

PLASMA REACTOR FOR PROCESSING GAS

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to plasma generators, and more particularly to devices for processing gas using microwave plasma.

2. Discussion of the Related Art

[0002] In recent years, microwave technology has been applied to generate various types of plasma. Typically, a microwave discharge, which is used as a plasma source, is achieved by coupling microwave energy into a discharge chamber containing gas to be processed. One of the difficulties in operating a conventional microwave plasma system includes sustaining plasma in a stable manner. Unstable plasma, as a result of suboptimal reactor geometry, gas inlet manifolds, chamber design, or gas flow rate, etc. may cause less than optimal condition for gas processing or reformation and may even cause the plasma to extinguish itself or damage the reactor.

[0003] As such, there is a need for microwave plasma system that has an improved plasma stability to thereby yield a higher efficiency reactor and throughput for better economics.

SUMMARY OF THE INVENTION

[0004] According to one aspect of the present invention, a plasma generating system that includes: a waveguide for transmitting a microwave energy therethrough; an inner wall disposed within the waveguide to define a plasma cavity, wherein a plasma is generated within the plasma cavity using the microwave energy; a first gas inlet mounted on a first side of the waveguide and configured to introduce a first gas into the plasma cavity and generate a first vortex flow within the plasma cavity using the first gas, the first gas inlet having a hole through which a gas processed by the plasma exits the plasma cavity; and a plasma stabilizer having a shape of a circular hollow cylinder and installed on a second side of the waveguide, an axial direction of the plasma stabilizer being in parallel to a rotational axis of the first vortex flow.

[0005] According to another aspect of the present invention, a plasma generating system includes: a waveguide for transmitting a microwave energy therethrough; an inner wall disposed within the waveguide to define a plasma cavity, wherein a plasma is generated within the plasma cavity using the microwave energy; a first gas inlet mounted on a first side of the waveguide and configured to introduce a first gas into the plasma cavity and generate a first vortex flow within the plasma cavity using the first gas, the first gas inlet having a hole through which a gas processed by the plasma exits the plasma cavity; and a plasma stabilizer having a shape of a circular hollow cylinder and installed on the first gas inlet, an axial direction of the plasma stabilizer being in parallel to a rotational axis of the first vortex flow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Figure 1 (“FIG. 1”) shows a schematic diagram of a plasma generating system according to embodiments of the present disclosure.

[0007] FIG. 2 shows a cross sectional view of a plasma chamber in FIG. 1, taken along the line 2-2, according to embodiments of the present disclosure.

[0008] FIG. 3 shows a perspective view of a forward flow inlet according to embodiments of the present disclosure.

[0009] FIG. 4 shows a cross sectional view of the forward flow inlet in FIG. 3, taken along the line 4-4, according to embodiments of the present disclosure.

[0010] FIG. 5 shows a perspective view of a reverse flow inlet according to embodiments of the present disclosure.

[0011] FIG. 6 shows a cross sectional view of the reverse flow inlet in FIG. 5, taken along the line 6-6, according to embodiments of the present disclosure.

[0012] FIG. 7 shows a perspective view of an inner vortex flow according to embodiments of the present disclosure.

[0013] FIG. 8 shows a perspective view of an outer vortex flow according to embodiments of the present disclosure.

[0014] FIG. 9 shows a cross sectional view of a plasma chamber according to embodiments of the present disclosure.

[0015] FIG. 10 shows a perspective view of an inner vortex flow according to embodiments of the present disclosure.

[0016] FIG. 11 shows a cross sectional view of a plasma chamber according to embodiments of the present disclosure.

[0017] FIG. 12 shows a perspective view of an outer vortex flow according to embodiments of the present disclosure.

[0018] FIG. 13 shows a cross sectional view of a plasma chamber according to embodiments of the present disclosure.

[0019] FIG. 14A shows a perspective view of a hollow cylinder according to embodiments of the present disclosure.

