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A NOZZLE FOR CONVEYING A PLASMA STREAM FOR PLASMA ABATMENT AND RELATED METHOD**FIELD OF THE INVENTION**

The present invention relates to a nozzle for conveying a plasma stream and a
5 method.

BACKGROUND

Thermal plasma torches are known and are typically used for treating an effluent
gas stream from a manufacturing process tool used in, for example, the
10 semiconductor or flat panel display manufacturing industry. During such
manufacturing, residual fluorinated or perfluorinated compounds (PFCs) and
other compounds exist in the effluent gas stream pumped from the process tool.
These compounds are difficult to remove from the effluent gas stream and their
release into the environment is undesirable because they are known to have
15 relatively high greenhouse activity.

One approach to remove the PFCs and other compounds from the effluent gas
stream is to use a radiant burner as described, for example, in EP1773474.
However, when fuel gases normally used for abatement by combustion are
20 undesirable or not readily available, it is also known to use a plasma torch
abatement device.

Plasmas for abatement devices can be formed in a variety of ways. Microwave
plasma abatement devices can be connected to the exhaust of several process
25 chambers. Each device requires its own microwave generator, which can add
considerable cost to a system. Plasma torch abatement devices are
advantageous over microwave plasma abatement devices in terms of scalability
and in dealing with powder (present in the effluent stream or generated by the
abatement reactions). In fact, with regard to microwave plasmas, if powder is
30 present it can modify the dielectric characteristic of the reaction tube and render
ineffective the microwave injection that sustains the discharge. The plasma

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generated by the plasma abatement device is used to destroy or abate unwanted compounds within the effluent gas stream.

Although these apparatus exist for processing the effluent gas stream, they each
5 have their own shortcomings. Accordingly, it is desired to provide an improved technique for processing and effluent gas stream.

SUMMARY

According to a first aspect, there is provided a nozzle for conveying a plasma
10 stream from a plasma generator to a reaction chamber, the nozzle comprising: a conduit extending between an inlet arranged to receive the plasma stream and an outlet arranged to fluidly couple with the reaction chamber, the plasma stream being conveyed by the conduit between the inlet and the outlet in an axial direction, wherein the nozzle is thermally-conductive and is arranged to receive
15 water for heating by the nozzle, the nozzle having at least one aperture therein, the aperture being arranged to deliver the heated water for mixing with the plasma stream.

The first aspect recognises that the destruction rate efficiency when trying to
20 remove compounds from an effluent gas stream may be sub-optimal. In particular, existing abatement apparatus employ a DC-arc plasma torch coupled with an inlet assembly, a restriction, a mixing (Venturi) cone and a reaction tube where the abatement reaction takes place. PFC abatement is mainly achieved by injecting compressed dried air (CDA) as a reagent before the Venturi cone.
25 Here the reagent mix with PFC gases and the N₂ plasma plume before entering the "hot" reaction area, which exists after the cone and is delimited by a reaction tube (which may be made by ceramic cement but can be of other materials such as metal). In the reaction area, O₂ reacts with the PFC gases before the gas temperature is reduced with a N₂ flow in the DeNO_x section and by water sprays
30 in the quench. As an example, two chemical reactions that can take place in the case of CF₄ abatement are: $2\text{CF}_4 + \text{O}_2 \rightarrow 2\text{COF}_2 + 2\text{F}_2$ (dominant reaction) and

$\text{CF}_4 + \text{O}_2 \rightarrow \text{CO}_2 + 2\text{F}_2$. Similarly, in the case of SF_6 abatement SOF_2 , SO_2F_2 can be formed in larger amounts than more soluble by-products SO_2 , F_2 , HF .

While this "dry" abatement has its inherent benefits such as no wasted energy
5 into converting H_2O into plasma phase and very low NO_x (mainly generated if N_2 radicals comes in contact with water) the lack of H_2 as reagent can present some weaknesses. Chiefly, by-products like COF_2 , SOF_2 and SO_2F_2 can be scrubbed with difficulty by fresh water and can be still present after the abatement at high concentrations and beyond acceptable levels. With regards to plasma torch
10 scrubbers, F_2 and Cl_2 molecules can be broken down in the reaction section but due to lack of H_2 radicals they can only be dealt with further downstream in the wet quench section where sprayed water can be employed to reduce the temperature of the gas exiting from the reaction section. This is a major difference with burners where H_2 radicals from CH_4 allow "easy" conversion of Cl_2
15 / F_2 to HCl / HF . In some abatement apparatus, Cl_2 abatement has been especially proven to be very dependent on the conditions upstream of the quench. Simple addition of H_2 is proved to be effective for CF_4 but flammable reagents are discouraged as "non-fuel" abatement solutions. Water vapour is instead a viable solution for SF_6 .

