

CONTROLLING EXHAUST GAS PRESSURE OF A PLASMA REACTOR FOR PLASMA STABILITY

BACKGROUND OF THE INVENTION

1. Field of the Invention

- 5 [0001] The present invention relates to plasma generators, and more particularly to devices for stabilizing plasma in plasma reactors.

2. Discussion of the Related Art

- [0002] In recent years, microwave technology has been applied to generate various types of plasma. A conventional plasma generating system for processing/reforming gas employs multiple plasma reactors to increase the throughput of the overall system, and the gas output from each independent plasma reactor is piped or connected to a common manifold or heat exchanger. Such a conventional plasma generating system often employs a multitude of fittings, such as joints, valves, fittings as well as bends in the piping to aid in the assembly and servicing of the plasma reactors to the manifold.

- 15 [0003] Typically, this geometry, and the resulting volume in the fittings, piping and manifold, are not optimized and may generate standing waves in the reactor product gas. The standing waves may result in pressure variations in the plasma reactor chamber and cause plasma instability, where this instability may cause the plasma to extinguish itself or create less than optimal conditions for gas processing or reformation. Furthermore, there may be a crosstalk issue where a disturbance in one plasma reactor (i.e. flameout) propagates to adjacent plasma reactors in the same circuit.

- 20 [0004] As such, there is a need for microwave plasma systems that have a mechanism to control/prevent the standing waves and/or crosstalk, to thereby stabilize the plasma in the plasma reactors.

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SUMMARY OF THE INVENTION

- [0005] According to one aspect of the present invention, a plasma generating system that includes: a waveguide for transmitting a microwave energy therethrough; a plasma chamber coupled to the waveguide and configured to generate a plasma therein using the microwave

energy; a flow inlet for introducing a gas into the plasma chamber; an exhaust gas pipe for carrying an exhaust gas from the plasma chamber, wherein the plasma converts the gas into the exhaust gas; and a pressure control device installed in the exhaust gas pipe and configured to control a pressure of the exhaust gas in the exhaust gas pipe.

- 5 [0006] According to another aspect of the present invention, a plasma generating system includes: a plurality of plasma reactors, each of the plurality of plasma reactors including: a waveguide for transmitting a microwave energy therethrough; a plasma chamber coupled to the waveguide and configured to generate a plasma therein using the microwave energy; a flow inlet for introducing a gas into the plasma chamber; an exhaust gas pipe for carrying an exhaust gas from the plasma chamber, wherein the plasma converts the gas into the exhaust gas; and a pressure control device installed in the exhaust gas pipe and configured to control a pressure of the exhaust gas in the exhaust gas pipe; and a manifold coupled to the exhaust gas pipes of the plurality of plasma reactors and configured to receive the exhaust gas from the exhaust gas pipes.
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BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 (“FIG. 1”) shows a schematic diagram of a plasma generating system having multiple plasma reactors according to embodiments of the present disclosure.

- 20 [0008] FIG. 2 shows a schematic diagram of a plasma reactor in FIG. 1 according to embodiments of the present disclosure.

[0009] FIG. 3 shows a cross sectional view of the plasma chamber in FIG. 2, taken along the line 3-3, according to embodiments of the present disclosure.

[0010] FIG. 4 shows a perspective view of a forward flow inlet according to embodiments of the present disclosure.

- 25 [0011] FIG. 5 shows a cross sectional view of the forward flow inlet in FIG. 4, taken along the line 5-5, according to embodiments of the present disclosure.

[0012] FIG. 6 shows a perspective view of a reverse flow inlet according to embodiments of the present disclosure.

- 30 [0013] FIG. 7 shows a cross sectional view of the reverse flow inlet in FIG. 6, taken along the line 7-7, according to embodiments of the present disclosure.

[0014] FIG. 8 shows a perspective view of an inner vortex flow according to embodiments of the present disclosure.

[0015] FIG. 9 shows a perspective view of an outer vortex flow according to embodiments of the present disclosure.