[0020] FIG. 14B shows a perspective view of a hollow cylinder according to embodiments of the present disclosure.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0021] In the following description, for purposes of explanation, specific details are set forth in order to provide an understanding of the disclosure. It will be apparent, however, to one skilled in the art that the disclosure can be practiced without these details. Furthermore, one skilled in the art will recognize that embodiments of the present disclosure, described below, may be implemented in a variety of ways.

[0022] Components, or modules, shown in diagrams are illustrative of exemplary embodiments of the disclosure and are meant to avoid obscuring the disclosure. It shall also be understood that throughout this discussion that components may be described as separate functional units, which may comprise sub-units, but those skilled in the art will recognize that various components, or portions thereof, may be divided into separate components or may be integrated together, including integrated within a single system or component. It should be noted that functions or operations discussed herein may be implemented as components.

[0023] Reference in the specification to “one embodiment,” “preferred embodiment,” “an embodiment,” or “embodiments” means that a particular feature, structure, characteristic, or function described in connection with the embodiment is included in at least one embodiment of the disclosure and may be in more than one embodiment. Also, the appearances of the

above-noted phrases in various places in the specification are not necessarily all referring to the same embodiment or embodiments.

[0024] The use of certain terms in various places in the specification is for illustration and should not be construed as limiting. The terms “include,” “including,” “comprise,” and “comprising” shall be understood to be open terms and any lists the follow are examples and not meant to be limited to the listed items.

[0025] Figure 1 (“FIG. 1”) shows a schematic diagram of a plasma generating system **10** according to embodiments of the present disclosure. As depicted, the plasma generating system **10** includes: a microwave cavity/waveguide **20** having a shape of a hollow tube; a plasma chamber **22** connected to the waveguide **20**; and a microwave supply unit **12** connected to the waveguide **20** and operative to provide microwave energy to the plasma chamber **22** via a microwave waveguide **20**. In embodiments, the plasma chamber **22** receives the microwave energy and processes gas by use of the received microwave energy. In embodiments, a gas tank **26** provides gas to the plasma chamber **22** via a gas line **24**, and a gas tank **30** provides gas to the plasma chamber **22** via a gas line **28**.

[0026] The microwave supply unit **12** provides microwave energy to the plasma chamber **22** and includes: a microwave generator **14** for generating microwaves; a power supply **16** for supplying power to the microwave generator **14**; and a tuner **18** for reducing the microwave energy reflected from the plasma chamber **22** and travelling toward the microwave generator **14**. In embodiments, the microwave supply unit **12** may include other components, such as an isolator having a dummy load for dissipating reflected microwave energy that propagates toward the microwave generator **14** and a circulator for directing the reflected microwave energy to the dummy load and a sliding short circuit disposed at the end of the waveguide **20**.

[0027] FIG. 2 shows a cross sectional view of a plasma chamber **22** in FIG. 1, taken along the line **2-2** (i.e. cut along a plane parallel to the paper), according to embodiments of the present disclosure. As depicted, the plasma chamber **22** includes: an inner wall(s) **40**; a plasma stabilizer **38**; a forward flow inlet **42** connected to the gas line **24** and configured to introduce the forward flow into the plasma chamber; and a reverse flow inlet **44** connected to the gas line **28** and configured to introduce the reverse flow into the plasma chamber. Here, the term plasma cavity refers to the enclosed space that is surrounded by the inner wall **40**, waveguide **20**, forward flow inlet **42** and reverse flow inlet **44**, where the reverse flow gas

and forward flows are processed/reformed in the plasma cavity by the microwave energy transmitted via the waveguide **20**.

[0028] In embodiments, the inner wall **40** is formed of a material that is transparent to the microwave energy, such as quartz or ceramic. In embodiments, the inner wall **40** is formed of any other suitable dielectric material that is desirable for uniform flow, thermal resistance, chemical resistance, and electromagnetic transparency. In embodiments, the inner wall **40** has preferably, but not limited to, a shape of hollow circular cylinder.

