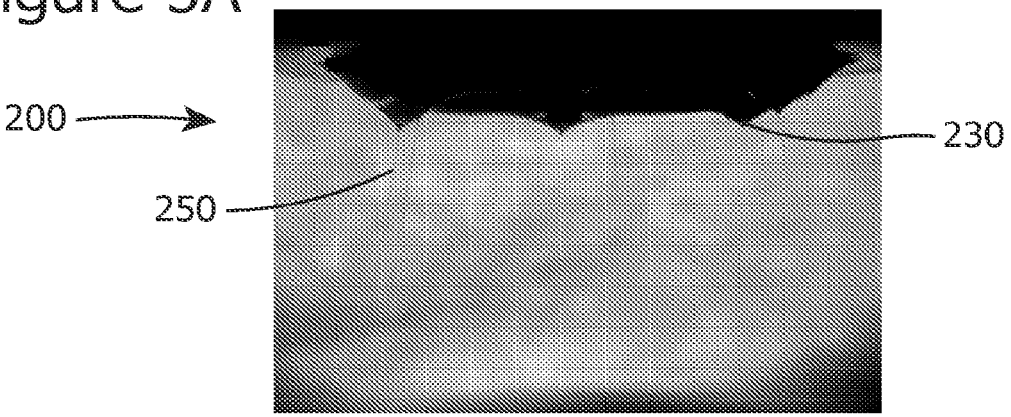


Figure 5B

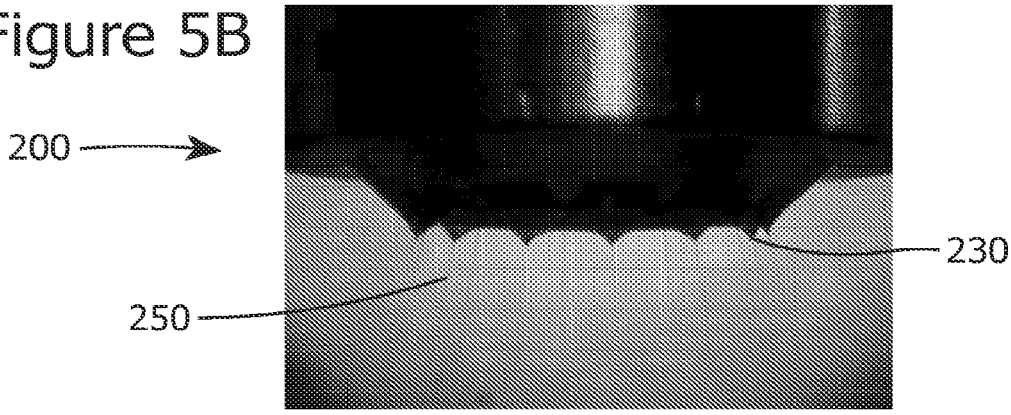


Figure 5C

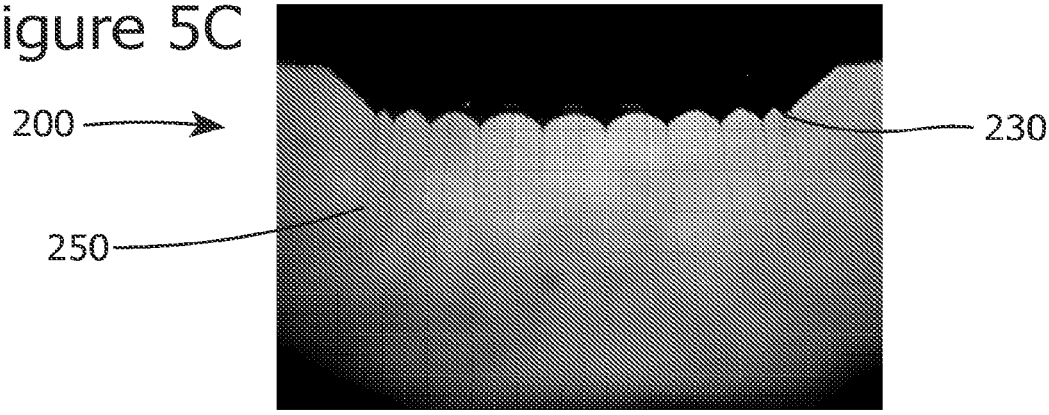


Figure 6A

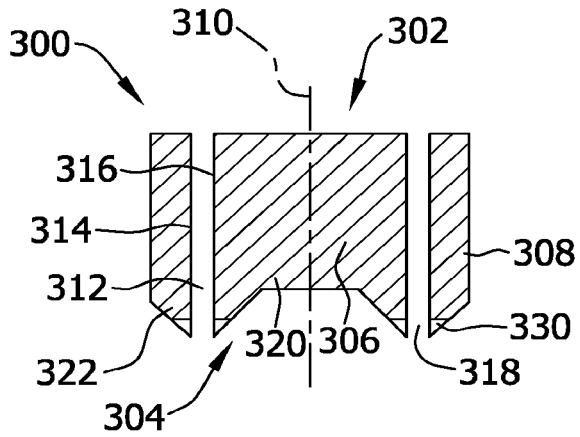


Figure 6B

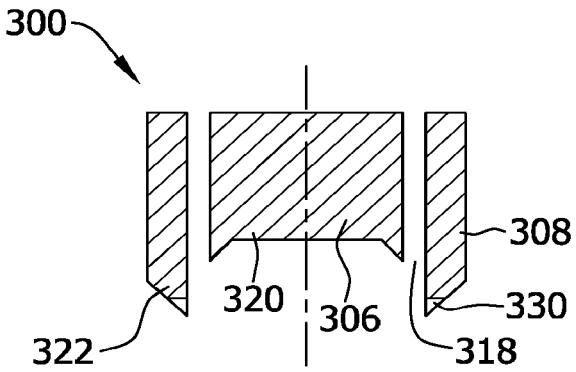


Figure 6C

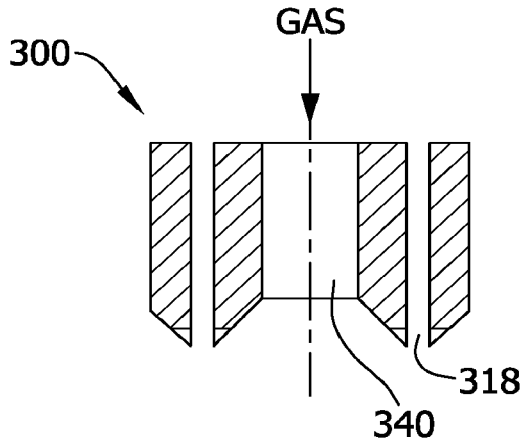


Figure 6D

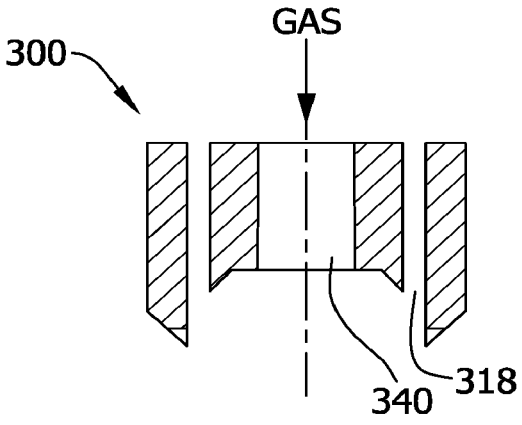


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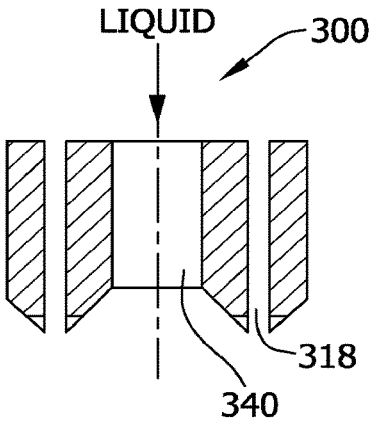


