Design of a Prototype of Water Purification by Plasma Technology as the Foundation for an Industrial Wastewater Plant

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Abstract. In order to mitigate the contamination of water sources due to the spill of sewage without any kind of treatment, mainly generated by the industrial sector; a prototype of water purification by plasma technology has been designed. The prototype will transform liquid water into plasma to eliminate the pathogens from the water, due to their exposure to ultraviolet radiation, electric fields and shock waves, which aid in the destruction of pollutants. The sewage will be accelerated at high speed to convert it into a liquid-gas mixture in order to transform it into plasma, which is achieved when the electrical discharge (of the type dielectric barrier discharge or DBD) is applied to the water by means of high voltage electrodes, from a source of alternating current (AC). Subsequently, the mixture slows down to be return into liquid phase and obtain clean water, all of these without a significantly rise of temperature. The device also has an automatic power control system. Finally, a short feasibility study was conducted in order to use this type of water cleaner in the future as a basis for a treatment plant of industrial waste water, so it comes to replace the current secondary and tertiary treatments used among the industry. It is intended that this new system will be more efficient and cheaper than the current waste water treatments.

1. Motivation

Water availability for human consumption is getting diminished every day. Despite de effort to improve water quality in some regions of the world, the pollution keeps growing; and unfortunately more than 80% of sewage in developing countries is discharged untreated, polluting rivers, lakes and coastal areas [1]. Once these water sources are contaminated, their recovery is almost null, adding that it is estimated that less than 20% of the world's drainage basins exhibit nearly pristine water quality [1].

Based on the statement above, there is a motivation for creating a prototype for water purification by plasma technology as the foundation for an industrial wastewater plant, coming from the industry's need of treating its used waters, which is regulated by law in many countries; in order to protect the environment, the health and common wellbeing. As seen before, wastewater spill without any kind of treatment threatens water sources worldwide, which can affect the human development, but hopefully with the device the treated water will count with such quality that can be reused in other process or even for human consumption.

2. Background on Industrial Wastewater Treatments

Industrial wastewater treatment typically consists of three phases or treatments. The primary treatments are mainly used to eliminate suspended matter, by means of mechanical operations and using chemical additives. The secondary treatments are biological processes, in which depuration of biodegradable organic matter from the wastewater is done by the action of microorganism. Tertiary treatments –which are usually expensive– eliminate the contaminants that last after primary and secondary treatments, such as the dissolved matter. Some of these treatments are stripping, precipitation, reverse osmosis and disinfection by advanced oxidation processes (AOP), which can use combinations of hydrogen peroxide, ultraviolet radiation, photocatalysis and ozone (O_3); focusing on the last one for this paper due to its oxidation potential.

Some of the many advantages of ozone oxidation (ozonation) compare to traditional methods like chlorination are [2]:

- Effective disinfectant without secondary effects.
- No need to store or handle chemicals.
- Ozonation sub products with no adverse effects over health and environment.
- The ozone can safely destroy a vast range of organic pollutants.
- Much more effective killing bacteria, viruses and spores, among others.
- The ozone helps in the removal of color, odor and suspended solid matter.

Based on the analysis of the wastewater treatments commonly used in the industry, an alternative treatment system is proposed with the usage of plasma.

3. Water Purification with Electric Discharges

One way to generate ozone for water purification is by applying an electric discharge on the liquid surface, in such way that it will produce active chemical species (such as OH•, H•, O•, O_3, H_2O_2) [2] capable of disinfecting the water.

The intensity of the electrical fields needed for the electrical discharges in water is lethal for a great variety of microorganisms, and show a synergistic lethal effect when combined with conventional disinfectants such as O_3 and H_2O_2. The electrical discharges in water may also produce ultraviolet (UV) radiation and shock waves, which help in the destruction of pollutants [2].

In the case of water purification by electrical discharges, there are basically three types: Contact Glow Discharge Electrolysis, Dielectric Barrier Discharges (DBD) and Pulsed Corona Discharges. Table 1 shows a summary of the characteristics of the discharges.

Table 1. Summary Table of Electrical Discharges in Water. (Barillas L), ([2])

Discharge type	Electrode characteristics	Voltage	Energy	Other characteristics
Glow Discharge Electrolysis	Thin wire	DC ~ 0.5 kV	100 eV max.	Equilibrium plasma. Anode and cathode can be isolated by a porous glass. Requires cooling system.
Dielectric Barrier Discharges (DBD)	Generally are parallel plates	AC ~ 15 kV	1 – 10 eV	Non-equilibrium plasma. At least one of the electrodes is covered by a dielectric material. No need for cooling system.

