Pulsed Corona Plasma Technology for Treating VOC Emissions from Wood Products Plants

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ABSTRACT

This DOE project DE-FC36-04GO14052 “Plasma Pilot Plant Test for Treating VOC Emissions from Wood Products Plants” was conducted by Drexel University in cooperation with Georgia-Pacific (G-P) and Kurchatov Institute (KI). The objective of this project was to test the Plasma Pilot Plant capabilities in wood industry. The final goal of the project was to replace the current state-of-the-art, regenerative thermal oxidation (RTO) technology by Low-Temperature Plasma Technology (LTPT) in paper and wood industry for Volatile Organic Components (VOC) destruction in High Volume Low Concentration (HVLC) vent emissions. MetPro Corporation joined the team as an industrial partner from the environmental control business and a potential leader for commercialization. Concurrent Technology Corporation (CTC) has a separate contract with DOE for this technology evaluation. They prepared questionnaires for comparison of this technology and RTO, and made this comparison. These data are presented in this report along with the description of the technology itself. Experiments with the pilot plant were performed with average plasma power up to 3.6 kW. Different design of the laboratory and pilot plant pulsed coronas, as well as different analytical methods revealed many new peculiarities of the VOC abatement process. The work reported herein describes the experimental results for the VOCs removal efficiency with respect to energy consumption, residence time, water effect and initial concentration.

INTRODUCTION

Low-temperature, non-equilibrium plasmas are an emerging technology for VOC-emission control. Under the DOE Office of Industrial Technologies, Forest Products program, four plasma technologies were evaluated under the project DE-FC07-00ID13868 “Experimental Assessment of Low-Temperature Plasma Technologies for Treating Volatile Organic Compound Emissions from Pulp Mills and Wood Products Plants”. This project was conducted by the team that included University of Illinois at Chicago (UIC); Argonne National Laboratory (ANL); Pacific Northwest National Laboratory (PNNL); Georgia-Pacific Corporation (G-P); Ecos Ltd., Kurchatov Institute of Atomic Energy, Moscow, Russia (KI); and Drexel University (DU). On the last stage of the project the trailored pulsed corona pilot plant was developed at Drexel University and prepared for the test at Georgia-Pacific Port Hudson mill in Zachary, Louisiana. The test supposed to be done at HVLC Brownstock Washer Vent system. As due to different reasons (mostly funding) the pilot plant was prepared for the test with significant delay, G-P rearranged their priorities in Low-Temperature Plasma Technologies (LTPT) commercialization and put on the first place a field test and commercialization of the technology for Oriented Strandboard (OSB) press vent emission. As this test demanded some modification of the technology and the Pilot Plant itself, this DOE project DE-FC36-04GO14052/A000 "Plasma Pilot Plant Test for Treating VOC Emissions from Wood Products Plants" was initiated. This project was started by Drexel University in cooperation with G-P and KI. The objective of this project was to test the Plasma Pilot Plant capabilities in wood industry. The final goal of the project was to replace the current state-of-the-art, regenerative thermal oxidation (RTO) technology by Low-Temperature Plasma Technology (LTPT) in paper and wood industry for VOC destruction in HVLC vent emissions.

Decision regarding the project funding was made in 2002, but real funding started from the beginning of 2004. The trailored Pilot Plant (PP) or Mobile Environmental Plasma Laboratory (Fig. 1) was completely built in the beginning of 2003. Cost of the system development appeared to be significantly lager than expected, so PP was developed partially with the Drexel University (DU) support. Also, DU supported maintenance of the PP between the two DOE funded projects.