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Hence, the first aspect also recognises that the presence of hydrogen concurrently with/instead of oxygen radicals can improve destruction rate efficiency of some compounds and greatly reduced the formation of noxious, hardly-soluble by-products. However, the introduction of such hydrogen radicals
25 from a source gas like H_2 , CH_4 , C_3H_8 etc. can be problematic, particularly when it is desired to minimise the presence of combustible compounds outside the abatement apparatus and the cost of operation of the equipment.

Accordingly, a nozzle such as a plasma stream nozzle is provided. The nozzle
30 may convey or transport a plasma stream or jet between a plasma generator and a reaction chamber. The nozzle may comprise a conduit. The conduit may extend between or have an inlet and an outlet. The inlet may receive the plasma

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stream. The outlet may fluidly couple with the reaction chamber. The plasma stream may be conveyed or transported by or through the conduit in an axial or elongate direction (or direction of flow). The nozzle may be thermally-conductive and may be arranged to receive water which may be heated by the nozzle to provide heated water. The nozzle may define one or more apertures, openings or nozzles. Those apertures may deliver the heated water in the axial direction which mixes with the plasma stream being conveyed. In this way, water is introduced into the plasma stream, which generates both hydrogen and oxygen radicals that help improve the destruction rate efficiency of the abatement apparatus. The nozzle itself may help pre-heat the water and may even vaporize it prior to delivery within the conduit in order to reduce the cooling effect on the plasma stream. Axial delivery is particularly useful when large flows of water reagent are required for the abatement and reduces quenching of the plasma stream. This provides for a particularly safe and convenient way to improve the destruction rate efficiency since no combustible materials are required to be supplied to the nozzle to generate those radicals.

In one embodiment, the conduit is defined by a wall defining the aperture therein and the aperture is arranged to deliver the heated water into the conduit for mixing with the plasma stream when transiting therethrough. Accordingly, the conduit may have a wall which may surround or circumscribe the plasma stream as it is conveyed or passes through the nozzle between the inlet and the outlet. The aperture may deliver the heated water into or proximate the conduit to be mixed with the plasma stream as it transits.

In one embodiment, the aperture is arranged to deliver the heated water for mixing with the plasma stream when transiting into the reaction chamber. Accordingly, the aperture may deliver the heated water to be mixed with the plasma stream as it passes into the reaction chamber.

In one embodiment, the aperture is orientated to deliver the heated water radially into the conduit and/or the reaction chamber. Delivering the heated water into

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the plasma stream in a direction having a radial component helps it to penetrate into and mix with the plasma stream. That is to say that the heated water enters the conduit and/or the reaction chamber and/or the plasma stream in a direction with at least a radial component with respect to the conduit and/or the reaction
5 chamber and/or the plasma stream.

In one embodiment, the aperture is orientated to deliver the heated water tangentially into the conduit. Delivering the water into the plasma stream in a direction having a tangential component helps to maintain stable flow of the
10 plasma stream within the nozzle and/or the reaction chamber by introducing a rotational component, improving the mixing of the effluent gas with the injected water reagent. That is to say that the water enters the conduit and/or the reaction chamber and/or the plasma stream in a direction with at least a tangential component with respect to the conduit and/or the reaction chamber and/or the
15 plasma stream.

In one embodiment, the aperture is orientated to deliver the heated water axially into the conduit. Delivering the water into the plasma stream in a direction having an axial component helps to maintain the stability of flow of the plasma stream
20 through the conduit and/or the reaction chamber. This configuration is particularly useful when large flows of water reagent are required for the abatement. That is to say that the water enters the conduit and/or the reaction chamber and/or the plasma stream in a direction with at least an axial component with respect to the conduit and/or the plasma stream.

25 In one embodiment, the nozzle comprises a plurality of the apertures. This helps to provide for a uniform distribution and/or an increased volume of water and subsequent radicals throughout the plasma stream.