Pulsed Corona Discharges	Configurations needle-plate, cylinder-wire (coaxial)	DC ~ 15-100 kV	~ 5 eV	Non-equilibrium plasma. Electrodes can be covered by a thin ceramic layer. Could require cooling system.

4. Design of the prototype

A DBD reactor type was chosen as the model to design, since it gives certain advantages for this case of study (building a prototype later on). The main advantage is that produces a non-thermal plasma that does not rise the temperature significantly; thus, there is no need for a cooling system, making the prototype cheaper and simpler to construct.

First of all, it is considered that the wastewater has gone through previous primary treatments, and that it does not contain solids nor major colloidal suspensions; for this reason, the prototype is considered as a tertiary treatment.

The prototype reactor, showed in **Figure 1**, will transform liquid water into plasma in order to kill the water's pathogens and pollutants, due to their exposure to UV radiation, electrical fields and shock waves. The device will feature a pump and a nozzle which accelerates the sewage to high speed to convert it into a liquid-gas mixture in order to transform it into plasma, which is obtained at the moment of the electrical discharge is applied into the water by means of high voltage electrodes from an AC power supply. Later, the mixture must be decelerated to return it into liquid state and obtain clean water, without a significant temperature rise due to the low pressure in the reactor. Figure 2 shows a general diagram of the prototype.

The main design parameters of the reactor are:

- **Reactor:** Coaxial geometry, copper electrodes, 490 mm long by 120 mm diameter. Outer electrode is hollowed and inner electrode is a solid copper bar. Borosilicate glass (Pyrex®) as dielectric barrier of 2.4 mm thickness.
- **Power Supply:** AC, 120 Vac/60 Hz, 20 kV p-p, 20-70 kHz
- **Nozzle:** Flowrate 10 l/min @ 50 psi
- **Pipelines:** PVC, Ø 1'' SCH 40
- **Pump:** 1 hp, single-phase, 120 Vac/60 Hz; Q = 10-50 l/min, $H_{máx}$ = 52 m
- **Tank:** 48 liters, fiberglass material
- **Control System:** made with relays 120 Vac/10 A
- **Others:** Variable Frequency Drive 0-500 Hz, 115 V, 1 hp. Also a Ø 1'' solenoid valve

The special features of the dynamic (constant flow) coaxial reactor design and the incorporation of a nozzle to create a liquid-gas mixture give a competitive advantage over other DBD reactors based on parallel plates geometries, which is that it provides a greater contact area between the discharge and wastewater (a surround interaction), while the traditional mentioned geometry only interacts with the static superficial layer of the wastewater.

There are especial considerations regarding the power supply, since it was not possible to find a model to characterize it, due to the geometrical configuration of the electrodes (coaxial). Next section will discuss this matter.

4.1. Power Supply Characterization

In order to characterize the power supply needed, a plates or discs electrodes reactor model published in "Characteristics of Dielectric Barrier Discharge Reactor for Material Treatment" by Kostov[3][1] was taken as the base for the current approach.

[1] Model by Kostov (2009) is not fully explained in this paper, for further details please refer to *"Characteristics of Dielectric Barrier Discharge Reactor for Material Treatment"* [3] paper.

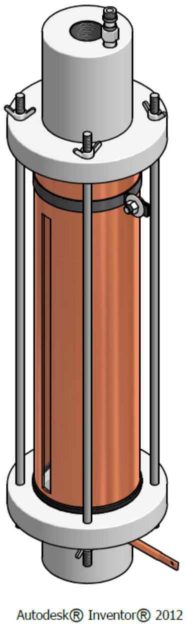

Figure 1. Proposed prototype reactor for water purification (Barillas L)