Figure 6F

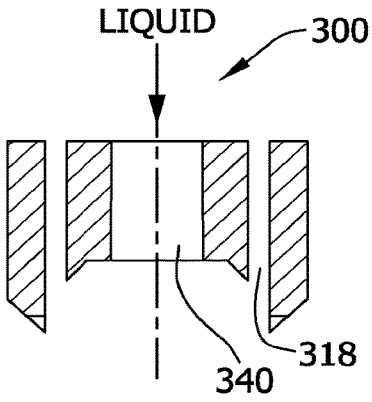


Figure 6G

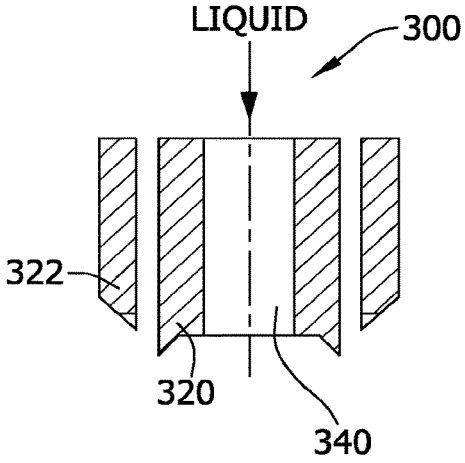


Figure 6H

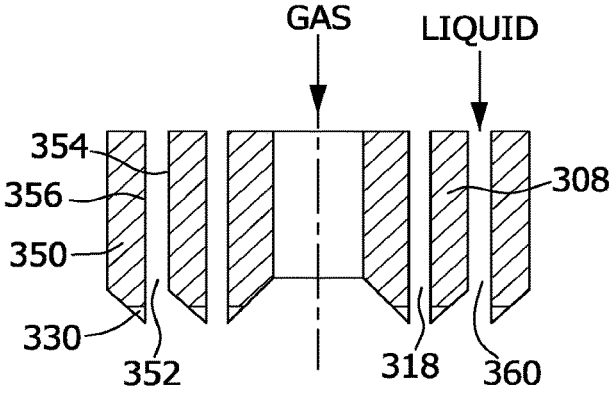


Figure 6I

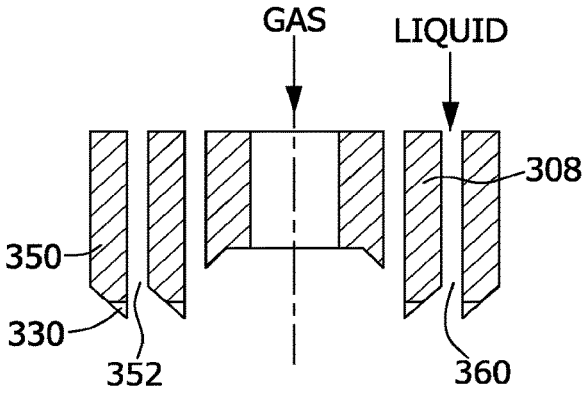


Figure 6J

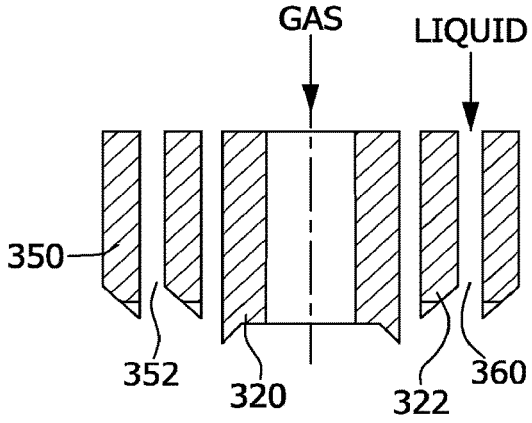


Figure 6K