[0029] FIG. 3 shows a perspective view of the forward flow inlet **42** according to embodiments of the present disclosure. FIG. 4 shows a cross sectional view of the forward flow inlet **42**, taken along the line **4-4**, according to embodiments of the present disclosure. As depicted, the forward flow inlet **42** has a hole/adaptor **47** for coupling to the gas line **24** and one or more gas passageways **48** that are formed in the wall thereof. In embodiments, the exits of the gas passageways **48** are located inside the plasma stabilizer **38** so that the plasma stabilizer **38** forms an inner vortex flow **43** using the flow exiting the gas passageways **48**. In embodiments, the inner diameter of the plasma stabilizer **38** may be varied to adjust the outer diameter of the inner vortex flow **43**. In embodiments, as discussed above, the plasma stabilizer **38** may have a shape of hollow circular cylinder and disposed concentrically to the forward flow inlet **42**.

[0030] In embodiments, each gas passageway **48** is arranged to impart spiral motion to the forward flow as the forward flow enters the plasma cavity via the gas passageway **48**. In embodiments, each gas passageway **48** may be curved to enhance the vorticity of the forward flow. In embodiments, the forward flow inlet **42** is formed of any suitable material, such as ceramic, so that the inlet is electrically isolated from the waveguide **20** and withstand the heat energy from the plasma **46**.

[0031] In embodiments, the plasma stabilizer **38** is formed of material that is transparent to the microwave energy, and preferably formed of the same material as the inner wall **40**. In embodiments, the plasma stabilizer **38** is attached to the waveguide **20**, protruding into the plasma cavity, where the axial direction of the plasma stabilizer **38** is parallel to the y-axis. In embodiments, as discussed above, the inner wall **40** may have a shape of a hollow circular cylinder and the plasma stabilizer **38** may be installed concentrically to the inner wall **40**. In embodiments, the forward flow inside the plasma stabilizer **38** forms the inner vortex flow **43**.

and proceeds toward the other end of the waveguide **20**, more specifically toward the gas outlet **32**. FIG. 7 shows a perspective view of the inner vortex flow **43** according to embodiments of the present disclosure. As depicted, the forward flow (or equivalently, inner vortex flow) travels the length of the inner wall **40** in a helical motion until the inner vortex flow exits the gas outlet **32**.

[0032] In embodiments, upon ignition of a plasma plume (or shortly, plasma) **46** by a plasma igniter (not shown in FIG. 2), the plasma **46** is sustained by the microwave energy transmitted by the microwave generator **14**. In embodiments, the plasma **46** is located within the inner vortex flow **43** so that the gas particles of the inner vortex flow **43** pass through the plasma **46**. In embodiments, the plasma stabilizer **38** determines the outer diameter of the inner vortex flow **43**, preventing the forward flow from bypassing the plasma **46** before exiting the plasma cavity through the gas outlet **32**. In embodiments, the plasma stabilizer **38** aids in keeping the plasma **46** stable by separating the inner vortex flow **43** from the outer vortex flow **45**.

[0033] FIG. 5 shows a perspective view of the reverse flow inlet **44** according to embodiments of the present disclosure. FIG. 6 shows a cross sectional view of the reverse flow inlet **44**, taken along the line **6-6**, according to embodiments of the present disclosure. As depicted, the reverse flow inlet **44** has a hole/adaptor **52** for coupling to the gas line **28**, a hole to form the gas outlet **32**, and one or more gas passageways **51** that are formed in the wall thereof. In embodiments, each gas passageway **51** is arranged to impart spiral motion to the reverse flow as the reverse flow enters the plasma cavity via the gas passageway **51**. In embodiments, each gas passageway **51** may be curved to enhance the vorticity of the reverse flow. In embodiments, the reverse flow inlet **44** is formed of preferably, but not limited to Ni alloy, such as Inconel or Hastelloy.