5 [0016] FIG. 10A shows a perspective view of a pressure control device according to embodiments of the present disclosure.

[0017] FIG. 10B shows a perspective view of a pressure control device according to embodiments of the present disclosure.

10 [0018] FIG. 10C shows a perspective view of a pressure control device according to embodiments of the present disclosure.

[0019] FIG. 10D shows a perspective view of a pressure control device according to embodiments of the present disclosure.

[0020] FIG. 10E shows a perspective view of a pressure control device according to embodiments of the present disclosure.

15 [0021] FIG. 10F shows a perspective view of a pressure control device according to embodiments of the present disclosure.

[0022] FIG. 10G shows a front view of the pressure control device in FIG. 10F according to embodiments of the present disclosure.

20 [0023] FIG. 11 shows a schematic diagram of a plasma reactor according to embodiments of the present disclosure.

[0024] FIG. 12 shows a schematic diagram of a plasma reactor according to embodiments of the present disclosure.

[0025] FIG. 13 shows a cross sectional view of a plasma chamber according to embodiments of the present disclosure.

25 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0026] 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.

[0027] 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.

[0028] 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.

[0029] 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.

[0030] Figure 1 (“FIG. 1”) shows a schematic diagram of a plasma generating system **100** according to embodiments of the present disclosure. As depicted, the plasma generating system **100** may include: one or more plasma reactors **101a – 101n**; and a manifold **127** for receiving product gas (or equivalently exhaust gas) from the plasma reactors. More specifically, the plasma generating system **100** may include: microwave supply units **112a – 112n** for generating microwave energy and providing the microwave energy to the plasma chambers **122a – 122n**, respectively; first input gas lines **124a – 124n**; second input gas lines **128a – 128n**; exhaust gas pipes **125a – 125n**; and the manifold **127** coupled to and in fluid communication with the exhaust gas pipes. In embodiments, each exhaust gas pipe (i.e., **125a**) may carry the exhaust gas from each plasma chamber (e.g. **122a**) to the manifold **127**.

[0031] FIG. 2 shows a schematic diagram of the plasma reactor **101a** according to embodiments of the present disclosure. As depicted, the plasma reactor **101a** may include: a

microwave cavity/waveguide **120** having a shape of a hollow tube; a plasma chamber **122a** connected to the waveguide **120**; and a microwave supply unit **112a** connected to the waveguide **120** and operative to provide microwave energy to the plasma chamber **122a** via the microwave waveguide **120**. In embodiments, the plasma chamber **122a** receives the microwave energy and processes the input gas by use of the received microwave energy. The input gas is introduced to the plasma chamber **122a** by one or both of forward flow inlet **142** and reverse flow inlet **144**. In embodiments, a gas tank **126** provides gas to the plasma chamber **122a** via the gas line **124a**, and a gas tank **130** provides gas to the plasma chamber **122a** via the gas line **128a**.

10 [0032] In embodiments, the microwave supply unit **112a** provides microwave energy to the plasma chamber **122a** and includes: a microwave generator **114** for generating microwaves; a power supply **116** for supplying power to the microwave generator **114**; and a tuner **118** for reducing the microwave energy reflected from the plasma chamber **122a** and travelling toward the microwave generator **114**. In embodiments, the microwave supply unit
15 **112a** may include other components, such as an isolator having a dummy load for dissipating reflected microwave energy that propagates toward the microwave generator **114** 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 **120**.

[0033] FIG. 3 shows a cross sectional view of a plasma chamber **122a** in FIG. 2, taken
20 along the line **3-3**, according to embodiments of the present disclosure. As depicted, the plasma chamber **122a** includes: an inner wall(s) **140**; a plasma stabilizer **138**; a forward flow inlet **142** connected to the gas line **124a** and configured to introduce the forward flow into the plasma chamber; and a reverse flow inlet **144** connected to the gas line **128a** and configured to introduce the reverse flow into the plasma chamber. Here, the term plasma cavity refers to
25 the enclosed space that is surrounded by the inner wall **140**, waveguide **120**, forward flow inlet **122** and reverse flow inlet **144**, where the reverse flow gas and forward flows are processed/reformed in the plasma cavity by the plasma **146** and the plasma **146** is sustained by the microwave energy transmitted via the waveguide **120**.