30 In one embodiment, the plurality of the apertures are positioned circumferentially around at least one of the nozzle and the conduit.

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In one embodiment, the plurality of the apertures are fluidly coupled with a gallery concentrically surrounding the conduit, the gallery being arranged to receive the water for delivery to the plurality of the apertures. The provision of a gallery is a convenient arrangement for delivery of water from a single source to multiple
5 apertures.

In one embodiment, the gallery comprises an inlet for receiving the water.

In one embodiment, the nozzle is arranged to be heated by direct exposure to the
10 plasma stream.

In one embodiment, the conduit comprises a restriction operable to generate turbulent flow to mix the heated water with the plasma stream. Generating turbulent flow with a restriction or discontinuity in or on the wall of the conduit
15 helps to mix the heated water with the plasma stream.

In one embodiment, the water comprises at least one of water droplets and water vapour.

20 In one embodiment, the nozzle comprises an aerosol device operable to generate the water droplets.

In one embodiment, the nozzle comprises a control device operable to control delivery of water to the aerosol device.
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In one embodiment, the inlet is arranged to receive the plasma stream together with an effluent stream.

In one embodiment, the nozzle comprises the plasma generator positioned
30 upstream of the inlet.

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In one embodiment, the plasma generator comprises a DC-arc, a microwave or an inductively-coupled discharge apparatus, which creates the plasma stream, plume or plasma jet.

- 5 In one embodiment, the nozzle comprises a process inlet arranged to deliver the effluent stream to the inlet.

In one embodiment, the nozzle comprises the reaction chamber positioned downstream of the outlet.

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- According to a second aspect, there is provided a method comprising: conveying a plasma stream from a plasma generator to a reaction chamber using a nozzle, the nozzle comprising a conduit extending in an axial direction between an inlet arranged to receive the plasma stream and an outlet arranged to fluidly couple
15 with the reaction chamber, wherein the nozzle is thermally conductive and the method comprises heating the water with the nozzle, the nozzle having at least one aperture therein; and the method comprises delivering the heated water through the aperture in the axial direction for mixing with the plasma stream.

- 20 In one embodiment, the conduit is defined by a wall defining the aperture therein and the aperture is arranged to deliver the heated water into the conduit for mixing with the plasma stream when transiting therethrough.

- In one embodiment, the aperture is arranged to deliver the heated water for
25 mixing with the plasma stream when transiting into the reaction chamber.

In one embodiment, the method comprises orientating the aperture to deliver the heated water radially into the conduit.

- 30 In one embodiment, the method comprises orientating the aperture to deliver the heated water tangentially into the conduit.

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In one embodiment, the method comprises orientating the aperture to deliver the heated water axially into at least one of the conduit and the reaction chamber.

In one embodiment, the method comprises providing a plurality of the apertures.

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In one embodiment, the method comprises positioning the plurality of the apertures circumferentially around at least one of the nozzle and the conduit.

10 In one embodiment, the method comprises fluidly coupling the plurality of the apertures with a gallery concentrically surrounding the conduit and receiving the water using the gallery for delivery to the plurality of the apertures.

In one embodiment, the method comprises receiving the water at an inlet of the gallery.

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In one embodiment, the method comprises heating the nozzle by direct exposure to the plasma stream.

20 In one embodiment, the method comprises generating turbulent flow to mix the water with the plasma stream using a restriction within the conduit.

In one embodiment, the water comprises at least one of water droplets and water vapour.

25 In one embodiment, the method comprises generating the water droplets with an aerosol device.

In one embodiment, the method comprises controlling delivery of water to the aerosol device.

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In one embodiment, the method comprises receiving the plasma stream together with an effluent stream at the inlet.

In one embodiment, the method comprises positioning the plasma generator upstream of the inlet.

- 5 In one embodiment, the plasma generator comprises a DC-arc, a microwave or an inductively-coupled discharge apparatus, which creates the plasma stream, plume or plasma jet.

- 10 In one embodiment, the method comprises delivering the effluent stream a process inlet for delivery to the inlet.

In one embodiment, the method comprises positioning the reaction chamber downstream of the outlet.

- 15 According to a third aspect, there is provided a nozzle for conveying a plasma stream from a plasma generator to a reaction chamber, the nozzle comprising: a conduit extending between an inlet arranged to receive the plasma stream and an outlet arranged to fluidly couple with the reaction chamber, the conduit being defined by a wall having at least one aperture therein, the aperture being
20 arranged to deliver water into the conduit for mixing with the plasma stream when transiting therethrough.