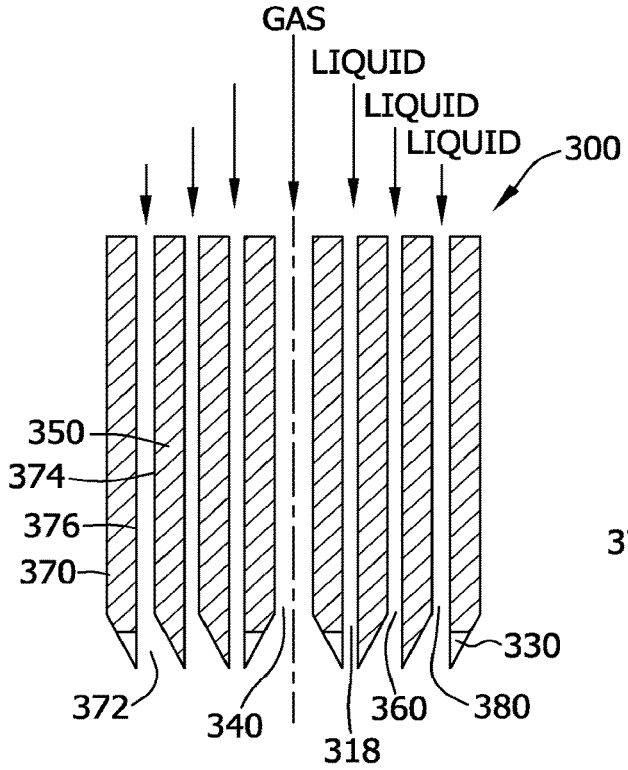


Figure 6L

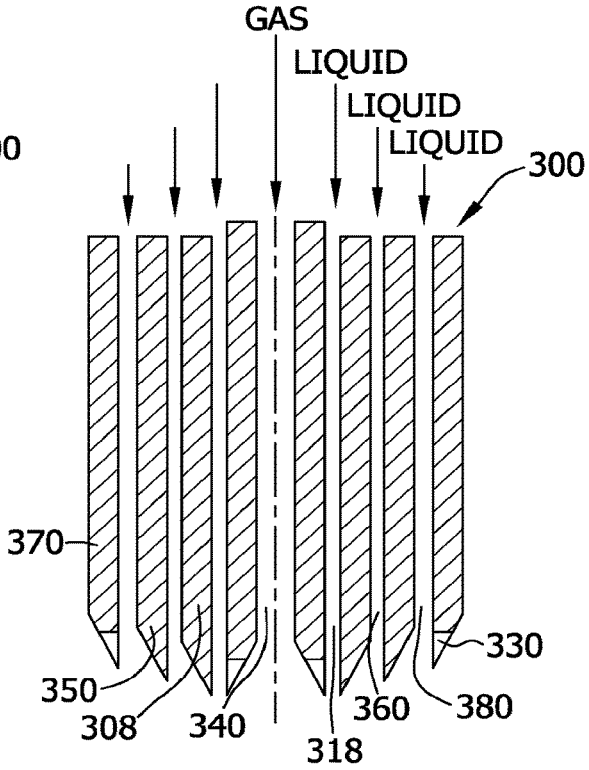


Figure 7

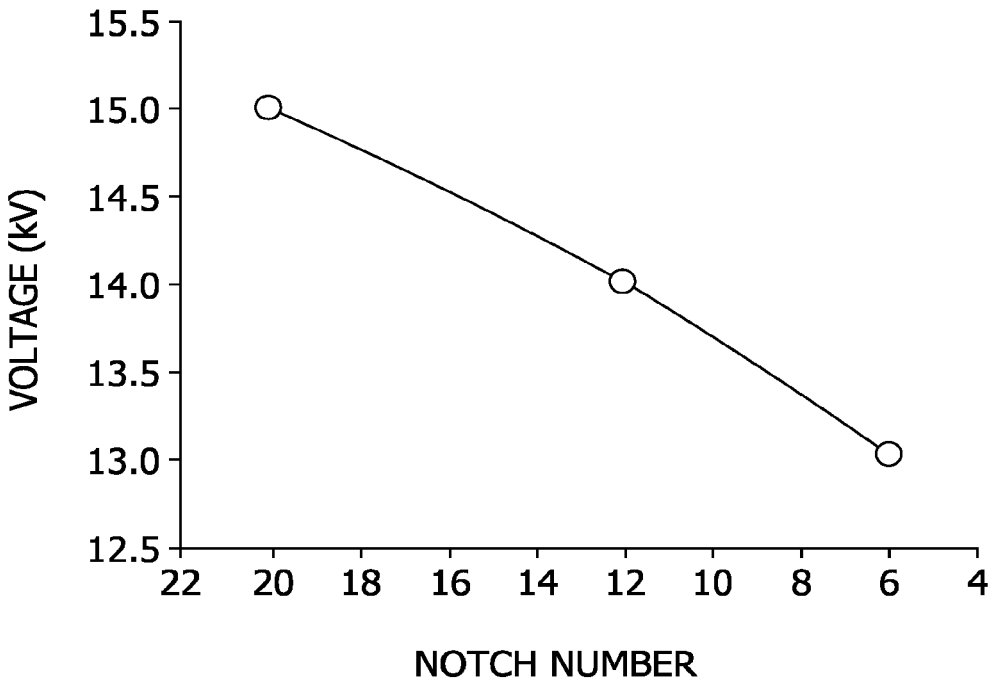

15.5
15.0
14.5
14.0
13.5
13.0
12.5
VOLTAGE (kV)
22
20
18
16
14
12
10
8
6
4
NOTCH NUMBER

Figure 8A

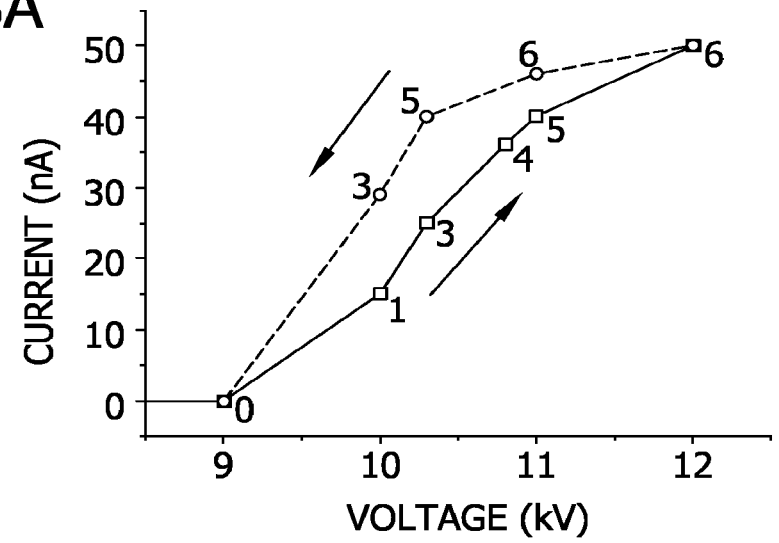


Figure 8B