[0034] In embodiments, the inner wall **140** is formed of a material that is transparent to the microwave energy, such as quartz or ceramic. In embodiments, the inner wall **140** is formed
30 of any other suitable dielectric material that is desirable for uniform flow, thermal resistance,

chemical resistance, and electromagnetic transparency. In embodiments, the inner wall **140** has preferably, but not limited to, a shape of hollow circular cylinder.

[0035] FIG. 4 shows a perspective view of the forward flow inlet **142** according to embodiments of the present disclosure. FIG. 5 shows a cross sectional view of the forward flow inlet **142**, taken along the line **5-5**, according to embodiments of the present disclosure. As depicted, the forward flow inlet **142** has a hole/adaptor **147** for coupling to the gas line **124** and one or more gas passageways **148** that are formed in the wall thereof. In embodiments, the exits of the gas passageways **148** are located inside the plasma stabilizer **138** so that the plasma stabilizer **138** forms an inner vortex flow **143** using the flow exiting the gas passageways **148**. In embodiments, the inner diameter of the plasma stabilizer **138** may be varied to adjust the outer diameter of the inner vortex flow **143**. In embodiments, as discussed above, the plasma stabilizer **138** may have a shape of hollow circular cylinder and disposed concentrically to the forward flow inlet **142**.

[0036] In embodiments, each gas passageway **148** is arranged to impart spiral motion to the forward flow as the forward flow enters the plasma cavity via the gas passageway **148**. In embodiments, each gas passageway **148** may be curved to enhance the vorticity of the forward flow.

[0037] In embodiments, the plasma stabilizer **138** is formed of material that is transparent to the microwave energy, and preferably formed of the same material as the inner wall **140**. In embodiments, the plasma stabilizer **138** is attached to the waveguide **120**, protruding into the plasma cavity, where the axial direction of the plasma stabilizer **138** is parallel to the y-axis. In embodiments, as discussed above, the inner wall **140** may have a shape of a hollow circular cylinder and the plasma stabilizer **138** may be installed concentrically to the inner wall **140**. In embodiments, the forward flow inside the plasma stabilizer **138** forms the inner vortex flow **143** and proceeds toward the other end of the waveguide **120**, more specifically toward the gas outlet **132**. FIG. 8 shows a perspective view of the inner vortex flow **143** according to embodiments of the present disclosure. As depicted, the forward flow (or equivalently, inner vortex flow) travels the length of the inner wall **140** in a helical motion until the inner vortex flow exits the gas outlet **132**.

[0038] In embodiments, upon ignition of a plasma plume (or shortly, plasma) **146** by a plasma igniter (not shown in FIG. 3), the plasma **146** is sustained by the microwave energy

transmitted by the microwave generator **114**. In embodiments, the plasma **146** is located within the inner vortex flow **143** so that the gas particles of the inner vortex flow **143** pass through the plasma **146**. In embodiments, the plasma stabilizer **138** determines the outer diameter of the inner vortex flow **143**, preventing the forward flow from bypassing the plasma **146** before exiting the plasma cavity through the gas outlet **132**. In embodiments, the plasma stabilizer **138** aids in keeping the plasma **146** stable by separating the inner vortex flow **143** from the outer vortex flow **145**.

[0039] FIG. 6 shows a perspective view of the reverse flow inlet **144** according to embodiments of the present disclosure. FIG. 7 shows a cross sectional view of the reverse flow inlet **144**, taken along the line 7-7, according to embodiments of the present disclosure. As depicted, the reverse flow inlet **144** has a hole/adaptor **152** for coupling to the gas line **128a**, a hole to form the gas outlet **132**, and one or more gas passageways **151** that are formed in the wall thereof. In embodiments, each gas passageway **151** is arranged to impart spiral motion to the reverse flow as the reverse flow enters the plasma cavity via the gas passageway **151**. In embodiments, each gas passageway **151** may be curved to enhance the vorticity of the reverse flow.