On one hand, G-P supposed to spend significant funds for the field test, one the other hand two universities (UIC and DU) have developed Intellectual Property (IP) [1-3] related to this technology and some uncertainty with the IP owner appeared. Therefore G-P announced the following requirements that should be satisfied before the field test:

- *A commercialization team should be developed and it should have a realistic commercialization plan.*
- *The team should include a major vendor with well known name in the environmental control business.*
- *IP and commercialization right issues should be clarified between the team members.*
- *The technology should be evaluated by the "third party" before the field test.*

Thus, Drexel University as a prime contractor for this project was involved in four different activities:

1. Commercialization efforts, including team development, IP rights negotiation, etc. to satisfy GP requirement;
2. Pilot Plant maintenance and modification for test in wood products industry;
3. Tests of the technology using the pilot plant. Previous laboratory test were made using system with only 20 Watts plasma power. It did not look reasonable to start a field test of the system with expected plasma power of 6 kW (300 times scaling!) without preliminary internal tests.
4. Co-operative efforts with the Concurrent Technology Corporation (CTC), the company selected by DOE as a "third party", in technology evaluation from the commercialization point of view.

The results of our efforts in all these directions are presented in the following chapters.

Fig. 1. Photographs of the Mobile Plasma Pilot Plant

TECHNOLOGY COMMERCIALIZATION

Commercialization efforts were directed by G-P requirements. UIC made separate efforts to commercialize the IP developed in UIC. They came with potential licensee, Commerce Services Corporation. This company is not a major player in environmental control business, so after a couple rounds of negotiations, G-P rejected this company as a potential leader for the technology commercialization in wood industry, at least on plants controlled by G-P. Nevertheless, UIC trying to commercialize their IP created a long delay in development of mutual agreement between universities and a potential major vendor (see below).

Drexel University initially contacted several companies involved in powerful electronic production, like Inductotherm Corporation [4] and NWL [5]. They express high interest in manufacturing of new plasma generation equipment, but they can not be major vendors for environment control equipment, so they should be subcontractors in the commercialization efforts.

Finally a potential major vendor was found. This is Met-Pro Corporation [6], a well-known company in the environmental control business. G-P confirmed that Met-Pro can be considered as a major vendor. Drexel University made several experiments using Pilot Plant (see results in the following chapters) together with MetPro representatives. These experiments convinced MetPro that this technology may have a bright future, and MetPro agreed to lead the commercialization efforts. Later MetPro have requested and analyzed IP from Drexel University and UIC. Mr. Clark Griffith was assigned by MetPro as their representative for technical issue discussion. Drexel University provided him with available information regarding different companies that has ability to manufacture pulsed power supplies. Now MetPro negotiates with Drexel University and UIC the licensing agreements.

Commercialization plan was discussed and developed with G-P representative (Mr. Lawrence Otwell) and MetPro representative (Mr. Thomas Edwards). The plan includes the following steps:

- Field test of the Pilot Plant at G-P facility at Brookneal, VA;
- Full-cycle one-year demonstration experiment with plasma power on the level of 100 kW. As this demonstration experiment will be relatively expensive, so it is expected that the cost of the experiment will be shared by G-P, DOE, a major vendor and sub-vendors. Therefore the appropriate proposal should be prepared and sent to DOE.
- In the case of successful demonstration experiment, the prime vendor should supply G-P with about 7 full size (about 300 kW plasma power) systems in years 2006-2008.

G-P had reserved for FY 2005 $300,000 for the Pilot Plant and Demonstrational experiments. Unfortunately, delay with mutual agreement between universities (caused by UIC separate efforts to commercialize their IP) results in a general delay in commercialization, and G-P reallocated the reserved funds for other purposes.

Concurrent Technology Corporation (CTC), the company selected by DOE as a “third party” evaluator (Project No. 01021.02.01) has prepared a couple of surveys: one for Georgia Pacific about available RTO technology and another for Drexel University about Plasma Technology. These surveys contain some questions related to the equipment erection, like price of the base, etc. Drexel University with the help of MetPro filled out all data related to the plasma technology; MetPro also filled out the data related to the RTO technology, as MetPro is a vendor of this kind of technology and equipment. All these data were submitted to CTC for their evaluation. This data are presented in the Attachments 1 and 2. Recently CTC sent to Drexel University a draft of their report to DOE [7]. They use data for RTO presented by G-P but not by MetPro through Drexel: “Drexel also supplied information on the RTO, but CTC believed, since this information differed significantly from that supplied by GP, that it was best to use the GP-supplied RTO data, since the RTO is owned and operated by GP.” CTC evaluation conclusion is positive for the plasma technology: “Using information provided to date by Drexel and GP, the results of the cost analysis performed by CTC show that with regard to treatment of the offgas from the OSB press vent at the GP Brookneal, Virginia facility, conversion from the baseline RTO to the alternative PCR would result in a cost savings. This would be dependent upon realization of the estimated $171,439 annual savings based on the data supplied. The majority of this annual cost savings is from reduced utility costs and an estimated materials cost reduction.”