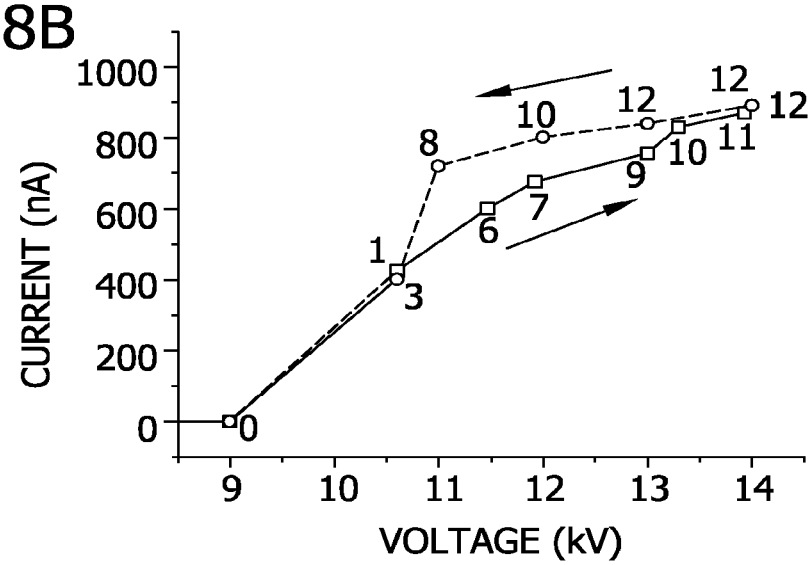


Figure 8C

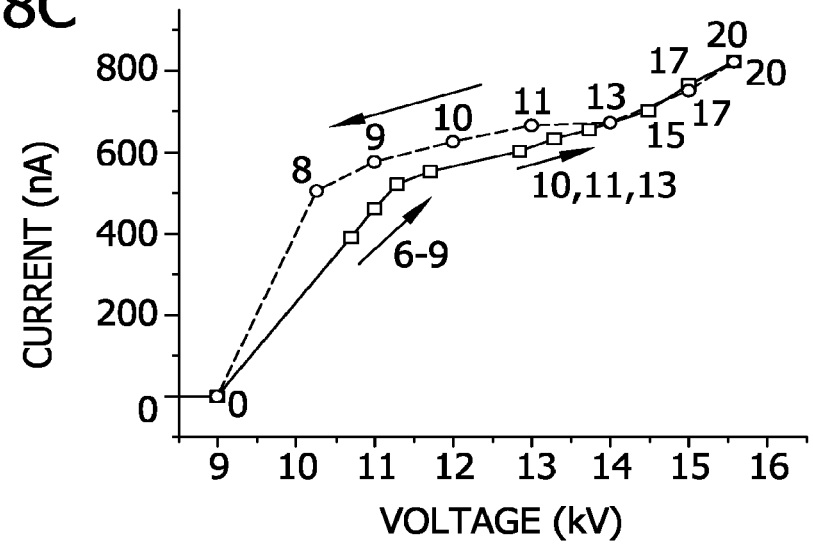


Figure 9

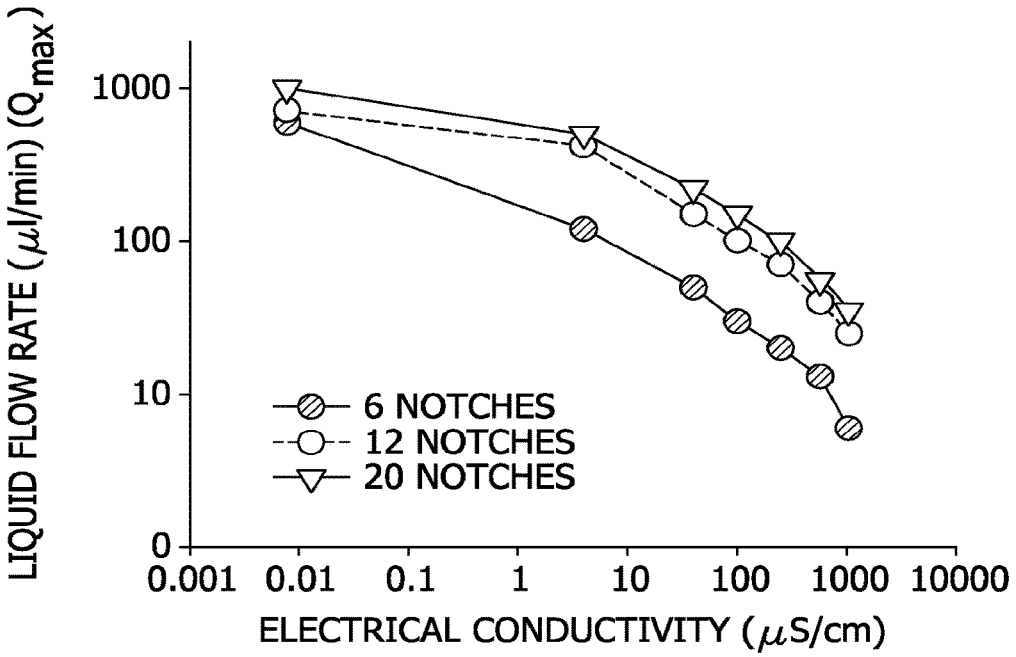


Figure 10

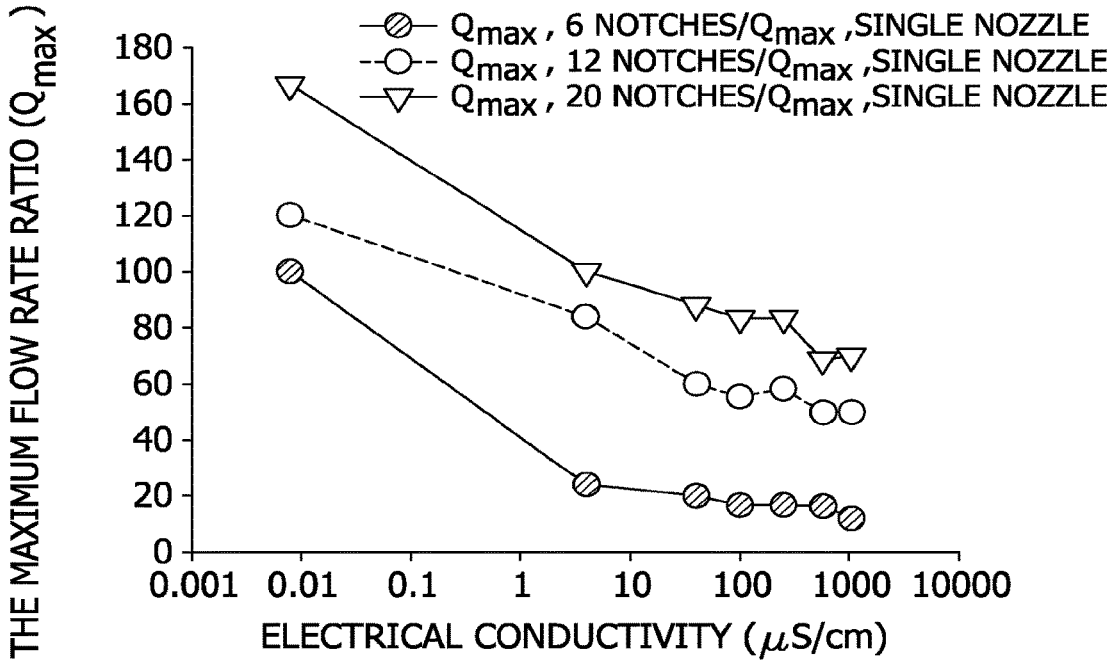


Figure 11

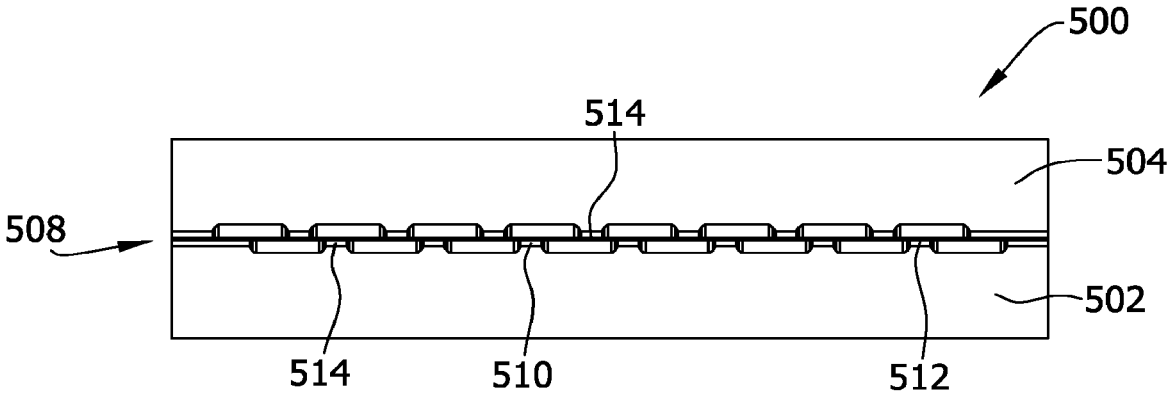
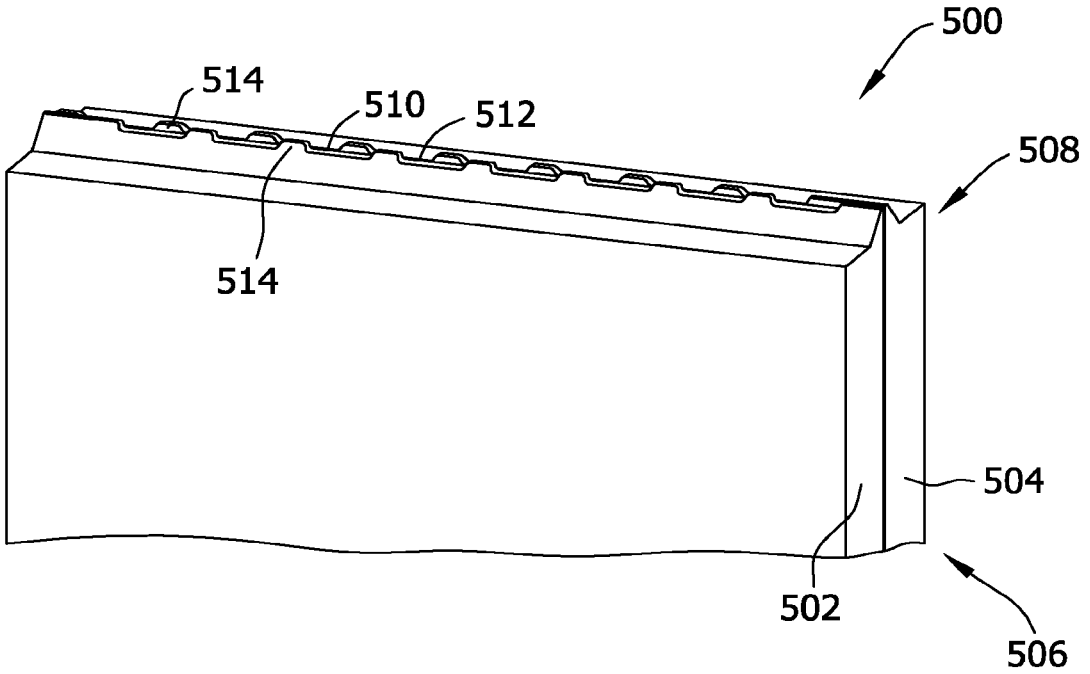