[0040] In embodiments, the reverse flow exiting the reverse flow inlet **144** travels toward to the inner wall **140** and then proceeds upwardly (y-axis direction) toward the other end of the waveguide **120** along the inner wall **140** in a helical motion. Subsequently, the reverse flow reverses the flow direction to proceed downwardly and form an outer vortex flow **145**. In embodiments, the rotational axis of the outer vortex flow **145** is substantially parallel to the y-axis. FIG. 9 shows a perspective view of the outer vortex flow **145** according to embodiments of the present disclosure. As depicted, the outer vortex flow **145** has a hollow cylinder shape and has two flow regions: inner downward flow region **145-1** and an outer upward flow region **145-2**. In embodiments, the inner vortex flow **143** is disposed in the middle hollow portion of the outer vortex flow **145** and surrounded by inner downward flow region **145-1**.

[0041] In embodiments, the outer vortex flow **145** surrounds the inner vortex flow **143**, to thereby shield the inner wall **140** from the plasma **146**. In embodiments, the reverse flow exiting the reverse flow inlet **144** may have the ambient temperature and take heat energy from the inner wall **140** as the outer vortex flow **145** travels upwardly along the inner wall **140** in the helical motion.

[0042] In embodiments, as discussed above, the inner diameter of the plasma stabilizer **138** determines the radial dimension of the inner vortex flow **143**. As such, in embodiments, the inner diameter of the plasma stabilizer **138** may be adjusted so that the outer vortex flow **145** surrounds the inner vortex flow **143** and maintain the flow regime of the inner vortex flow **143** in a stable manner to thereby stabilize the plasma and yield improved throughput and efficiency

[0043] In embodiments, the plasma **146** is used to reform the inlet gas to the desired product gas, where the inlet gas is introduced into the plasma cavity by one or both the forward flow inlet **142** and the reverse flow inlet **144**. In embodiments, the gas composition of the inner vortex flow exiting the forward flow inlet **142** includes CO₂, CH₄ and O₂, and the gas exiting the gas outlet **132** includes CO and H₂ as well as a non-reacted portion of forward flow gas. In embodiments, the distribution for the forward flow is 0%-100% by mass of the total flow into the plasma chamber **122a**. 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. 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 **122a**.

[0044] As depicted in FIG. 3, a pressure control device **300** may be installed within the exhaust gas pipe **125a** to adjust the pressure of exhaust gas exiting from the plasma chamber **122a**, creating a back-pressure within the plasma chamber. In embodiments, the pressure control device **300** may limit/change the cross sectional area of the exhaust gas pipe **125a** (i.e., the pressure control device **300** may provide the flow impedance) to dampen the pressure wave propagating through the exhaust gas pipe. FIG. 10A shows a perspective view of a pressure control device **1000** according to embodiments of the present disclosure. In embodiments, the pressure control device **1000** may be used as the pressure control device **300** in FIG. 3. In the present disclosure, for the purpose of illustration, it is assumed that the cross sectional shape of the exhaust gas pipe (e.g. **125a**) is a circle, while the exhaust gas pipe may have other suitable cross sectional shapes, such as oval or rectangle.

[0045] As depicted in FIG. 10A, the pressure control device **1000** may have a shape of a flat disk, where an orifice (or equivalently hole) **1002** is formed therein. The dimension of the orifice **1002** may be changed to vary the obstruction geometry, to thereby control the amount of back-pressure in the plasma chamber and to optimize the stability of the plasma

146. In embodiments, a wave, such as standing wave, may be formed in the exhaust gas pipe **125a** and/or the manifold **127**, where the wave may be associated with the time-varying pressure fluctuations. In embodiments, the pressure control device **1000** may control/modulate the time-varying pressure fluctuations in the exhaust gas pipe **125a**, to
5 thereby optimize the stability of the plasma **146**.