[0034] In embodiments, the reverse flow exiting the reverse flow inlet **44** travels toward to the inner wall **40** and then proceeds upwardly (y-axis direction) toward the other end of the waveguide **20** along the inner wall **40** in a helical motion. Subsequently, the reverse flow reverses the flow direction to proceed downwardly and form an outer vortex flow **45**. In embodiments, the rotational axis of the outer vortex flow **45** is substantially parallel to the y-axis. FIG. 8 shows a perspective view of the outer vortex flow **45** according to embodiments of the present disclosure. As depicted, the outer vortex flow **45** has a hollow cylinder shape and has two flow regions: inner downward flow region **45-1** and an outer upward flow region

45-2. In embodiments, the inner vortex flow **43** is disposed in the middle hollow portion of the outer vortex flow **45** and surrounded by inner downward flow region **45-1**. It is noted that the gas from the forward flow inlet **42** is mixed with the flow from the reverse flow inlet **44** to form the inner vortex flow **43**.

[0035] In embodiments, the outer vortex flow **45** surrounds the inner vortex flow **43**, to thereby shield the inner wall **40** from the plasma **46**. In embodiments, the reverse flow exiting the reverse flow inlet **44** may have the ambient temperature and take heat energy from the inner wall **40** as the outer vortex flow **45** travels upwardly along the inner wall **40** in the helical motion.

[0036] In embodiments, as discussed above, the inner diameter of the plasma stabilizer **38** determines the radial dimension of the inner vortex flow **43**. As such, in embodiments, the inner diameter of the plasma stabilizer **38** may be adjusted so that the outer vortex flow **45** surrounds the inner vortex flow **43** and maintain the flow regime of the inner vortex flow **43** in a stable manner to thereby stabilize the plasma and yield improved throughput and efficiency.

[0037] In embodiments, the plasma **46** is used to reform the inlet gas to the desired product gas, where the inlet gas is introduced into the plasma cavity by the forward flow inlet **42** and reverse flow inlet **44**. In embodiments, the gas composition of the inner vortex flow exiting the forward flow inlet **42** includes CO₂, CH₄ and O₂, and the gas exiting the gas outlet **32** includes CO and H₂ as well as a non-reacted portion of forward flow gas. In embodiments, the preferred distribution for the forward flow is 5%-95% by mass of the total flow into the plasma chamber **22**. In embodiments, the reverse flow may have the same gas composition of the forward flow. In alternative embodiments, the forward flow may have different gas composition from the reverse flow. Also, the gas composition of the forward flow (and/or reverse flow) may be changed during operation. For instance, the forward flow may include a slug of argon to aid ignition of the plasma **46**. In embodiments, the gas compositions and flow rates of the forward and reverse flows may be adjusted to enhance the plasma stability and efficiency of the chemical reaction in the plasma chamber **22**.

[0038] FIG. 9 shows a cross sectional view of a plasma chamber **122** according to embodiments of the present disclosure. As depicted, the plasma chamber **122** is similar to the plasma chamber **22** in FIG. 2, with the difference that the plasma stabilizer **138** is disposed on

the reverse flow inlet **144**, protruding into the plasma cavity. In embodiments, the plasma stabilizer **138** is located inside the outer vortex flow **145**, and preferably separates the inner upward flow region (similar to **45-1**) of the outer vortex flow **143** from the outer downward flow region (similar to **45-2**) of the outer vortex flow **143**, i.e., the plasma stabilizer **138** is located at the boundary between the inner and outer flow regions of the outer vortex flow **143**.