Figure 12



ELECTROHYDRODYNAMIC ATOMIZATION NOZZLE EMITTING A LIQUID SHEET

BACKGROUND

[0001] Electrohydrodynamic atomization, often called electrospray (ES), has recently attracted great attention for potential and practical particle applications in fine powder production, food processing, medicine, pharmaceutics, biology, and chemistry. The technique enables the production of un-agglomerated, monodisperse particles of various materials with sizes ranging from micro-meter to nano-meter. In known ES systems, a liquid meniscus at the exit of a capillary nozzle is subjected to an electrical stress, resulting from a divergent electrical field established between a spray head and a reference electrode. Due to the geometry of capillary nozzles, however, known ES systems have low mass throughput, which makes the feasibility of large scale implementation difficult.

[0002] Several recent electrohydrodynamic atomization techniques reportedly increase the mass throughput. For example, in a single-capillary ES nozzle, a multi-jet mode can be generated when the applied voltage exceeds a voltage range for a cone-jet mode. However, multiple liquid jets initiated from a single-capillary head are unstable. Arranging a number of individual capillaries in a one-dimensional linear array also increases the total spray liquid flowrate. However, although the one-dimensional arrangement of individual capillaries is easy to construct for laboratory investigation, it is not practical for industrial scale applications. Further each individual capillary uses a separate feeding and/or distribution channel.

SUMMARY

[0003] In a first aspect, a nozzle for electrohydrodynamic atomization is provided. The nozzle includes an inner rod, an outer tube concentrically aligned with the inner rod, an annular channel defined between the inner rod and the outer tube, the annular channel forming a circular slit at a spray end of the nozzle, and at least one electrically chargeable notch located on at least one of the inner rod and the outer tube proximate the circular slit.

[0004] In another aspect, a system for electrohydrodynamic atomization is provided. The system includes a nozzle including a source end, a spray end, a first component including a first surface, a second component including a second surface, a fluid channel defined between the first surface and the second surface, the fluid channel forming an exit slit at the spray end of the nozzle (e.g., a circular exit slit, a planar or linear exit slit, etc.), and at least one electrically chargeable notch located on at least one of the first component and the second component proximate the exit slit. The system may further include a voltage source electrically coupled to the nozzle and configured to supply a voltage to the at least one electrically chargeable notch, and a syringe pump in flow communication with the source end of the nozzle, the syringe pump configured to propel a spray liquid through the nozzle.

[0005] In yet another aspect, a method for electrohydrodynamic atomization is provided that may use one or more of the nozzle configurations described herein. For example, in one aspect the method may include providing a nozzle including an inner rod, an outer tube concentrically aligned with the inner rod, an annular channel defined between the inner rod and the outer tube, the annular channel forming a circular slit at a spray end of the nozzle, and a plurality of notches located on at least one of the inner rod and the outer tube proximate the circular slit. The method further may include supplying a voltage to the plurality of notches, and pumping a spray liquid through the annular channel of the nozzle.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The embodiments described herein may be better understood by referring to the following description in conjunction with the accompanying drawings.

[0007] FIG. **1** is a schematic diagram of an exemplary electrospray system.

[0008] FIG. **2** is a cross-sectional view of an exemplary nozzle that may be used with the system of FIG. **1**.

[0009] FIGS. **3**A and **3**B are perspective views of exemplary nozzles that may be used with the system of FIG. **1**.

[0010] FIGS. **4**A and **4**B are plan views of the exemplary nozzles of FIGS. **3**B and **3**B.

[0011] FIGS. **5**A-**5**C are images of exemplary nozzles that may be used with the system of FIG. **1**.

[0012] FIGS. **6**A-**6**L are cross-sectional views of exemplary nozzles that may be used with the system of FIG. **1**.

[0013] FIG. **7** is a graph that illustrates the applied voltage for establishing stable multi-jet operation for nozzles of various numbers of notches.

[0014] FIGS. **8**A-**8**C are graphs illustrating spray current as a function of applied voltage for nozzles with six, twelve, and twenty notches.

[0015] FIG. **9** is a graph that illustrates maximum liquid flowrate as a function of electrical conductivity of a spray liquid.

[0016] FIG. **10** is a graph illustrating a ratio of maximum liquid flowrate of a liquid sheet nozzle to the maximum liquid flowrate of a single-capillary nozzle.

[0017] FIG. **11** is a plan view of an exemplary nozzle that may be used with the system of FIG. **1**.

[0018] FIG. **12** is a perspective view of the exemplary nozzle shown in FIG. **11**.

DETAILED DESCRIPTION

[0019] Embodiments provide electrohydrodynamic atomization using a liquid sheet to produce un-agglomerated, monodisperse droplets. In contrast to the capillaries/tubes used in known electrospray (ES) systems, nozzles with exit slit openings shape a spray liquid into a thin liquid sheet as the spray liquid exits from the slit opening. Stable multi-jet operation is achieved by including notches along the edge of the slit. The notches separate the liquid sheet into multiple jets to provide anchoring and stable multi-jet operation. That is, each notch anchors a corresponding jet by preventing the corresponding jet from migrating around the nozzle, substantially fixing the position of the corresponding jet. In some embodiments, the liquid sheet electrospray techniques and nozzles described herein provide high mass throughput and versatile multiplexing spray systems while reducing the engineering effort and high manufacturing cost.

[0020] A schematic diagram of an exemplary electrospray system **100** is shown in FIG. **1**. System **100** includes a syringe pump **102**, a nozzle **104**, and a high-voltage source **106**. In an exemplary embodiment, syringe pump **102** is a

Harvard Apparatus PHD2000 series pump. Alternatively, syringe pump **102** is any pump that enables system **100** to function as described herein.

[0021] High-voltage source **106** is coupled to nozzle **104** such that high-voltage source **106** enables a voltage to be applied to a spray end **108** of nozzle **104**. In an exemplary embodiment, high-voltage source **106** provides a voltage ranging from 13 kV to 16 kV to spray end **108**. Alternatively, high-voltage source may apply any voltage to nozzle **104** that enables system **100** to function as described herein.

[0022] System **100** also includes a monitoring system **110**. Monitoring system **110** includes a microscopic lens **112**, a digital camera **114**, a monitor **116**, and a computer **118**, which enable monitoring system **110** to monitor the spray produced by nozzle **104**.

[0023] System **100** also includes a current system **120**. Current system **120** includes a multimeter **122** electrically coupled to a ground **124** and electrically coupled to ring **126** across a resistor **128**. By measuring the voltage across resistor **128**, current system **120** can measure the current of the spray produced by nozzle **104**. Through multimeter **122**, ring **126** is also electrically coupled to ground **124**.