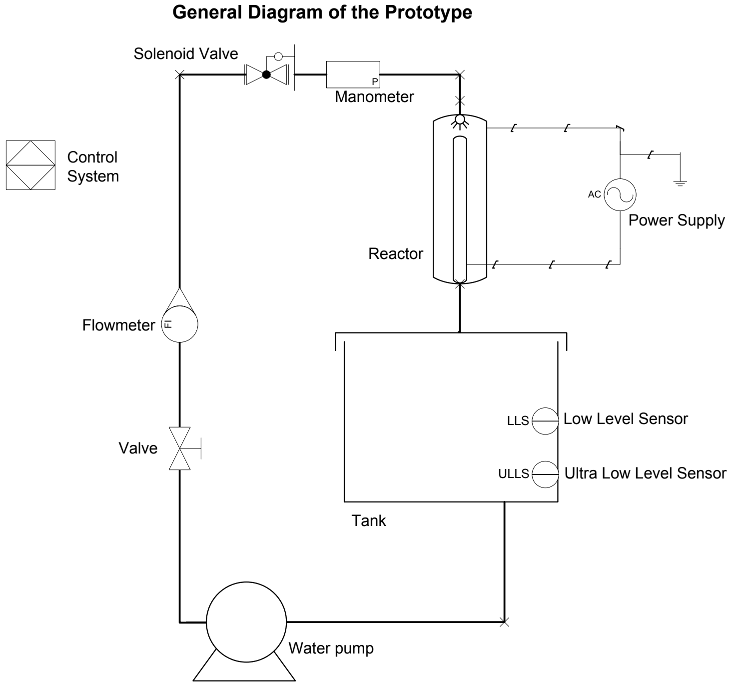

Figure 2. General diagram of the prototype for wastewater purification. (Barillas L)

This model has an equivalent electrical circuit for DBD reactor with parallel plates with two layers of dielectric over each metallic electrode, as shown in Figure 3.

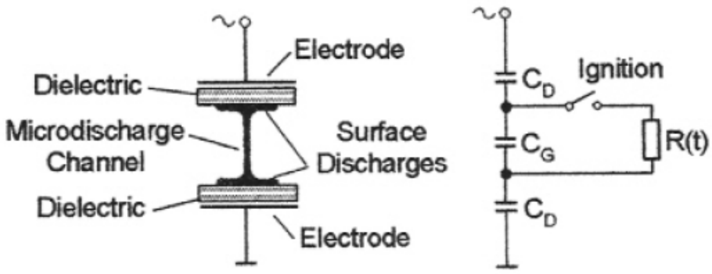

Figure 3. Layout of a parallel plates DBD reactor and its equivalent circuit. ([3])

After a series of equations and analysis of this circuit[1], and assuming that DBD discharge is constituted by various micro-discharges in parallel the plasma resistance can be approximately expressed as $R \cong x\rho/A_{EF}$, where ϱ is the resistivity of a discharge channel, A_{EF} is the total cross section occupied by the micro-discharges, C_D is the capacitance of the dielectric layer and C_G is the capacitance of the discharge gap [3]; then the mean reactor power can be expressed in term of a discharge gap x:

$$\bar{P} = \frac{V^2}{2}\frac{A_{EF}}{x\rho}\left[\left(1+4\frac{C_G}{C_D}+4\frac{C_G^2}{C_D^2}\right)+\left(\frac{4}{\omega^2 C_D^2}\frac{A_{EF}^2}{x^2\rho^2}\right)\right]^{-1}$$

Equation 1

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In order to adapt this model to the coaxial geometry reactor, as well as simplify calculations, the cylindrical electrodes will be taken as two sheets, by extending the inner surface of the hollowed electrode (outer electrode), and the surface of the solid electrode. This will result in different areas (A), affecting the term C_D, as $C_{D1} = \frac{k\varepsilon_0 A_1}{d_1}$ and $C_{D2} = \frac{k\varepsilon_0 A_2}{d_2}$; where k is the dielectric constant of the material, d is the thickness of each dielectric barrier, A_1 is the inner area of the cylindrical hollow electrode and A_2 is the area of the surface of the inner electrode.

Thus, Equation 1 must be modified as:

$$\bar{P} = \frac{V^2}{2}\frac{A_{EF}}{x\rho}\left[\left(1 + 4\frac{C_G}{C_{D1}} + 4\frac{C_G^2}{C_{D1}C_{D2}}\right) + \left(\frac{4}{\omega^2 C_{D1}C_{D2}}\frac{A_{EF}^2}{x^2\rho^2}\right)\right]^{-1}$$

Equation 2

With this approach, by having electrodes with different areas, then A_{EF} can be arranged as a trapeze, as shown in Figure 4, indicated in red:

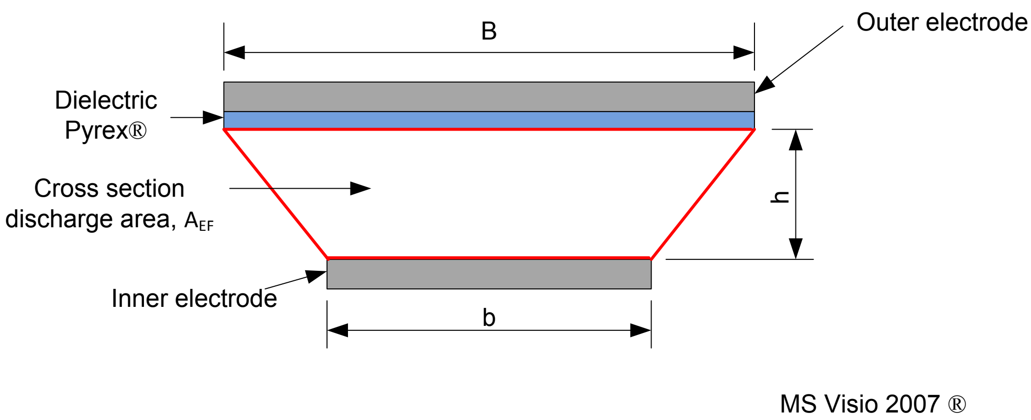
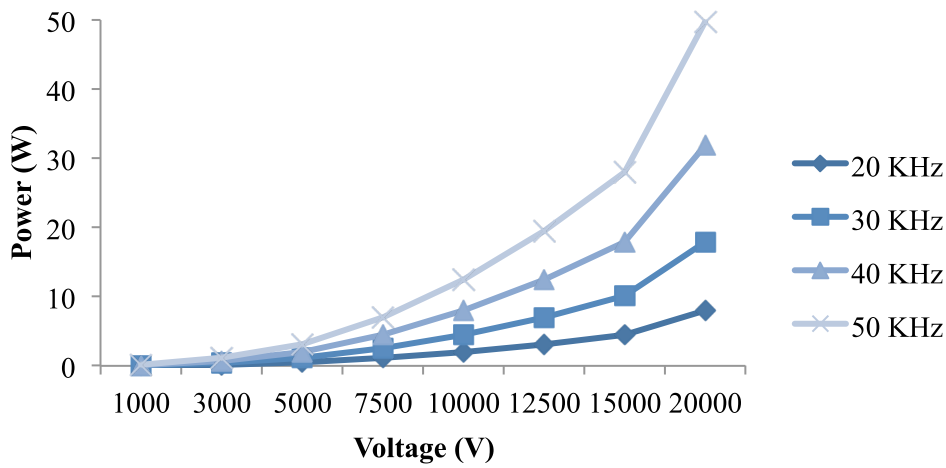


Figure 4. Diagram of the cross section occupied by the micro-discharges, assuming the cylindrical electrodes as sheets to adapt them into the parallel plates electrodes model. (Barillas L)

With this approach, is was possible to build a datasheet in order to determine the voltage (from 1 kV to 20 kV) and frequency (20 kHz to 50 kHz) as functions of power (W). The behaviour of these variables is shown in Graph 1.



Graph 1. Voltage and frequency as functions of mean power. (Barillas L)

Also, simulations were computed in the AC/DC® Module of COMSOL Multiphysics® Version 4.1, with the electrodes coaxial geometry, in order to determine the optimal values for the power supply. Figure 5 shows the electric potential at different frequencies for the power supply, in a cross section view, around the middle of the reactor length.