[0039] As depicted, the components of the plasma chamber **122** include: inner wall **140**; waveguide **120**; forward flow inlet **142** and reverse flow inlet **144**, where these components have the similar structures and functions of their counterparts, respectively. Unlike in the plasma chamber **22**, the radial dimension of the forward flow is not controlled by the inner diameter of the plasma stabilizer **138**; instead, the radial dimension of the inner vortex flow **143** is determined by the flow rate of the forward flow exiting the forward flow inlet **142**. Thus, as shown in FIG. 10, the inner vortex flow **143** may have a substantially uniform radial dimension along the longitudinal direction (y-axis). In embodiments, the outer vortex flow **145** has the similar geometry as the outer vortex flow **45** in FIG. 8.

[0040] In embodiments, the plasma stabilizer **138** is located inside the outer vortex flow **145** and suppresses the fluctuation of the radial dimension of the inner upward flow region (similar to **45-1**) of the outer vortex flow **145** during operation, to thereby stabilize the overall flow regime of the inner vortex flow **143** and, in turn, stabilize the plasma **146**.

[0041] FIG. 11 shows a cross sectional view of a plasma chamber **222** according to embodiments of the present disclosure. FIG. 12 shows a perspective view of an outer vortex flow **245** according to embodiments of the present disclosure. As depicted, the plasma chamber **222** is similar to the plasma chamber **22** in FIG. 2, with the difference that the plasma chamber **222** does not include any forward flow inlet. As such, the plasma chamber **222** generates only the outer vortex flow **245** inside the plasma cavity, where the outer vortex flow **245** includes the inner downward flow region **245-1** and outer upward flow region **245-2**.

[0042] As depicted, a plasma **246** is sustained inside the outer vortex flow **245**, more specifically, the inner downward flow portion **245-1** of the outer vortex flow **245**. In embodiments, the plasma **246** processes/reforms the gas particles in the inner downward flow

portion **245-1** of the outer vortex flow **245** and the reformed gas exits the gas outlet formed in the reverse flow inlet **244**.

[0043] In embodiments, the height (i.e. the length along the y-axis) of the plasma stabilizer **238** affects the height of the outer vortex flow **245**. Whilst not being bound by theory, the plasma stabilizer **238** appears to suppress the fluctuation of the flow regime in the plasma cavity, to thereby stabilize the outer vortex flow **245** and the plasma **246** formed inside the outer vortex flow **245**.

[0044] FIG. 13 shows a cross sectional view of a plasma chamber **322** according to embodiments of the present disclosure. As depicted, the plasma chamber **322** is similar to the plasma chamber **122** in FIG. 9, with the difference that the plasma chamber **322** does not include any forward flow inlet. In embodiments, the plasma stabilizer **338** is located inside the outer vortex flow **345** that is similar to the outer vortex flow **245**, and preferably separates the inner upward flow region (similar to **245-1**) of the outer vortex flow **345** from the outer downward flow region (similar to **245-2**) of the outer vortex flow **345**, i.e., the plasma stabilizer **338** is located at the boundary between the inner and outer flow regions of the outer vortex flow **345**.

[0045] In embodiments, the plasma stabilizer **338** is located inside the outer vortex flow **345** and suppresses the fluctuation of the radial dimension of the inner upward flow region of the outer vortex flow **345** during operation, to thereby stabilize the overall flow regime of the outer vortex flow **345** and, in turn, stabilize the plasma **346**.

[0046] In embodiments, the vortical motion of the inner and outer vortex flows in FIGS. 1 – 13 enhances the stability of the flow regimes in the plasma cavities. In embodiments, one or more of the components in the plasma chambers in FIGS. 1 – 13 may be rifled or finned to further impart vortical motion to the vortex flows. For instance, the outer vortex flow **45** is in direct contact with the inner surface of the inner wall **40**, and as such, the inner surface of the inner wall **40** may be rifled or finned to impart helical motion to the outer vortex flow. In another example, the plasma stabilizer **38** is in direct contact with the inner vortex flow **43**, and as such, the inner surface of the plasma stabilizer **38** may be rifled or finned to impart helical motion to the inner vortex flow. FIG. 14A shows a perspective view of a hollow cylinder **400** according to embodiments of the present disclosure. As depicted the inner surface of the hollow cylinder **400** includes one or more groves (or fins) **402** to impart helical

motion to the gas as the gas flows along the inner surface of the cylinder. In embodiments, the cylinder **400** may be used as the plasma stabilizers and/or the inner walls in FIG. 1 – 13.