- According to a fourth aspect, there is provided a method comprising: conveying a plasma stream from a plasma generator to a reaction chamber using a nozzle,
25 the nozzle comprising a conduit extending between an inlet arranged to receive the plasma stream and an outlet arranged to fluidly couple with the reaction chamber, the conduit being defined by a wall having at least one aperture therein; and delivering water through an aperture in a wall which defines the conduit for mixing with the plasma stream.

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According to a fifth aspect, there is provided an abatement apparatus comprising the nozzle of the first or third aspect.

Further particular and preferred aspects are set out in the accompanying independent and dependent claims. Features of the dependent claims may be combined with features of the independent claims as appropriate, and in
5 combinations other than those explicitly set out in the claims.

Where an apparatus feature is described as being operable to provide a function, it will be appreciated that this includes an apparatus feature which provides that function or which is adapted or configured to provide that function.

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BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the present invention will now be described further, with reference to the accompanying drawings, in which:

Figure 1 illustrates a plasma abatement apparatus according to one embodiment;

15 Figure 2a illustrates a nozzle with radial delivery;

Figure 2b illustrates a nozzle with axial delivery;

Figure 2c illustrates a nozzle with tangential delivery;

Figure 3 illustrates a summarized change of state of the water reagent; and

Figure 4 illustrates an aerosol device according to one embodiment.

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DESCRIPTION OF THE EMBODIMENTS

Before discussing the embodiments in any more detail, first an overview will be provided. Embodiments provide a technique for the safe generation of hydrogen and/or oxygen radicals to improve the destruction rate efficiency of a plasma
25 abatement apparatus. Typically, liquid water is introduced into a nozzle which conveys the plasma stream to the reaction chamber in order to generate those radicals. The water may be injected or forced into the conduit or from a downstream face of the nozzle carrying the plasma stream and/or drawn in by a Venturi effect due to a pressure difference between the water and plasma stream
30 flowing through the conduit into the reaction chamber. The nozzle itself typically pre-heats the water prior to being delivered to the nozzle conduit which both assists in nozzle cooling and in minimizing cooling of the plasma stream by the

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water. Different arrangements for dispensing the water into the conduit or reaction chamber are envisaged, to help with mixing of the water with the plasma stream and effluent gas stream, while retaining stability of that stream and an adequate plasma temperature profile, when required. The provision of water in the plasma stream causes hydrogen and oxygen radicals to be generated which helps improve the destruction rate efficiency of the abatement apparatus.

General Arrangement - Abatement Apparatus

Figure 1 illustrates a plasma abatement apparatus, generally 10, according to one embodiment. The plasma abatement apparatus has a plasma torch 20 comprising a cathode 30 and an anode 40. The anode 40 comprises an annular structure which defines a tubular void, with the cathode 30 being coaxially aligned with an elongate axis of that tubular void.

A nozzle 50 is coaxially aligned with the plasma torch 20, located further along the elongate axis, away from the anode 40. The nozzle 50 also comprises an annular structure defining a tubular conduit extending along the elongate axis. The nozzle 50 comprises a water dispenser 55 arranged to convey water for delivery into the tubular conduit and/or from a downstream face 57 of the nozzle 50. In each of those delivery arrangements, the water may be conveyed into the conduit and/or reaction chamber 70 with axial, radial and/or tangential directional components of flow.

The nozzle 50 is received within a concentrically-surrounding casing 60 which defines a reaction chamber 70. The casing 60 is cooled by a water jacket 80.

In operation, a plasma-forming gas stream 80 is introduced between the cathode 30 and the anode 40 which are electrically charged and undergo a DC arc discharge to generate a plasma stream 90 which flows in a direction of flow A which is aligned with the elongate axis. The plasma stream 90 flows through the tubular conduit of the anode 40 and exits towards the nozzle 50. An effluent gas stream 100, typically together with a compressed dried air stream 110, enters the

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tubular conduit of the nozzle 50. As the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110 travel through the nozzle 50 towards the reaction chamber 70, water is dispensed by the water dispenser 55. The water dispensed by the water dispenser 55 generates hydrogen and oxygen radicals which also enter the reaction chamber 70 where abatement of compounds within the effluent gas stream 100 occurs.

