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A Study on Off-Gas Treatment of an Air Stripping Tower Using a Plasma Reactor

Gye-Gyu Lim, Ho-Sik Yoo[1)]

Dept. of Environmental Eng., Hoseo Univ., Chung Nam, Korea
[1)]Dept. of Environmental Eng., Kyonggi Univ., Kyong Kee, Korea
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Abstract

An evaluation of a plasma reactor was conducted to investigate its potential as a feasible and economical off-gas control technology for an air stripping tower (AST). The plasma reactor was powered by an alternating current with frequencies up to 1000Hz. The study showed that over 90% conversion of gas-phase trichloroethylene (TCE) can be achieved. An optimum frequency for the alternating current existed for maximum power input. The optimum frequency was dependent on the reactor geometry and the primary voltage applied. For a fixed geometry, a plasma reactor has a limited capacity for flow rate. Even though it is a feasible process to control off-gases, further investigations should be conducted to develop a more economic process.

KEYWORDS : air stripping, off-gas, economics, plasma, trichloroethylene.

1. INTRODUCTION

There are several technologies commonly used to treat water contaminated with volatile organic chemicals (VOCs). The most viable methods for VOC removal (Hand, et al., 1989) are granular activated carbon (GAC) adsorption and packed tower air stripping (AST). In the GAC system, however, the adsorbent must be regenerated and the regenerant must be processed to isolate the original adsorbates from the adsorbent. Regeneration of exhausted adsorbents or isolation of adsorbates is one of major reasons to increase the total cost of the system. Therefore, ASTs are often the least expensive and most popular method to remove VOCs. Additional reasons to choose ASTs are ; (A) Easy to operate with minimum skill, (B) Less operation and management cost than carbon adsorption, (C) Aerating to remove one specific contaminant will also reduce concentrations of other VOCs.

With the all advantages listed above, however, air stripping does not permanently remove the VOCs from the environment. It removes the VOCs from the liquid-phase and transfers it in the vapor-phase. So, water pollution is just transferred to air pollution. Regulations concerning air pollution have been becoming more stringent. It is necessary to develop off-gas control devices for ASTs.

The development of a method to incinerate and ultimately dispose of the toxic wastes in an air stream is the goal of this research. This research investigates the possibility of using a plasma reactor as the off-gas control technology of an AST.

In general, plasmas can be thought of as an ionized gas mixture. Gases are normally good electrical insulators. Under the influence of an applied electric field of sufficient strength, however, gas molecules can be ionized. Electric conduction then takes place and an electrical dis-

charge occurs. The most familiar type of gas discharge which can occur is a hot localized arc. Under the right current conditions, an incomplete breakdown of the gas can occur and a silent discharge results. This discharge can be maintained and its properties are very different from an arc. It is cooler and more diffuse and actually fills the gap between the electrodes with a soft glow.

The plasma reactors utilize electrical energy to create a relatively low temperature plasma (electric discharge) in a reactor cavity. The ionized species and electrons are accelerated to high speed by electromagnetic energy. When organic material flows into the plasma, their chemical bonds are broken by collision with electrons, causing dissociation to occur. The resulting fragments recombine along the pathways to form simple reaction products.

The use of a plasma reactor to destroy volatile organic compounds has been studied by several investigators. Some studies (Sheinson, et al., 1987 ; Fraser, et al., 1985 ; Piatt, 1988) were done to investigate the destruction of methane in a plasma reactor. Sheinson et al., (1987) showed increasing methane destruction with increasing power input in a plasma reactor. They also found the existence of an optimum frequency for the alternating current that yields maximum power input. Trichloroethylene (TCE) is a common volatile contaminant found in groundwater. Thus it was used as the target compound in this study.

Robert et al., (1989) studied the reactions of chlorinated hydrocarbons including TCE with water vapor or molecular hydrogen in a low-pressure microwave plasma. All those studies have not been intended to treat the off-gases from ASTs. This paper reports the results of a feasibility study that used an alternating current plasma reactor to treat off-gas from an AST.