[0024] FIG. **2** is a cross-sectional view of an exemplary nozzle **200** that may be used with system **100**. Nozzle **200** includes a source end **202** and a spray end **204**. Nozzle **200** includes an inner rod **206** coaxially aligned with an outer tube **208** along a longitudinal axis **210** of nozzle **200**. An annular flow channel **212** is defined between an inner surface **214** of outer tube **208** and an outer surface **216** of inner rod **206**. At spray end **204**, annular flow channel **212** becomes a circular slit **218**. In an exemplary embodiment, an inner diameter **220** of circular slit **218** is 2,950 μm, and an outer diameter **222** of circular slit **218** is 3,250 μm, such that a width **224** of circular slit **218** is 150 μm. Alternatively circular slit **218** may have any dimensions that enable nozzle **200** to function as described herein.

[0025] In operation, syringe pump **102** applies a pressure to a spray liquid, such that the spray liquid is pushed towards nozzle **200** and received at source end **202** of nozzle **200**. The spray liquid is then evenly distributed into annular flow channel **212** and emitted from circular slit **218** as a thin liquid sheet. In the exemplary embodiment shown in FIG. **2**, the emitted liquid sheet is substantially cylindrical.

[0026] Nozzle **200** further includes one or more notches **230** proximate to circular slit **218**. As used herein, a "notch" refers to a protruding element that extends from a spray end of a nozzle, such as notches **230** extending from spray end **204** of nozzle **200**. For example, such notches may extend or protrude further in the direction of the spray jet than other regions of the spray end separating such notches. In an exemplary embodiment, notches **230** are located on both inner rod **206** and outer tube **208**. Alternatively, notches **230** may be located only on inner rod **206** or outer tube **208**. When high-voltage source **106** applies a voltage to spray end **204** of nozzle **200**, the shape and configuration of notches **230** facilitate local enhancement of an electric field at notches **230**. When the spray liquid reaches the circular slit **218**, it exits nozzle **200** as a thin liquid sheet due to the shape of annular flow channel **212**. With a sufficiently high voltage applied to spray end **204** of nozzle **200**, the thin liquid sheet is separated into multiple jets. Each jet is located at one of notches **230** due to the locally intensified electric field at each notch **230**. Further, with a high enough voltage applied to spray end **204**, stable multi-jet operation may be achieved. In some embodiments, "stable multi-jet operation" means that a jet of spray liquid is emitted from each notch **230** on nozzle **200**.

[0027] FIGS. **3**A and **3**B are perspective views of exemplary nozzles **200** that may be used with the system of FIG. **1**. FIGS. **4**A and **4**B are plan views of the nozzles **200** shown in FIGS. **3**A and **3**B. The embodiment shown in FIGS. **3**A and **4**A includes six notches **230**, and the embodiment shown in FIGS. **3**B and **4**B includes twenty notches **230**. Notches **230** are circumferentially spaced apart from one another by a circumferential distance, **240**. In some embodiments, circumferential distance **240** is no less than a size of a notch **230**. Circumferential distance **240** is chosen such that the number of notches **230** is maximized while maintaining regions of intensified electric field. That is, if circumferential distance **240** between notches **230** is too small, the electric field generated at one notch **230** will interfere with the electric field generated at an adjacent notch **230**. However, as the circumferential distance **240** between notches **230** increases, fewer notches **230** can be located on nozzle **200**. With fewer notches **230**, fewer jets are created, and the overall mass throughput of nozzle **200** is decreased.

[0028] FIGS. **5**A-**5**C are images of nozzles **200** producing multiple jets **250** of a spray liquid. The nozzles **200** in FIGS. **5**A, **5**B, and **5**C include six, twelve, and twenty notches **230**, respectively.

[0029] FIGS. **6**A-**6**L are cross-sectional views of exemplary nozzles **300** that may be used with the system of FIG. **1**. As demonstrated by the embodiments shown in FIGS. **6**A-**6**L, several different configurations of nozzle **300** enable nozzle **300** to function as described herein. Moreover, configurations of nozzle **300** are not limited to those specifically described herein.

[0030] Each nozzle **300** in FIGS. **6**A-**6**L includes a source end **302** and a spray end **304**. Further, each nozzle **300** includes an inner rod **306** coaxially aligned with an outer tube **308** along a longitudinal axis **310** of nozzle **300**. An annular flow channel **312** is defined between an inner surface **314** of outer tube **308** and an outer surface **316** of inner rod **306**. At spray end **304**, annular flow channel **312** becomes a circular slit **318**. Further, at spray end **304**, inner rod **306** includes a center piece **320**, and outer tube **308** includes an end portion **322**. Each nozzle **300** also includes a plurality of notches **330** which function substantially similar to notches **230** shown in FIG. **2**. The embodiments of FIGS. **6**A-**6**L are each discussed in detail below.

[0031] In the embodiment of nozzle **300** shown in FIG. **6**A, both inner rod **306** and outer tube **308** includes notches **330** thereon. Further, center piece **320** is not retracted or extended with respect to end portion **322**. During operation of the embodiment shown in FIG. **6**A, a spray liquid is emitted from circular slit **318**.

[0032] In the embodiment of nozzle **300** shown in FIG. **6**B, only outer tube **308** includes notches **330** thereon. That is, inner rod **306** does not include notches **330**. Further, center piece **320** is retracted with respect to end portion **322**. During operation of the embodiment shown in FIG. **6**B, the spray liquid is emitted from circular slit **318**.

[0033] The embodiment of nozzle **300** shown in FIG. **6**C is substantially similar to the embodiment shown in FIG. **6**A, except that the embodiment shown in FIG. **6**C includes a central flow channel **340** defined through inner rod **306**. Likewise, the embodiment of nozzle **300** shown in FIG. **6**D is substantially similar to the embodiment shown in FIG. **6**B,

except that the embodiment shown in FIG. **6**D includes central flow channel **340** defined through inner rod **306**. In the embodiments of FIGS. **6**C and **6**D, a stabilizing gas is emitted from central flow channel **340**. The emitted gas facilitates maintaining the thin liquid sheet shape of the spray liquid when the spray liquid is emitted from circular slit **318**.

[0034] The embodiments of nozzle **300** shown in FIGS. **6**E and **6**F are substantially similar to the embodiments shown in FIGS. **6**C and **6**D respectively, except that instead of a stabilizing gas, a stabilizing liquid is emitted from central flow channel **340**. Similar to the stabilizing gas, the stabilizing liquid facilitates maintaining the thin liquid sheet shape of the spray liquid when the spray liquid is emitted from circular slit **318**. The embodiment of nozzle **300** shown in FIG. **6**G is substantially similar to the embodiment shown in FIG. **6**F, except that center piece **320** is extended with respect to end portion **322**.

[0035] The embodiments of nozzle **300** shown in FIGS. **6**H and **6**I are substantially similar to the embodiments shown in FIGS. **6**C and **6**D respectively, except that the embodiments of FIGS. **6**H and **6**I further include a second outer tube **350**. Second outer tube **350** is concentrically aligned with outer tube **308** such that a second annular flow channel **352** is defined between an outer surface **354** of outer tube **308** and an inner surface **356** of second outer tube **350**. Second annular flow channel **352** becomes a second circular slit **360** at spray end **304**.

[0036] In the embodiments shown in FIGS. **6**H and **6**I, second outer tube **350** includes notches **330** thereon. In addition to the spray liquid emitted from first circular slit **318**, a sheath liquid is emitted from second circular slit **360** in a thin liquid sheet shape. With the spray liquid and the sheath liquid both emitted from nozzle **300**, particle encapsulation is facilitated, such that the particles produced by nozzle **300** include particles of spray liquid encapsulated by particles of sheath liquid and/or particles of sheath liquid encapsulated by particles of spray liquid. Similar to the embodiments shown in FIGS. **6**C and **6**D, a stabilizing gas emitted from central flow channel **340** facilitates maintaining the thin liquid sheet shape of the spray liquid and the sheath liquid. Alternatively, similar to FIGS. **6**E-**6**G, a stabilizing liquid may be emitted from central flow channel **340**. The embodiment shown in FIG. **6**J is substantially similar to the embodiment shown in FIG. **6**I, except that the center piece **320** is extended with respect to end portion **322**.