Radial Nozzle

Figure 2a illustrates a nozzle, 50A. An upstream inlet 51A has a bevelled edge which defines a conical structure into which the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110 can be optionally received. The tubular inner wall 52A extends from the inlet 51A to an outlet 53A. Four apertures 54A are positioned circumferentially around the inner wall 52A at a position along the elongate axis. The apertures 54A, in this example, are uniformly distributed around the inner wall 52A, spaced 90 degrees apart. The apertures 54A are orientated to deliver water radially into the tubular conduit for mixing with the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110. Although these apertures 54A are shown positioned along the elongate axis, it will be appreciated that they may also be positioned around the outlet 53A and orientated to deliver water radially into the downstream reaction chamber for mixing with the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110.

Although not illustrated to improve clarity, a gallery 55A is provided which communicates with each aperture 54A in order to convey water to each aperture 54A.

In this embodiment, the nozzle 50A is thermally conductive and so pre-heats the water prior to being dispensed through the apertures 54A.

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In operation, the combined plasma stream 90 and effluent gas stream 100 mix with the dispensed water and exit the outlet 53A and enter the reaction chamber

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70. Compressed dried air 110 can be added upstream to this mix, depending on the species present in the effluent gas stream to abate.

Axial Nozzle

- 5 Figure 2b illustrates a nozzle 50B, according to one embodiment. The arrangement of this nozzle 50B is identical to the arrangement described above with the exception that the apertures 54B are instead orientated to deliver the water in the elongate axial direction. In this embodiment, there are 12 apertures 54B, each located circumferentially. In this embodiment, the water is dispensed
- 10 downstream of a discontinuity 56B, which causes turbulence to promote mixing between the water and the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110. Although these apertures 54B are shown positioned along the elongate axis, it will be appreciated that they may also be positioned around the outlet 53B (for example, the discontinuity 56B may be
- 15 omitted) and orientated to deliver water axially into the downstream reaction chamber 70 from the downstream face 57B of the nozzle 50B which couples with the reaction chamber 70 for mixing with the combined plasma stream 90, effluent gas stream 100 and compressed dried air stream 110. These embodiments are particularly suitable for treating effluent gas streams requiring high flows of water as a reagent. Delivering the heated water axially helps to form a layered
- 20 concentric shroud of heated water which mixes with the effluent gas stream 100 and compressed dried air stream 110 and helps prevent quenching of the plasma stream 90.
- 25 Although not illustrated to improve clarity, a gallery 55B is provided which communicates with each aperture 54B in order to convey water to each aperture 54B.

Tangential Nozzle

- 30 Figure 2c illustrates a nozzle, generally 50C, according to one embodiment. The arrangement of this nozzle 50C is identical to the arrangement described above with the exception that the apertures 54C are instead orientated to deliver the

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water in a tangential axial direction. In this embodiment, there are four apertures 54C, each located circumferentially. Although these apertures 54C are shown positioned along the elongate axis, it will be appreciated that they may also be positioned around the outlet 53C and orientated to deliver water radially into the downstream reaction chamber for mixing with the combined plasma stream 90,
5 effluent gas stream 100 and compressed dried air stream 110. This embodiment is particularly suited to enhancing the mixing of the effluent gas stream with the water as a reagent.

10 Although not illustrated to improve clarity, a gallery 55C is provided which communicates with each aperture 54C in order to convey water to each aperture 54C.

It will be appreciated that intermediate arrangements of apertures are also
15 possible, which introduce water into the tubular conduit and/or the reaction chamber with a radial and/or tangential and/or axial component. Also, the water may be introduced at one or more different locations along the elongate axis of the tubular conduit, either with or without a discontinuity. Also, the location and number of apertures may be adjusted to suit individual requirements.

20 Furthermore, different apertures of the plurality of apertures may be orientated in different directions.

Embodiments provide a technique to inject water as a reagent in a thermal plasma abatement system. The water is vaporized by the plasma hot
25 temperature in the vicinity of the injection nozzles featured by the specially-designed mixing cone (Venturi). This technique aims at delivering the "right" amount of water and at the "most appropriate" point of the abatement reaction zone in order to minimize both NO_x emissions and concurrently improve abatement efficiency. This method can tackle chemical by-products originating
30 from PFC abatement as well as improving abatement performances of halogens such as F₂ and Cl₂ currently achieved by plasma abatement systems. The vaporization is achieved without employing an expensive evaporator or other

complex, "gold plated" solutions. Embodiments utilise different nozzle positions and different devices to feed the liquid water to them.