[0046] If the pressure control device **1000** is not used, a pressure disturbance in one plasma chamber (e.g. **122a**) may propagate to another plasma chamber (e.g. **122b**) through the exhaust gas pipe **125a**, manifold **127**, and exhaust gas pipe **125b**, i.e., a crosstalk may occur between two or more plasma chambers. In embodiments, the pressure control device
10 **1000** may also suppress the crosstalk, to enhance the plasma stability.

[0047] It should be apparent to those of ordinary skill in the art that the pressure control device **1000** may include more than one orifice to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure fluctuations/disturbances through the exhaust gas pipe **125a**.

[0048] In embodiments, the pressure control device **300** may have other suitable shapes, as shown in FIGS. 10B – 10G. FIG. 10B shows a pressure control device **1010** according to embodiments of the present disclosure. As depicted in FIG. 10B, the pressure control device **1010** may be a sphere that has one or more holes **1012**. In embodiments, the diameter of the pressure control device **1010** may be the same as the inner diameter of the exhaust gas pipe
20 **125a**. In embodiments, the size and number of holes **1012** may be changed to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure fluctuations/disturbances.

[0049] FIG. 10C shows a pressure control device **1020** according to embodiments of the present disclosure. As depicted in FIG. 10C, the pressure control device **1020** may be formed
25 of a mesh fabric **1022**, where the mesh fabric may be formed of suitable material, such as metallic, non-metallic, or both. In embodiments, the strands of the mesh fabric **1022** may be entangled or have a grid-like structure, and the size of the strands and spacing between the strands may be changed to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure
30 fluctuations/disturbances through the exhaust gas pipe **125a**.

[0050] FIG. 10D shows a pressure control device **1030** according to embodiments of the present disclosure. As depicted in FIG. 10D, the pressure control device **1030** may be a flat disk having one or more edge cutouts/grooves **1032** may be formed along the side surface of the disk. As in the pressure control device **1000**, the size and number of the edge cutouts
5 **1032** may be changed to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure fluctuations/disturbances through the exhaust gas pipe **125a**.

[0051] FIG. 10E shows a pressure control device **1040** according to embodiments of the present disclosure. As depicted in FIG. 10E, the pressure control device **1040** may be a tube,
10 where the cross sectional dimension of the tube may vary along the axial direction thereof. In embodiments, the outer diameter D2 of the tube at its both ends may be the same as the inner diameter of the exhaust gas pipe **125a**. In embodiments, the minimum inner diameter D1 of the tube **1040** may be changed to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure
15 fluctuations/disturbances through the exhaust gas pipe **125a**.

[0052] FIG. 10F shows a pressure control device **1050** according to embodiments of the present disclosure. As depicted, the pressure control device **1050** may include a series of baffles **1052** that are secured to the inner surface of the exhaust gas pipe **125a**. FIG. 10G shows a front view of the baffle **1052** according to embodiments of the present disclosure. In
20 embodiments, the number and shape of the baffles **1052** may be changed to optimize the pressure in the exhaust gas pipe **125a** and the back-pressure in the plasma chamber **122a** while suppressing the propagation of pressure fluctuations/disturbances through the exhaust gas pipe **125a**.

[0053] FIG. 11 shows a schematic diagram of a plasma reactor **1100** according to
25 embodiments of the present disclosure. As depicted, the plasma reactor **1100** may be similar to the plasma reactor **101a**, with the difference that a feedback control unit **1103** may be used to control the pressure in the exhaust gas pipe **1125**. In embodiments, the feedback control unit **1103** may include: a sensor **1106**, such as a pressure transducer, for measuring the gas pressure in the exhaust gas pipe **1125**; a valve **1108**, such as variable orifice valve, for
30 controlling the gas pressure in the exhaust gas pipe **1125**; and a control unit **1110** coupled to and configured to control the sensor **1106** and the valve **1108**. In embodiments, the control unit **1110**, which may be a computing device, may receive the signal from the sensor **1106**

and, in response to the signal, control the valve **1108** to adjust the pressure through the exhaust gas pipe **1125**, to thereby optimize the pressure in the exhaust gas pipe **1125** and the back-pressure in the plasma chamber **1122** while suppressing the propagation of pressure fluctuations/disturbances through the exhaust gas pipe **1125**.