2. METHOD AND MATERIALS

The experiment consisted of two phases. In the first phase, TCE destructive tests were done on a bench scale. These tests were designed to determine the destruction efficiency of the plas-

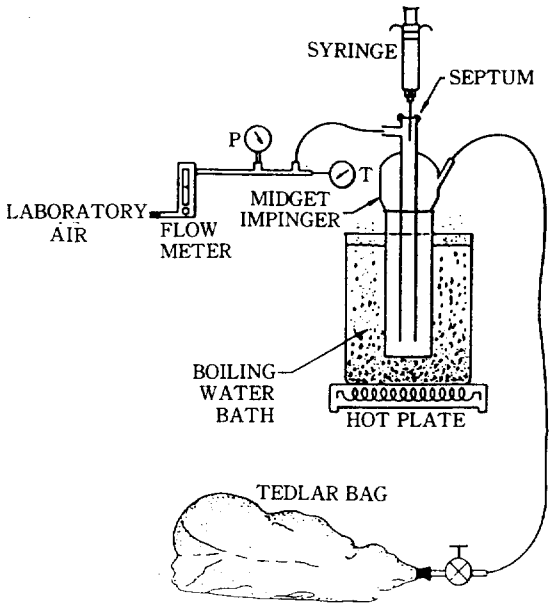

Fig. 1. Train for TCE saturation.

Table 1. GC method used in destruction test.

GC Column : 3% SP-1000 on 100/120 Supelcoport
Detector : Electron Capture Detector
Oven Temp. : 75℃
Run Time : 3min
Injector Temp. : 100℃
Detector Temp. : 275℃
Carrier Gas(5% Methane+95% Argon) : 60cc/min

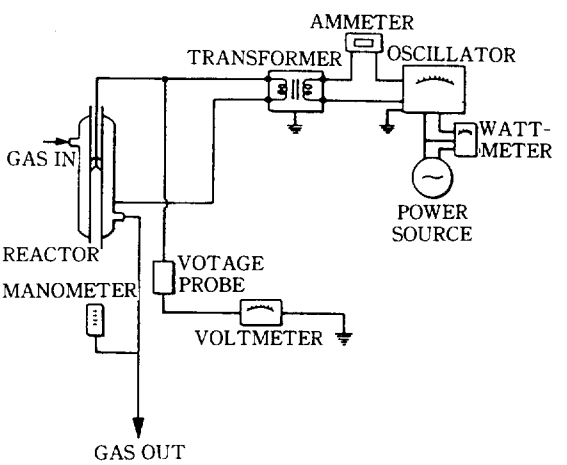

Fig. 2. Schematic of plasma reactor system

ma reactor. TCE-contaminated gas was generated in a saturation device (Figure 1), similar to that employed by the U.S. EPA (Brad, 1983), was used to simulate the AST off-gas. In the first phase of destructive study, the gas chromatography (GC) method given in Table 1 was used. The experimental apparatus used in the first stage is shown in Figure 2. The apparatus inclu-des a power source (California Instruments Model 161T oscillator with a range of 0 to 120 volts and frequency generation of 40 to 5000Hz), transformer (Jefferson Electric with a maximum secondary voltage of 15000 volts), high voltage test probe, ammeter, gas carrier system, reactor, and an outlet gas analysis system. The reactor was constructed using pyrex glass and consisted of coaxial glass tubes (Figure 3). The inside of the inner tube and outside of the outer tube were coated with inorganic silver paint that acts as electrodes. The geometries of the various reactors are given in Table 2. In case of reactor #3, the outer diameter of the inner tube is 2.0cm, the inner diameter of the outer tube is 2.64cm, and the gap between inner and outer tube is 0.32cm. When an electric potential is applied across these electrodes, the glass walls serve as a dielectric causing the current to diffuse into a plasma in the annulus. Using this reactor design, plasmas can be generated at atmospheric pressure using frequencies below 1000Hz. For the measurement of the secondary voltage, a Simpson AC high voltage probe was used in conjunction with a Simpson 620 multimeter. The primary power input (total power input to plasma reactor) was measured by General Electric wattmeter. Gas flow rate to the reactor was measured using a calibrated rotameter.

Table 2. Geometries of the plasma reactors.