Embodiments aim to solve the by-products reductions and improve halogen DRE performances. Table 1 reports some experimental evidence for the case of SF₆ by-products. SOF₂, SO₂F₂ and SO₂ have a known toxicity and a tabulated concentration, considered to be of Immediate Danger to Life and Health (IDLH). The experimental data shows below-IDLH emissions of SF₆ by-products (SO₂F₂, SOF₂, SO₂) if H₂O is used instead of CDA.

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kVA	SF6 in	Reagent	pump purge	Qout	%	SF6 Out	HF	SO2F2	SOF2	SO2	NOx
Power	[slm]		Qin [slm]	[slm]	DRE	ppm	ppm	ppm	ppm	ppm	mg/min
CDA injection											
10.61	0.5	CDA= 2 slm	150	271	94.5%	103	BDL	732	202	15	3.1.E+01
Water Injection											
10.41	0.5	H2O= 1.1 g/min	150	271	96.5%	66	0.3	BDL	2	4	1.6.E+02

Table 1

Table 2 shows some experimental data in the case of Cl₂ abatement. If H₂O is used instead of CDA, a lower plasma power can be used to treat Cl₂ below IDLH concentrations.

15

kVA	Cl2 in	Reagent	pump purge	Qout	%	Cl2	NOx
Power	[slm]		Qin [slm]	[slm]	DRE	ppm	mg/min
CDA injection							
13.33	1.0	CDA= 3 slm	90	189	99.998%	< 5	2.2.E+02
Water Injection							
8.64	1.0	H2O= 1.2 g/min	90	179	99.930%	< 5	2.2.E+02

Table 2

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Also, it is advantageous to avoid the evaporator /steam generator where possible to reduce complexity and capital cost. Some embodiments therefore use the hot temperature at which the nozzle 50 is running to convert liquid water into water vapour. The primary function of the nozzle 50 is to mix the effluent gas with the "hot" plasma stream, jet or plume 90. If the nozzle 50 is made of corrosion resistant metal alloys (such as but not limited to stainless steel, hastelloy, monel

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etc.), it can be thermally-conductive. In this way, the nozzle 50 can be water-cooled on its outer edge (hence preserving its gas and water seals), while it can still experience high temperatures on its inner ring, which is in contact with the "hot" plasma stream or plume 90. In embodiments, the steam generated around
5 the annular chamber due to the plasma proximity is expelled by small nozzles and eventually converted into plasma radicals inside the reaction section in order to form compounds with the effluent gas which are easier to water-scrub.

Figure 3 illustrates a summarized change of state of the water reagent.

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The liquid water can be fed in different ways. A needle valve can be used with a rotameter or ultrasonic flowmeter to measure the flow. Also envisaged is the use of a liquid mass flow controller (MFC) or a syringe pump. A bubbler coupled with a needle valve and a flow-measurement device is a further alternative.

15

Figure 4 illustrates an aerosol device (which is similar to a bubbler) according to one embodiment which comprises an immersed semi-permeable membrane 120 in a shaft 130 where some water flows and generates water droplets for delivery to the nozzles. The purge gas can be nitrogen or CDA and allows the fine control
20 of the amount of water fed to the annular chamber. This arrangement is particular useful when CDA has to be used concurrently with H₂O to abate flammables such as chemical vapour deposition (CVD) precursors. The water exerts a pressure onto the membrane and creates some droplets in a small nitrogen flow stream; not shown the needle valve that allows to control water pressure and
25 hence the amount of water passed into the aerosol.

In embodiments, the annular chamber feeds the nozzles and which are positioned to provide the injection just after the plasma super-sonic expansion of the plasma stream, jet or plume 90. One advantage of embodiments is that H₂O
30 can immediately convert F₂/Cl₂ radicals originating from PFCs, BCl₃, SiF₄ and/or SiCl₄ in the effluent stream to HF/HCl rather than leaving their treatment further downstream in the wet stages.