5 **[0054]** In embodiments, each of the plasma reactors **101a – 101n** may have the feedback control unit **1103**. In alternative embodiments, each of the plasma reactors **101a – 101n** may have the sensor **1106** and the valve **1108**, while the sensors and valves of the plasma reactors are controlled by one control unit **1110**, i.e., the exhaust gas pressures are controlled by one centralized control unit.

10 **[0055]** FIG. 12 shows a schematic diagram of a plasma reactor **1200** according to embodiments of the present disclosure. As depicted, the plasma reactor **1200** may be similar to the plasma reactor **101a**, with the difference that a container **1206** may be attached to and in fluid communication with an exhaust gas pipe **1202**, where container **1206** may be used to disrupt or shift the frequency of standing wave in the exhaust gas pipe **1202**, to thereby
15 improve plasma stability and/or attenuate crosstalk between plasma reactors through the manifold **1227**.

[0056] It is noted that the plasma chamber **122a** in FIG. 3 may have different components and arrangement of the components. For instance, the plasma chamber may not include the forward flow inlet **142**. In another example, the plasma stabilizer **138** may be mounted on the
20 reverse flow inlet **144**. The description of various embodiments of the plasma chamber **122a** can be found in a copending U.S. Patent Application Ser. No. 16/752,689, entitled “Plasma reactor for processing gas,” filed on January 26, 2020, which is hereby incorporated by reference in its entirety.

[0057] In embodiments, the plasma chamber **122a** in FIG. 3 may not include the reverse
25 flow inlet **144**. FIG. 13 shows a cross sectional view of a plasma chamber **400** according to embodiments of the present disclosure. In embodiments, the plasma chamber **400** may be used for the plasma reactors in FIG. 1. As depicted, the plasma chamber **400** includes the forward flow inlet **442** that has the similar structures and functions as the forward flow inlet **142** in FIG. 3, but the plasma chamber **400** does not include a reverse flow inlet. In
30 embodiments, the plasma stabilizer **438** is an optional components. In embodiments, the gas processed by the plasma **446** exits through the gas outlet **432**, and the pressure control device

500 installed in the exhaust gas pipe **445** has the similar structures and functions as the pressure control device **300**.

[0058] As discussed above, each of the plasma reactors **101a** – **101n** in FIG. 1 may use the pressure control devices in FIGS. 10A – 10G. Also, the feedback control unit **1103** in FIG. 11 and the chamber **1206** in FIG. 12 may be used to improve plasma stability and attenuate crosstalk between plasma reactors through the manifold **127**. Thus, it should be apparent to those of ordinary skill in the art that each of the plasma reactors in FIG. 1 may use one or more of the pressure control devices in FIGS. 10A – 10G, the feedback control unit **1103** in FIG. 11 and the chamber **1206** in FIG. 12. Similarly, it should be apparent to those of ordinary skill in the art that each of the plasma chamber in FIG. 13 may use one or more of the pressure control devices in FIGS. 10A – 10G, the feedback control unit **1103** in FIG. 11 and the chamber **1206** in FIG. 12.