Reactor	Diameter				Gap	Diameter Ratio	Length	Effective Discharge Zone
	Inner Tube		Outer Tube					
	D1 (cm)	D2 (cm)	D3 (cm)	D4 (cm)	(D3-D2)/2 (cm)	(D3/D2)	(cm)	(cm)
#1	1.27	1.50	2.19	2.50	0.345	1.460	37.5	20.2
#2	1.55	1.80	2.19	2.50	0.195	1.217	37.5	20.2
#3	1.77	2.00	2.64	3.00	0.320	1.320	37.5	20.2

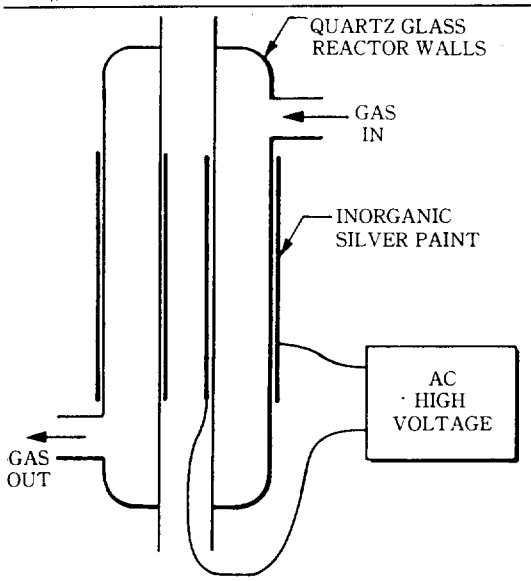

Fig. 3. Alternating current plasma reactor.

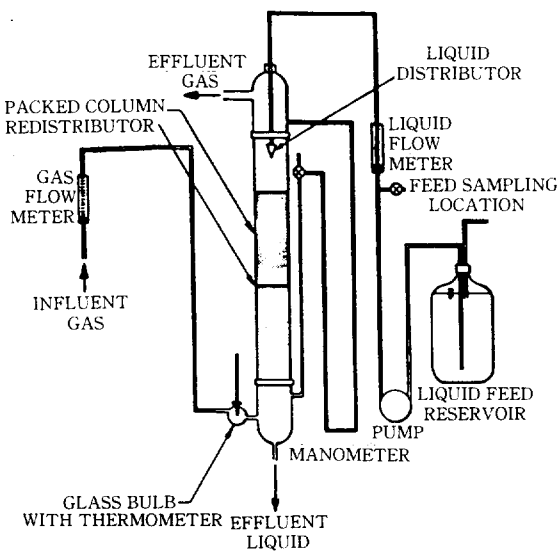

Fig. 4. Schematic of air stripping system.

In the second phase, feed gas to the plasma reactor was supplied from a pilot scale AST, instead of the TCE-saturation device. TCE was not added to the feed water of the AST. Therefore, a TCE-free off-gas was fed to the plasma reactor. The reason for using the pilot-scale AST was to generate large quantities of off-gas with the appropriate temperature and humidity. A schematic of the air stripping system is shown in Figure 4. The air stripping tower was composed of a glass column with an inside diameter of 7.52cm (3in) and a length of 1.83m (6ft). The column was packed with a ceramic packing material. The packing height was 1m. The AST operating condition were : Water (TCE-free) flow rate, 1 ℓ/min ; Water temperature, 22℃ ; Air flow rate, 30 ℓ/min ; Air temperature, 24℃ ; Pressure drop across the tower, 80N/m³/m.

The experimental procedures for the non-destructive tests was ;

(A) The AST was turned on and the water and air flow rates were set to 1 ℓ/min and 30 ℓ/min, res-pectively. These flow rates were kept constant throughout the experiment.

(B) A small portion of the off-gas flow from the AST was separated from the main flow using a T-connection. The amount of the slip stream was adjusted by using a control valve to obtain the desired flow rate. The branch stream was directed to the top port of the reactor and exited from the bottom. The off-gas from the reactor and AST was vented to a hood.

(C) The supply power was turned on and the primary voltage was set.

(D) The frequency was varied from 60Hz to 1000Hz with a 100Hz increment. The secondary voltage and primary power input (watts) were recorded for each frequency. There were some fluctuations in all the gage-readings at the frequency that is nearest to breakdown (optimum frequency). About 10 minutes was allowed to pass to establish steady state conditions.

(E) With the same reactor, the steps 3 and 4 were repeated for three different primary voltages.

(F) Tests were continued for other reactors.

(G) For reactor #3, tests were repeated for the different flow rates (1 to 12 ℓ/min) to the reactor.