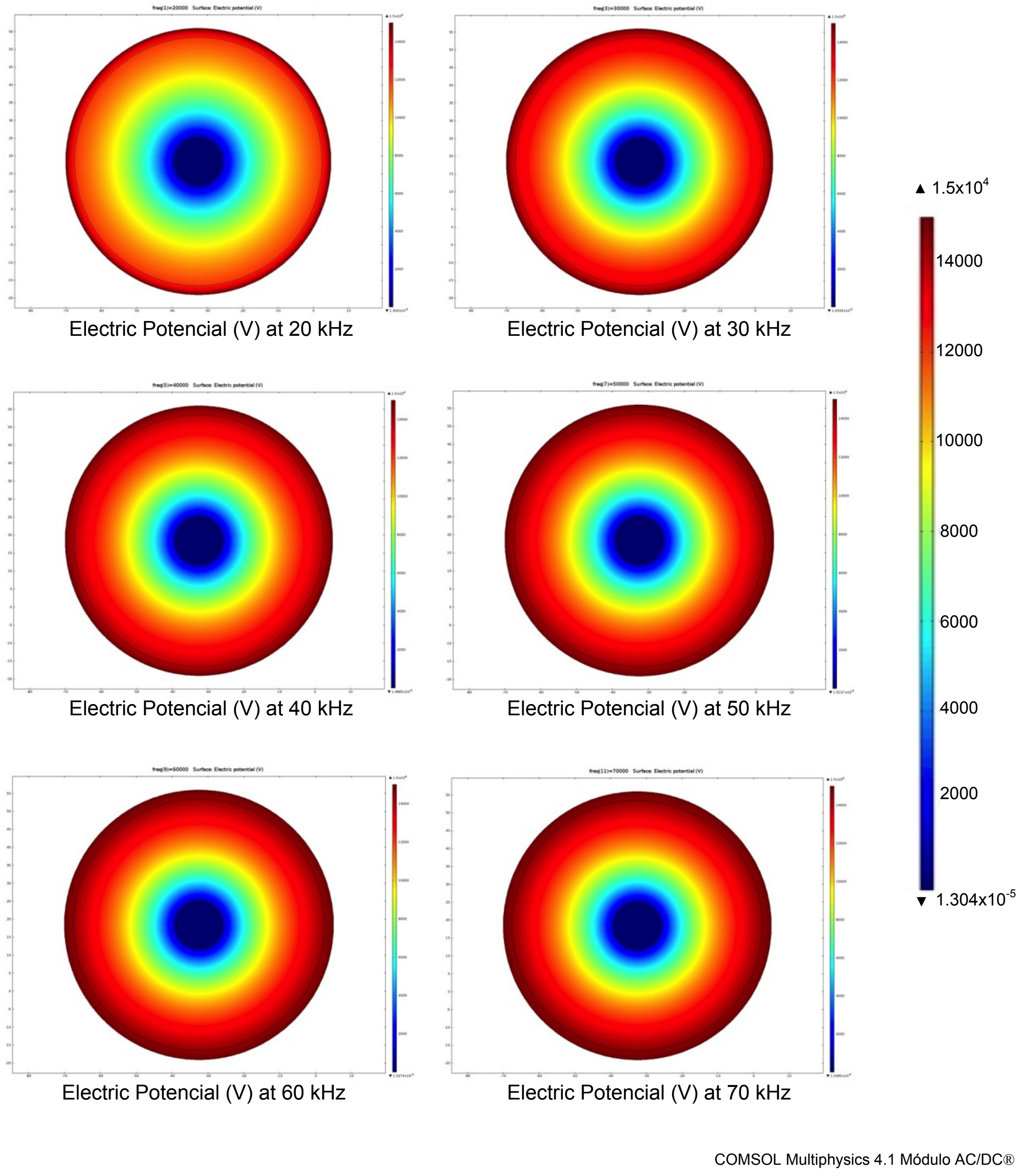


Figure 5. Electric potential at different frequencies for the power supply (20 kHz to 70 kHz), at 15 kV, in a cross section view, around the middle of the reactor length. (Barillas L)

Data from the simulations shows that there is an increase in the intensity of the electric potential towards the centre of the geometry; however, from 50 kHz to 70 kHz there is no significant variation, differently as seen from 20 kHz to 50 kHz. Among other data obtained, in conclusion, it was clear that one can obtain a higher electrical field in the reactor's ionization area from high frequencies and voltages from the AC power supply. After this analysis, a variable power supply (output from 0 to 20 kV peak-peak, 20 kHz to 70 kHz) was chosen with the intention of let the researchers experience with different parameters, in order to find the optimal efficiency parameters.

It is important to mention that many results will only be known in an experimental way, this means, many parameters could change once the prototype is built. Also, the prototype has been design in such way that it could be escalated depending on the demand needs; e.g. if 100 l/min need to be treated, then a 10 coaxial reactor matrix would be set up, since each of them purifies 10 l/min.

5. The Prototype as the Foundation for an Industrial Wastewater Plant.

As explained in section 1, the industrial market shows an obvious need for treating wastewaters, first due to law requirements, and second due to water sources preservation.

The intended use of this plasma water purifier, is to replace a wastewater tertiary treatment, but depending on the effluent quality from the primary treatment, it could even replace the secondary phase in a wastewater plant. Current secondary and tertiary wastewater treatments are expensive and require large installation areas, as well as high maintenance. For example, for activated sludge, great land areas and high cellular retention time are needed, which makes the water take several days to be treated (1 month average).