[0037] The embodiment of nozzle **300** shown in FIG. **6**K is substantially similar to the embodiment shown in FIG. **6**H, except that the embodiment of FIG. **6**K further includes a third outer tube **370**. Third outer tube **370** is concentrically aligned with second outer tube **350** such that a third annular flow channel **372** is defined between an outer surface **374** of second outer tube **350** and an inner surface **376** of third outer tube **370**. Third annular flow channel **372** becomes a third circular slit **380** at spray end **304**.

[0038] In the embodiment shown in FIG. **6**K, third outer tube **370** includes notches **330** thereon. In addition to the spray liquid emitted from first circular slit **318** and the sheath liquid emitted from second circular slit **360**, an outer liquid is emitted from third circular slit **380** in a thin liquid sheet shape. The emission of liquids from first circular slit **318**, second circular slit **360**, and third circular slit **380** facilitates particle encapsulation and the production of multi-layered particles. Similar to the embodiments shown in FIGS. **6**C and **6**D, a stabilizing gas emitted from central flow channel **340** facilitates maintaining the thin liquid sheet shape of the emitted liquids. Alternatively, similar to FIGS. **6**E-**6**G, a stabilizing liquid may be emitted from central flow channel **340**.

[0039] The embodiment shown in FIG. **6**L is substantially similar to the embodiment shown in FIG. **6**K, except that the circular slits **318**, **360**, and **380** are arranged in a stepped configuration, such that outer tube **308** is extended with respect to second outer tube **350**, and second outer tube **350** is extended with respect to third outer tube **370**. Due to the stepped configuration, less voltage may be applied to the embodiment shown in FIG. **6**L than the embodiment shown in FIG. **6**K to achieve stable multi-jet operation. In the embodiments shown in FIGS. **6**L and **6**K, the outer liquid emitted from third circular slit **380** may be the same liquid as at least one of the spray liquid emitted from first circular slit **318** and the sheath liquid emitted from second circular slit **360**. Alternatively, the spray liquid, the sheath liquid, and the outer liquid may all be different liquids. Furthermore, while in the embodiments shown in FIGS. **6**A-**6**L, certain flow channels are denoted as containing a gas or a liquid, alternatively, any suitable fluid (i.e., gas, liquid) may be provided in any flow channel that enables nozzle **300** to function as described herein.

[0040] Multiple experiments were executed utilizing the nozzles described herein. In the following examples, Isopropanol was selected as the spray liquid, and nitric acid was used as an ion additive to vary the electrical conductivity of the spray liquid from 0.0079 μS/cm (pure isopropanol) to 1,044 μS/cm. The electrical conductivity of the spray liquid was measured by a conductivity meter (Orion 162A, Thermo Electron Corporation), and the electrical resistance of pure isopropanol was measured by a lab-made liquid cell. Alternatively, those of ordinary skill in the art will understand that any spray liquid may be utilized which allows system **100** to function as described herein.

[0041] FIG. **7** is a graph that illustrates the applied voltage for establishing stable multi-jet operation for nozzles having various numbers of notches. The graph demonstrates that the applied voltage increases with the number of notches. It was also determined that the applied voltage for establishing stable multi-jet operation is also slightly proportional to the feed flowrate of the spray liquid.

[0042] In one example, to study the evolution in the formation of multiple jets, the spray current was measured, and the number of jets was counted as the applied voltage was continuously increased and then decreased. FIGS. **8**A-**8**C are graphs illustrating the spray current as a function of the applied voltage for nozzles with six, twelve, and twenty notches, respectively. The spray current and the number of jets increased with the increase of applied voltage. The stable multi-jet operation, in which the number of jets is the same as the number of notches, was achieved at a sufficiently high applied voltage. When the applied voltage was reduced, the number of jets correspondingly decreased. Further, as shown in the graphs, a hysteresis phenomenon was observed.

[0043] In another example, to determine the mass throughput of the nozzles, spray liquids with various electrical conductivities were used to find the maximum liquid flowrate (Q max) for nozzle operation. FIG. **9** is a graph that illustrates the maximum liquid flowrate as a function of the electrical conductivity of the spray liquid. The graph dem-

onstrates that the value of Q max significantly decreases as the electrical conductivity of the spraying liquid increases, due to the fact that spray liquids with higher electrical conductivity generally use a stronger electric field to establish stable multi-jet operation. The graph also demonstrates that Q max increases as the number of notches increases. This is because a greater number of notches allow more jets to be established, thus increasing the spray liquid flowrate and the overall mass throughput.

[0044] FIG. **10** is a graph illustrating a ratio of the maximum liquid flowrate of the liquid sheet nozzles described herein to the maximum liquid flowrate of a known single-capillary nozzle as a function of the electrical conductivity of the spray liquid. In this example, the diameter of the single-capillary nozzle and the width of the circular slit in the liquid sheet nozzle were both 150 μm. As illustrated in the graph of FIG. **10**, when using a spray liquid with an electrical conductivity of 0.0079 μS/cm, the maximum liquid flowrate, Q max, of the liquid sheet nozzle with 20 notches was one hundred and sixty-six times greater than the maximum liquid flowrate for the single-capillary nozzle. Further, when using a spray liquid with an electrical conductivity of 1,044 μS/cm μS/cm, the maximum liquid flowrate of the liquid sheet nozzle with twenty notches was seventy times greater than the maximum liquid flowrate for the single-capillary nozzle.

[0045] Notably, the value of Q max for a liquid sheet nozzle with twenty notches is much higher than the sum of the total liquid flowrates for twenty single-capillary nozzles. This same phenomenon was also observed using liquid sheet nozzles with six and twelve notches. This indicates that, as compared to existing one-dimensional and two-dimensional arrays of single-capillary nozzles, liquid sheet nozzles have potential to drastically increase the mass throughput for spray liquids having a wide range of electrical conductivity.

[0046] FIG. **11** is a plan view of an alternative nozzle **500** that may be used with system **100**. FIG. **12** is a perspective view of nozzle **500** shown in FIG. **11**. In an exemplary embodiment, nozzle **500** includes a first plate **502**, a second plate **504**, a source end **506**, and a spray end **508**. A planar flow channel **510** is defined between first plate **502** and second plate **504**. Planar flow channel **510** becomes a linear slit **512** at spray end **508**. In operation, a spray liquid is emitted from nozzle **500** from linear slit **512**. While the thin liquid sheet emitted from nozzle **200** is substantially cylindrical, the thin liquid sheet emitted from nozzle **500** is substantially planar.

[0047] In an exemplary embodiment, a plurality of notches **514** are located on both first plate **502** and second plate **504**, and staggered with respect to one another. Alternatively, notches **514** may only be located on one of first plate **502** and second plate **504**. With a voltage applied to notches **514**, notches **514** facilitate separating the thin liquid sheet into a plurality of jets, substantially similar to notches **230** of nozzle **200**.

[0048] The nozzles illustrated in FIGS. **1**-**6**L, **11**, and **12** constitute exemplary means for emitting a liquid sheet. Further, the notches illustrated in FIGS. **2**-**6**L, **11**, and **12** constitute exemplary means for separating a liquid sheet emitted by a nozzle into multiple jets. Moreover, nozzles illustrated in FIGS. **6**C-**6**L constitute exemplary means for maintaining a shape of a liquid sheet emitted from a nozzle.