3. RESULTS AND DISCUSSION

In the first phase, highly contaminated air with TCE (9000ppm) was created and used as a feed stream to the plasma reactor. The gas-phase concentration, ppb or ppm, was expressed on a volume/volume basis and not by a weight/weight basis in this study. Grab samples of the feed and effluent were taken during test runs and analyzed on an GC equipped with an electron capture detector (ECD). Destruction efficiencies of TCE based on peak area were 92.0% and 93.8% for the two tests with only a trace of by-products showing up on the chromatograms. Air with high concentration of TCE did not require more electric power than blank (uncontami-nated) air did. After taking those two data points, TCE destructive tests were not continued as part of this study. Later, TCE destructive tests were conducted by other researcher (Tsai, 1990), and high destruction efficiencies (>95%) were obtained. The results from the tests (Tsai, 1990) were used in this study for the cost calculations of the plasma reactors.

In the second phase, the plasma reactor was connected to the AST to investigate the electrical characteristics of the total system with respect to power, frequency, and voltage. A series of breakdown tests with TCE-free air (non-destructive tests) were performed to determine the breakdown voltages and frequencies of the plasma reactor. Here, breakdown means that the flowing gas is ionized so that a plasma is established in the reactor cavity.

The frequency of the current was varied from 60Hz to 1000Hz in 100Hz increments. Figures 5, 6, and 7 show the variations of secondary voltage with frequency at different primary voltages for the various reactors. The voltage remains fairly constant until a noticeable increase of voltage is observed at breakdown or corona starting frequency followed by a gradual decrease. As the primary voltage increases from 20V to 60V, the frequency that draws maximum secondary voltage decreases in all reactors.

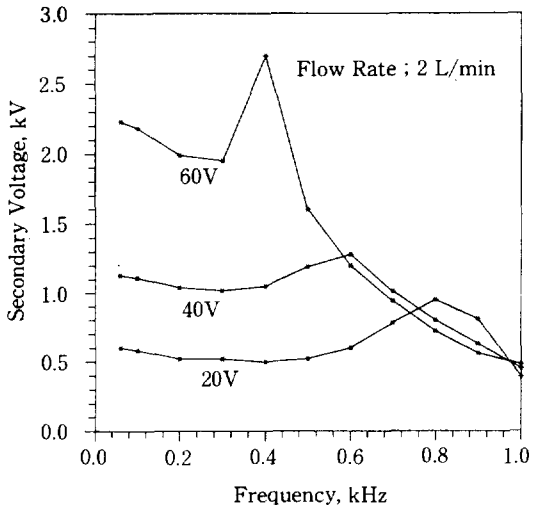

Fig. 5. Effect of frequency and primary voltage on secondary voltage for reactor #1.

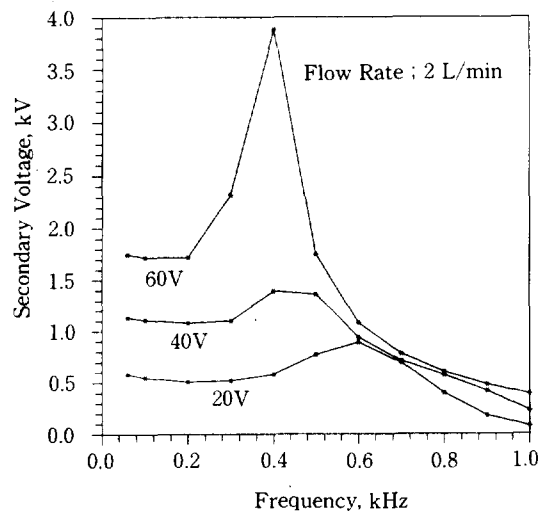

Fig. 6. Effect of frequency and primary voltage on secondary voltage for reactor #2.

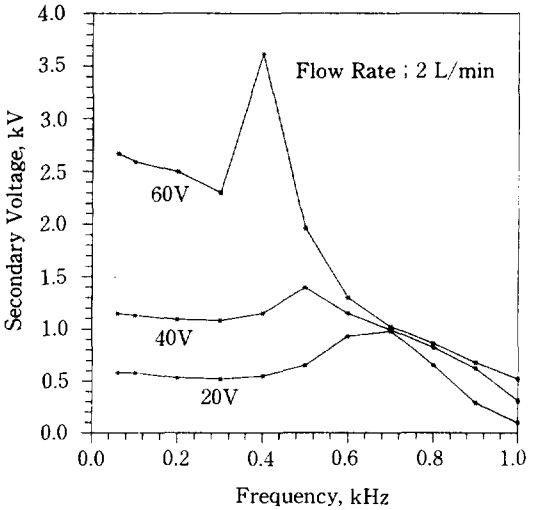

Fig. 7. Effect of frequency and primary voltage on secondary voltage for reactor #3.