[0047] In embodiments, the plasma stabilizer (e.g. **338**) is located inside the outer vortex flow (e.g. **345**) and as such, both the inner and outer surfaces of the plasma stabilizer **338** may be rifled or finned to further impart helical motion to the outer vortex flow **345**. FIG. 14B shows a perspective view of a hollow cylinder **420** according to embodiments of the present disclosure. As depicted, both the inner and outer surfaces of the hollow cylinder **420** include one or more grooves (or fins) **422** to impart helical motion to the gas as the gas flows along the inner and/or outer surface of the cylinder. In embodiments, the cylinder **420** may be used as the plasma stabilizers and/or the inner walls in FIG. 1 – 13.

[0048] One skilled in the art will recognize no computing system or programming language is critical to the practice of the present disclosure. One skilled in the art will also recognize that a number of the elements described above may be physically and/or functionally separated into sub-modules or combined together.

[0049] It will be appreciated to those skilled in the art that the preceding examples and embodiments are exemplary and not limiting to the scope of the present disclosure. It is intended that all permutations, enhancements, equivalents, combinations, and improvements thereto that are apparent to those skilled in the art upon a reading of the specification and a study of the drawings are included within the true spirit and scope of the present disclosure. It shall also be noted that elements of any claims may be arranged differently including having multiple dependencies, configurations, and combinations.

What is claimed is:

1. A plasma generating system, comprising:

a waveguide for transmitting a microwave energy therethrough;

an inner wall disposed within the waveguide to define a plasma cavity, a plasma being generated within the plasma cavity using the microwave energy;

a first gas inlet mounted on a first side of the waveguide and configured to introduce a first gas into the plasma cavity and generate a first vortex flow within the plasma cavity using the first gas, the first gas inlet having a hole through which a gas processed by the plasma exits the plasma cavity; and

a plasma stabilizer having a shape of a circular hollow cylinder and installed on a second side of the waveguide and protruding into the plasma cavity, a longitudinal direction of the plasma stabilizer being parallel to a rotational axis of the first vortex flow.

2. The plasma generating system as recited in claim 1, wherein the inner wall is formed of a material that is transparent to the microwave energy.

3. The plasma generating system as recited in claim 1, wherein the first vortex flow has an outer region that proceeds toward the second side of the waveguide in a helical motion and an inner region that proceeds toward the first side of the waveguide in a helical motion and wherein the plasma is generated in the inner region of the first vortex flow.

4. The plasma generating system as recited in claim 1, wherein the first gas inlet has one or more passageways through which the first gas is introduced into the plasma cavity and each of the one or more passageways is arranged to impart a vortical motion to the first gas that passes therethrough.

5. The plasma generating system as recited in claim 1, further comprising:

a second gas inlet mounted on the second side of the waveguide and configured to introduce a second gas toward the plasma stabilizer,

wherein the second gas inlet is configured to generate a second vortex flow within the plasma cavity using the second gas.

6. The plasma generating system as recited in claim 5, wherein the second vortex flow is located inside the first vortex flow and the plasma is generated in the second vortex flow.
7. The plasma generating system as recited in claim 5, wherein the second gas inlet includes one or more passageways through which the second gas flows and each of the one or more passageways is arranged to impart a vortical motion to the second gas that passes therethrough.
8. The plasma generating system as recited in claim 5, wherein a flow rate of the second gas ranges 5 - 95 % by mass of a total flow rate of gas flowing into the plasma cavity.
9. The plasma generating system as recited in claim 1, wherein at least one of the inner wall and the plasma stabilizer has a surface that is rifled to impart helical motion to a gas that is in contact with the surface.