[0049] In addition to the cylindrical and planar nozzles specifically described herein, those of ordinary skill in the art will understand that any nozzle shape and/or configuration may be utilized which allows system **100** to function as described herein.

[0050] Embodiments described herein enable electrohydrodynamic atomization, or electrospray (ES), using nozzles that produce a thin liquid sheet. The methods and systems described herein increase the mass throughput of ES systems while decreasing the design and manufacturing costs as compared to known ES systems utilizing multiple single-capillary nozzles. The nozzles described herein include annular and/or planar slits designed emit a thin liquid sheet of spray liquid. To separate the thin liquid sheet into multiple jets and to anchor the jets for stable operation, a plurality of notches are included at the annular and/or planar slits. That is, each notch anchors a corresponding jet by preventing the corresponding jet from migrating around the nozzle, substantially fixing the position of the corresponding jet. When a voltage is applied to the nozzles described herein, these notches enable local enhancement of an electric field. Further, stable multi-jet operation of the nozzles described herein can be established for a wide range of spray liquids having various electrical conductivities.

[0051] Moreover, as compared to known ES systems utilizing arrays of single-capillary nozzles, multiple liquid flow feeding and/or distribution channels are no longer necessary for the nozzles described herein. As such, the design concept and fabrication of the nozzles described herein is simpler than known nozzles, enabling flexibility in the design and/or geometry of the nozzles.

[0052] Through experimentation utilizing the nozzles described herein, it was demonstrated that the applied voltage for establishing stable multi-jet operation increased as both the number of jets and the liquid flowrate increased. Further, the maximum operational flowrate through the nozzles described herein was a function of the electrical conductivity of the spray liquid. Moreover, the maximum flowrate for liquid sheet nozzles with various numbers of notches was consistently greater than the total flowrate sum of an array of an equivalent number of single-capillary nozzles. Accordingly, the liquid sheet nozzles described herein enable superior ES techniques. Further, the liquid sheet shape of the spray liquid, as opposed to the cone jet emitted from known single-capillary nozzles, enables the nozzle design to have various geometries, including, but not limited to annular and/or planar slits.

[0053] The order of execution or performance of the operations in the embodiments of the disclosure illustrated and described herein is not essential, unless otherwise specified. That is, the operations may be performed in any order, unless otherwise specified, and embodiments of the disclosure may include additional or fewer operations than those disclosed herein. For example, it is contemplated that executing or performing a particular operation before, contemporaneously with, or after another operation is within the scope of aspects of the disclosure.

[0054] When introducing elements of aspects of the disclosure or embodiments thereof, the articles "a," "an," "the," and "said" are intended to mean that there are one or more of the elements. The terms "comprising," including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements.

[0055] This written description uses examples to disclose the disclosure, including the best mode, and also to enable any person skilled in the art to practice the disclosure,

including making and using any devices or systems and performing any incorporated methods. The patentable scope of the disclosure is defined by the claims, and may include other examples that occur to those skilled in the art. Such other examples are intended to be within the scope of the claims if they have structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal language of the claims.

What is claimed is:

1. A nozzle for electrohydrodynamic atomization, said nozzle comprising:

an inner rod;

an outer tube concentrically aligned with said inner rod;

an annular channel defined between said inner rod and said outer tube, said annular channel forming a circular slit at a spray end of said nozzle; and

at least one electrically chargeable notch located on at least one of said inner rod and said outer tube proximate said circular slit.

2. A nozzle in accordance with claim **1**, wherein said inner rod comprises a central flow channel defined therethrough.

3. A nozzle in accordance with claim **2**, wherein said central flow channel is configured to facilitate flow of at least one of a stabilizing gas and a stabilizing liquid therethrough.

4. A nozzle in accordance with claim **1** further comprising an outermost tube concentrically aligned with said inner rod and said outer tube such that an outer flow channel is defined between said outer tube and said outermost tube.

5. A nozzle in accordance with claim **4**, further comprising at least one electrically chargeable notch located on said outermost tube.

6. A nozzle in accordance with claim **1**, wherein said at least one electrically chargeable notch is located on only one of said inner rod and said outer tube.

7. A nozzle in accordance with claim **1**, wherein said inner rod comprises a center piece at the spray end of said nozzle and said outer tube comprises an end portion at the spray end of said nozzle, said center piece recessed with respect to said end portion.

8. A nozzle in accordance with claim **1**, wherein said inner rod comprises a center piece at the spray end of said nozzle and said outer tube comprises an end portion at the spray end of said nozzle, said center piece extended with respect to said end portion.

9. A nozzle in accordance with claim **1**, wherein said at least one electrically chargeable notch comprises a plurality of notches, said plurality of notches spaced a distance apart from one another such that when said plurality of notches are electrically charged, an electric field produced by one notch of said plurality of notches does not interfere with an electric field produced by an adjacent notch of said plurality of notches.

10. A system for electrohydrodynamic atomization, said system comprising:

a nozzle comprising:

a source end;

a spray end;

a first component comprising a first surface;

a second component comprising a second surface;

a fluid channel defined between said first surface and said second surface, said fluid channel forming an exit slit at said spray end of said nozzle; and

at least one electrically chargeable notch located on at least one of said first component and said second component proximate said exit slit;

a voltage source electrically coupled to said nozzle and configured to supply a voltage to said at least one electrically chargeable notch; and

a syringe pump in flow communication with said source end of said nozzle, said syringe pump configured to propel a spray liquid through said nozzle.

11. A system according to claim **10**, wherein said first component comprises a first plate and said second component comprises a second plate, such that said fluid channel is substantially planar.

12. A system according to claim **10**, further comprising a nozzle means for emitting a liquid sheet.

13. A system in accordance with claim **10**, further comprising notch means for separating a liquid sheet emitted from said nozzle into multiple jets.

14. A system in accordance with claim **10**, further comprising means for maintaining a shape of a liquid sheet emitted from said nozzle.

15. A system in accordance with claim **10**, wherein said at least one electrically chargeable notch comprises a first notch and a second notch, said first and second notches spaced a distance apart from one another such that when a voltage is supplied to said first and second notches, an electric field produced by said first notch does not interfere with an electric field produced by said second notch.

16. A method for electrohydrodynamic atomization, said method comprising:

providing a nozzle comprising an inner rod, an outer tube concentrically aligned with the inner rod, an annular channel defined between the inner rod and the outer tube, the annular channel forming a circular slit at a spray end of the nozzle, and a plurality of notches located on at least one of the inner rod and the outer tube proximate the circular slit;

supplying a voltage to the plurality of notches; and

pumping a spray liquid through the annular channel of the nozzle.

17. A method in accordance with claim **16**, wherein the inner rod includes a central flow channel defined therethrough, said method further comprising pumping a stabilizing gas through the central flow channel.

18. A method in accordance with claim **16**, wherein the inner rod includes a central flow channel defined therethrough, said method further comprising pumping a stabilizing liquid through the central flow channel.

19. A method in accordance with claim **16**, further comprising:

providing an outermost tube concentrically aligned with the inner rod and the outer tube, such that a outer flow channel is formed between the outer tube and the outermost tube; and

pumping a sheath liquid through the outer flow channel.

20. A method in accordance with claim **16**, wherein supplying a voltage comprises supplying a voltage such that a jet of spray liquid is formed at each of the plurality of notches.

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