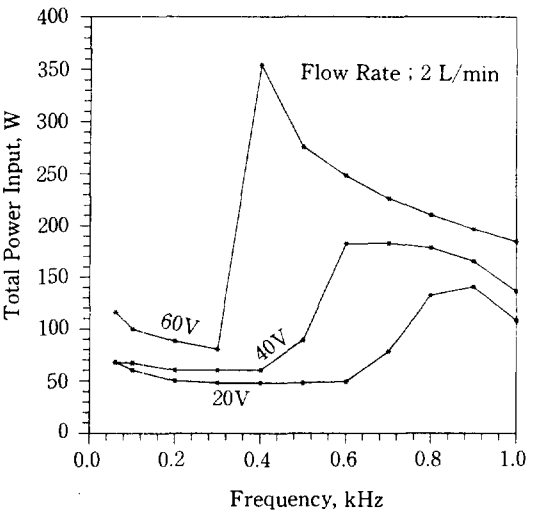

Fig. 8. Effect of frequency and primary voltage on total power input for reactor #1.

Total power input for the reactor is shown in Figures 8, 9, and 10. The word, total, is used here because the net power input to sustain the plasma will be a portion of the total power. The other remaining portion of the total power will be dissipated in other electrical devices such as the frequency generator and transformer. The net power input to the plasma reactor was not measured due to the lack of avail-able measuring devices. However, the total power input to the plasma reactor is actually what the reactor electrical cost is based on. The total power input reaches a maximum value immediately after the plasma is established. Total power input to the system is dependent on frequency. As the frequency increases, the power input remains fairly constant until a steep increase up to a maximum is observed followed by a gradual decrease. All three reactors showed the same trend. As showed in other study(Tsai, 1990), the maximum power

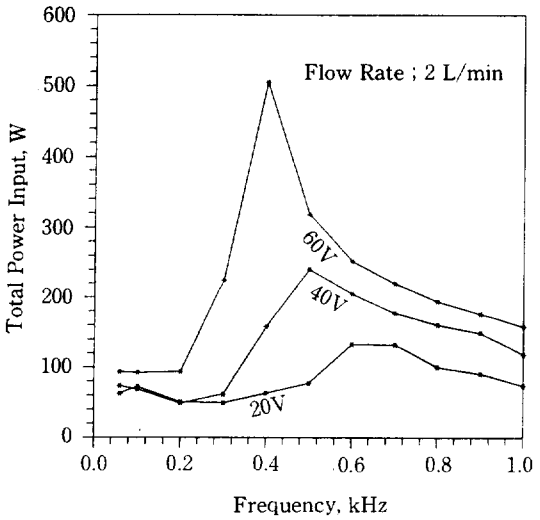

Fig. 9. Effect of frequency and primary voltage on total power input for reactor #2.

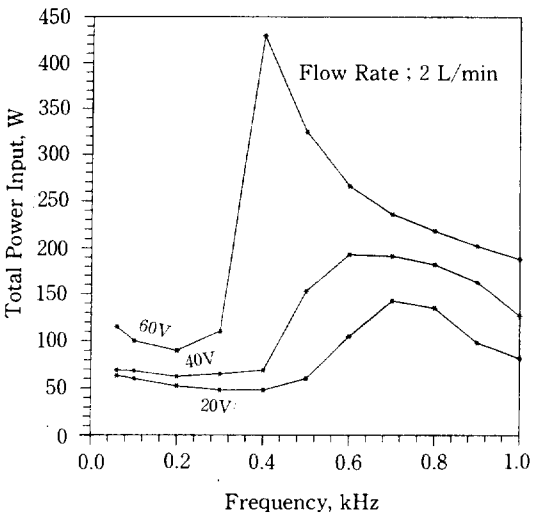

Fig. 10. Effect of frequency and primary voltage on total power input for reactor #3.

input yielded the maximum conversion of the target contaminant. Therefore, the frequency that draws the maximum power input may be called the optimum frequency. The optimum frequency was also dependent on the reactor geometry and the primary voltage applied as showed in Figures 8, 9, and 10. As the primary voltage increases from 20V to 60V, the optimum frequency decreases in all reactors. The optimum frequency roughly coincides with the frequency that draws maximum secondary voltage in Figures 5, 6, and 7. The system can be tuned by varying the frequency to obtain higher power input. A higher primary voltage increases secondary voltage and total power input for all reactors.