[0059] 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;
a plasma chamber coupled to the waveguide and configured to generate a plasma
5 therein using the microwave energy;
a flow inlet for introducing an input gas into the plasma chamber;
an exhaust gas pipe for carrying an exhaust gas from the plasma chamber, wherein the
plasma converts the input gas into the exhaust gas; and
a pressure control device installed in the exhaust gas pipe and configured to control a
10 pressure of the exhaust gas in the exhaust gas pipe.
2. A plasma generating system as recited in claim 1, wherein the pressure control
device is a disk having at least one orifice formed therein.
- 15 3. A plasma generating system as recited in claim 1, wherein the pressure control
device is a sphere having at least one hole through which the exhaust gas passes.
4. A plasma generating system as recited in claim 1, wherein the pressure control
device includes a mesh fabric.
- 20 5. A plasma generating system as recited in claim 1, wherein the pressure control
device is a disk having one or more edge cutouts.
6. A plasma generating system as recited in claim 1, wherein the pressure control
25 device is a tube and a diameter of the tube varies along a downstream direction of the tube.
7. A plasma generating system as recited in claim 1, wherein the pressure control
device includes a feedback control unit and comprises:
a sensor for measuring a pressure of the exhaust gas in the exhaust gas pipe;
30 a valve for adjusting the pressure of the exhaust gas in the exhaust gas pipe;
and
a control unit for receiving a signal associated with the pressure and

controlling the valve in response to the signal.

8. A plasma generating system, comprising:

a waveguide for transmitting a microwave energy therethrough;

5 a plasma chamber coupled to the waveguide and configured to generate a plasma therein using the microwave energy;

a flow inlet for introducing an input gas into the plasma chamber;

an exhaust gas pipe for carrying an exhaust gas from the plasma chamber, wherein the plasma converts the input gas into the exhaust gas; and

10 a container attached to a side surface of the exhaust gas pipe and in fluid communication with the exhaust gas pipe.

9. A plasma generating system, comprising:

a plurality of plasma reactors, each of the plurality of plasma reactors including:

15 a waveguide for transmitting a microwave energy therethrough;

a plasma chamber coupled to the waveguide and configured to generate a plasma therein using the microwave energy;

a flow inlet for introducing a gas into the plasma chamber;

an exhaust gas pipe for carrying an exhaust gas from the plasma chamber,

20 wherein the plasma converts the gas into the exhaust gas; and

a pressure control device installed in the exhaust gas pipe and configured to control a pressure of the exhaust gas in the exhaust gas pipe; and

a manifold coupled to the exhaust gas pipes of the plurality of plasma reactors and configured to receive the exhaust gas from the exhaust gas pipes.

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10. A plasma generating system as recited in claim 9, wherein the pressure control device is a disk having at least one orifice formed therein.

11. A plasma generating system as recited in claim 9, wherein the pressure control

30 device is a sphere having at least one hole through which the exhaust gas passes.

12. A plasma generating system as recited in claim 9, wherein the pressure control device includes a mesh fabric.

13. A plasma generating system as recited in claim 9, wherein the pressure control device is a disk having one or more edge cutouts.

5 14. A plasma generating system as recited in claim 9, wherein the pressure control device is a tube and a diameter of the tube varies along a downstream direction of the tube.

15. A plasma generating system as recited in claim 9, wherein the pressure control device includes a feedback control unit and comprises:

10 a sensor for measuring a pressure of the exhaust gas in the exhaust gas pipe;
 a valve for adjusting the pressure of the exhaust gas in the exhaust gas pipe;
 and
 a control unit for receiving a signal associated with the pressure and
 controlling the valve in response to the signal.

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16. A plasma generating system, comprising:

a plurality of plasma reactors, each of the plurality of plasma reactors including:

 a waveguide for transmitting a microwave energy therethrough;

 a plasma chamber coupled to the waveguide and configured to generate a

20 plasma therein using the microwave energy;

 a flow inlet for introducing a gas into the plasma chamber;

 an exhaust gas pipe for carrying an exhaust gas from the plasma chamber,

wherein the plasma converts the gas into the exhaust gas; and

 a container attached to a side surface of the exhaust gas pipe and in fluid

25 communication with the exhaust gas pipe; and

 a manifold coupled to the exhaust gas pipes of the plurality of plasma reactors and
configured to receive the exhaust gas from the exhaust gas pipes.