With the proposed project, the installation areas would be smaller, in such way that the reactor matrix could fit in a machinery (engine) room; and it is pretended that the water is purified almost immediately when passing through the reactors (1 cycle), but even if more cycles are needed, it would only take one day (this is not clear yet due to lack of experimental data).

As an example to characterize the project, it was compared to a traditional wastewater plant that treats 200 m^3/day, with a maximum demand of 277.2 l/min. The primary treatment would remain the same (grills, a grit chamber and a fat and grease trap), and then, the designed device would take place. In this case, for the required demand, a 28 reactor matrix would be needed (it must be remember that each reactor has the capacity of 10 l/min, which is determined by the nozzle flow rate). Figure 6 shows a diagram of the proposed location in a wastewater plant for the designed device.

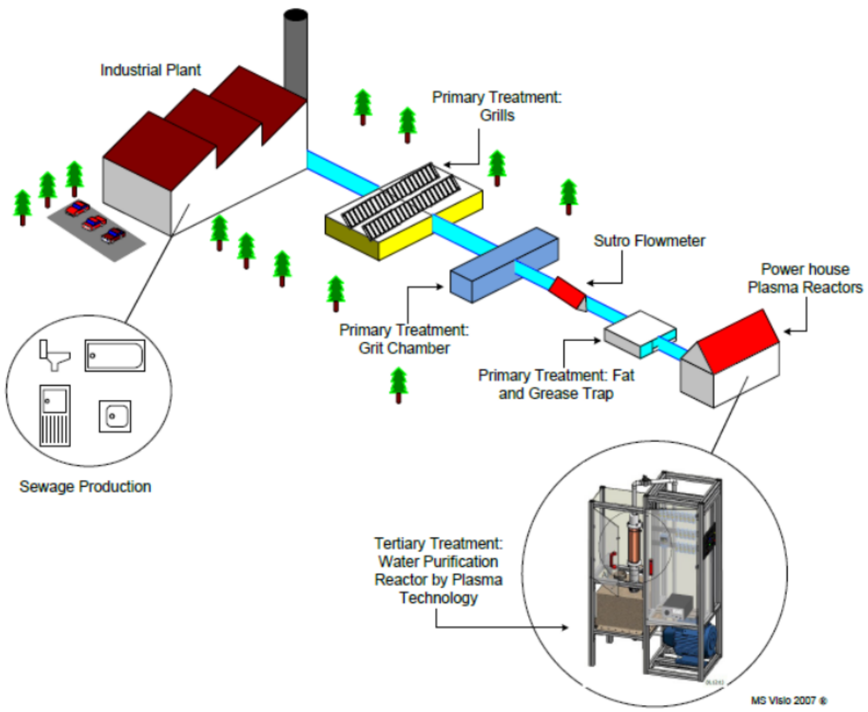


Figure 6. Diagram of the proposed location in a wastewater plant for the designed device. (Barillas L)

Regarding costs, Table 2 shows the possible capitalization costs for the wastewater plant project using the designed water purification reactor by plasma technology.

Table 2. Possible Capitalization Costs for a Plasma Wastewater Plant. (Barillas L)

Specification	Cost (USD)
Prototype reactor	\$3,500.00
Traditional activated sludge wastewater plant, with no primary treatment	\$160,000.00
Plasma Wastewater Plant, including primary treatment	\$130,000.00
Savings	\$30.000,00 (20% less)

Summarizing, the competitive advantages of this treatment over traditional treatments, are that it is more effective, efficient, faster, compacter and more economic; aside from the fact that it will not use chemicals, which will make it also safer for people and environment.

6. Conclusions

As mentioned, industries must treat the wastewater in order to ensure the protection of the environment, the health and common wellbeing. It is possible that, due to the high cost and maintenance of traditional treatment plants, people find it difficult to properly treat the used waters. Although experimental data is still pending and some parameters will only be definitive until the device is built and tested, it is intended that with the proposed device, cost, maintenance and space could decrease significantly; which could lead industries (especially from developing countries) to re-consider discharge untreated sewage.

Finally, the ideal state is to offer a whole new cost-improvement, effective, efficient and innovative concept on wastewater plants, also including the primary treatment; for example, by using plasma-synthetized nanostructures that could segregate and retain certain organic/inorganic components from the water, and then, eliminate biodegradable organic matter (like microorganisms, bacteria, virus, etc.) by means of the proposed reactor; in order to obtain a high quality water effluent that can be used in other processes.

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