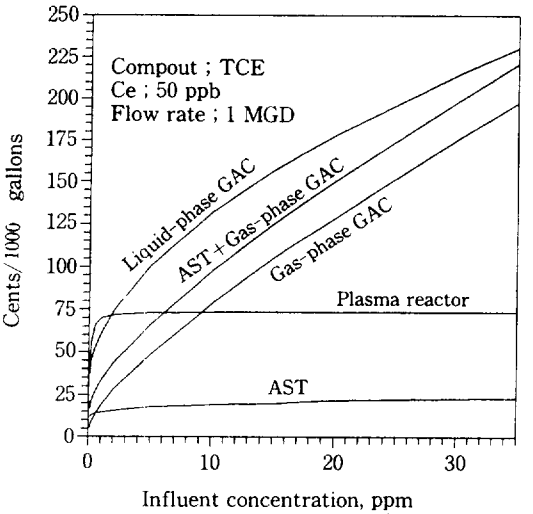

Fig. 11. Effect of influent concentration on the cost of treatment processes.

Volumetric flow rate of the feed gas determines the residence time of the gas in the discharge zone. Flow rates were varied from 1 ℓ/min to 12 ℓ/min with reactor #3. Power input did not change as the flow rates changed at each frequency (60-1000Hz) and at each primary voltage (20V, 40V, and 60V). That is, the shape of the Figure 10 did not change at varying flow rate. There were some fluctuations in power input at the optimum frequency as the flow rate increased. This power fluctuation over time was a typical phenomenon of the plasma even at constant flow rates.

Preliminary Economics : The power cost of the plasma reactor was estimated and compared to the total cost of other processes such as liquid-phase GAC and AST+gas-phase GAC. Capital cost, by-products removal cost, and operation & management cost were not included in the plasma reactor evaluation. A total power input of 130W and an air flow rate of 7 ℓ/min, the highest flow rate in the destruction tests (Tsai, 1990),

were used for cost estimation. The results from the study conducted by Yoo were used (Yoo, 1991). Figure 11 shows the results. The effluent concentration, Ce, is the liquid-phase concentration coming out of the AST or liquid-phase GAC. A removal rate of 95% from the off-gas of an AST is assumed using either gas-phase GAC or a plasma reactor. The influent liquid-phase concentration was varied from 100ppb to 35000ppb TCE. The 35000ppb (35ppm) represents one of extreme groundwater contamination (Council, 1981). Air stripping without off-gas control was shown to be the least cost option. Off-gas control using gas-phase GAC costs more than air stripping itself in the high concentration range (>0. 5ppm). However, the combined cost of the two processes is less expensive than liquid-phase adsorption using GAC. The cost of a gas-phase or liquid-phase GAC contactor is highly dependent on contaminant concentration while that of plasma is not. Plasma reactor will have an advantage at high contaminant concentrations. In adilute system which is a common groundwater contamination level, however, the plasma reactor is an expensive process in spite of the fact that the cost represents only electric power cost. Moreover, this price should be added to that of the air stripping process to obtain a total system cost. It may be too early, to conclude that the plasma reactor is not suitable as an off-gas control device for ASTs. The experiments were not conducted on a fully optimized design. Also, scaling up may increase the power efficiency that is actually transferred to the plasma reactor.

4. CONCLUSIONS

A preliminary evaluation of a plasma reactor was conducted to investigate its potential as a feasible and economical off-gas control technology for an AST. The specific findings of the study are summarized below :

(A) Destruction tests conducted on an air stream containing TCE showed a plasma reactor was capable of greater than 90% destruction efficiency.

(B) Studies conducted to investigate the electrical characteristics of the plasma reactor showed that an optimum frequency for the alternating current exists for maximum power input. The optimum frequency is dependent on the reactor geometry and the primary voltage applied.

(C) The total power input to the plasma reactor did not increase as the air flow rate to the unit increased from 1 to 12 ℓ /min.

(D) For heavily contaminated air streams, the plasma reactor is a economical treatment technology than a gas-phase GAC system. In a dilute system, however, the plasma reactor is a more expensive process at this stage of development.

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