Embodiments are particularly suited to semiconductor etch markets where PFC gases and halogens have to be abated. In this case a small amount of reagent water is required and the nozzles can be directed in the radial direction, 5 perpendicularly to the flare. The same concept can be utilized to abate effluent gases originating in clean steps typical of CVD process. In this case large amounts of F_2 are generated by NF_3 used in remote plasma cleaning and have to be dealt with a plasma abatement apparatus. Finally, FPD etch processes employ larger amount of halogens/PFCs than semiconductor etch. In these cases 10 a larger amount of reagent water may be required and this can be injected in a parallel direction to the plasma plume and into its external "tails", avoiding excessive quenching of the plasma itself. This region is still chemically active for abatement reactions to take place. Other variations comprise the use of different devices to inject liquid as described above.

15 Although illustrative embodiments of the invention have been disclosed in detail herein, with reference to the accompanying drawings, it is understood that the invention is not limited to the precise embodiment and that various changes and modifications can be effected therein by one skilled in the art without departing 20 from the scope of the invention as defined by the appended claims and their equivalents.

REFERENCE SIGNS

plasma abatement apparatus	10
plasma torch	20
cathode	30
anode	40
nozzle	50; 50A; 50B; 50C
inlet	51A;
inner wall	52A;
outlet	53A; 53B; 53C
aperture	54A; 54B; 54C
water dispenser/gallery	55; 55A; 55B; 55C
discontinuity	56B
downstream face	57; 57B
casing	60
reaction chamber	70
plasma forming gas stream	80
plasma stream/jet/plume	90
effluent gas stream	100
compressed dried air stream	110
membrane	120
shaft	130
direction of flow	A

CLAIMS

1. A nozzle for conveying a plasma stream from a plasma generator to a reaction chamber, said nozzle comprising:
 - 5 a conduit extending between
 - an inlet arranged to receive said plasma stream and
 - an outlet arranged to fluidly couple with said reaction chamber, said plasma stream being conveyed by said conduit between said inlet and said outlet in an axial direction, wherein said nozzle is thermally-
 - 10 conductive and is arranged to receive water for heating by said nozzle, said nozzle having
 - at least one aperture therein, said aperture being arranged to deliver said heated water in said axial direction for mixing with said plasma stream.
- 15 2. The nozzle of claim 1, wherein said conduit is defined by a wall defining said aperture therein and said aperture is arranged to deliver said heated water into said conduit for mixing with said plasma stream when transiting therethrough.
- 20 3. The nozzle of claim 1 or 2, wherein said aperture is arranged to deliver said heated water for mixing with said plasma stream when transiting into said reaction chamber.
- 25 4. The nozzle of any preceding claim, wherein said aperture is orientated to deliver said heated water at least one of radially and tangentially into at least one of said conduit and said reaction chamber.
- 30 5. The nozzle of any preceding claim, wherein said aperture is orientated to deliver said heated water axially into at least one of said conduit and said reaction chamber.

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6. The nozzle of any preceding claim, comprising a plurality of said apertures.
- 5 7. The nozzle of claim 6, wherein said plurality of said apertures are positioned circumferentially around at least one of said nozzle and said conduit.
8. The nozzle of claim 6 or 7, wherein said plurality of said apertures are
10 fluidly coupled with a gallery concentrically surrounding said conduit, said gallery being arranged to receive said water for delivery to said plurality of said apertures.
9. The nozzle of claim 8, wherein said gallery comprises an inlet for receiving
15 said water.
10. The nozzle of any preceding claim, wherein said conduit comprises a restriction operable to generate turbulent flow to mix said heated water with said plasma stream.
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11. The nozzle of any preceding claim, wherein said water comprises water droplets.
12. The nozzle of any preceding claim, wherein said inlet is arranged to
25 receive said plasma stream together with an effluent stream.
13. The nozzle of any preceding claim, comprising a process inlet arranged to deliver said effluent stream to said inlet.
- 30 14. A plasma abatement apparatus comprising the nozzle as claimed in any proceeding claim.

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15. A method comprising:
- conveying a plasma stream from a plasma generator to a reaction chamber using a nozzle, said nozzle comprising a conduit extending in an axial direction between an inlet arranged to receive said plasma stream and an outlet
- 5 arranged to fluidly couple with said reaction chamber, wherein said nozzle is thermally conductive and said method comprises
- heating said water with said nozzle, said nozzle having at least one aperture therein and said method comprises
- delivering said heated water through said aperture in said axial direction
- 10 for mixing with said plasma stream.