Two provisional patent applications [2, 3] (see Attachments 3 and 4) were submitted to the US patent office as a result of technology development and commercialization efforts. One invention is on the disclosure stage yet and is not presented here.

Thus, all requirements of G-P were fulfilled, unfortunately with significant delay cased by the reasons that are out of our control.

PILOT PLANT MAINTENANCE AND MODIFICATION

The Pilot Plant is an expensive facility with modern equipment that was developed to work in a field conditions, but should not be stored in unsecured place. On the other hand, this is a very balky facility from the University point of view: mounted on a trailer of 48’ length, 8’ width and with total height of almost 13’. Special room was designed and built for PP placement in the basement of the former publishing house in the center of Philadelphia (Fig. 2).

The room has an access for a trailer and tractor, power, water, ventilation and a drainage line for the PP tests. The room was designed and built and the space is still rented for the Drexel University money.

Fig. 2. Photograph of the Mobile Plasma Pilot Plant storing place (left) in the basement of One Drexel Plaza building (right).

As it was mentioned before, the trailored Pilot Plant (PP) or Mobile Environmental Plasma Laboratory (Fig. 1) was completely built in the beginning of 2003. It was built according to the requirements discussed earlier with G-P representatives in December of 2000, at G-P hosted meeting at the Port Hudson facility. At the end of 2003 it was the second meeting at the Port Hudson facility where description of the existing pilot plan were presented in details and technical questions were discussed. During this meeting some new safety, legal and technical issues were raised by G-P team. One very simple technical issue – requirement to have oil-catching tanks under the oil-filled high-voltage transformers, was unexpected and rather difficult to satisfy, as the transformers were already firmly mounted on the trailer, and installation of the tanks demanded considerable reconstruction of the Pilot Plant. Finally, this issue was resolved after precise measurements of the transformers volumes and available space (see Fig. 3). The oil-catching tanks were designed, ordered, manufactured, built and installed.

Fig. 3. Oil-Catching tanks installed under the high-voltage transformers.

Preliminary experiments with the Pilot Plant pulsed corona demonstrated that its working conditions were far from the optimal ones. Additional efforts were made with the help of KI representatives to improve matching between the power supply and pulsed corona, and as a result the plasma power of the corona system was increased. Nevertheless, an important mistake was made during the power supply manufacturing – the high voltage transformer cases were made from magnetic steel. As a result these cases absorb significant part of electrical power (about 1 kW according to our evaluations made using oil temperature measurements during a long term test). This power absorption together with possible operation in a hot climate leads to the requirement of transformer oil cooling. Special system of oil cooling was developed (Fig. 4) that consists from a closed oil loop with an oil pump, two transformer cases (in parallel), and a water cooled plate-type heat exchanger.

Fig. 4. Oil-cooling system elements installed between the high voltage transformers: the oil pump and plate-type heat exchanger.

After a year of the pilot plant in use some problems appears in the control system (Fig. 5) cooling: water temperature during summer is not low enough to run long experiments with full power.

Fig. 5. Pulsed corona control unit.

Analysis of this problem showed that the reason of low-efficiency cooling is the design of transistor-holding heat exchanger (Fig. 6). Large cross section of the water channel results in laminar flow in the heat-exchanger, and aluminum material results in thermal barrier formation on the internal heat exchanger wall. Totally this results in system overheating even if the exhaust cooling water is relatively low. This problem was resolved by development of a new copper-based heat-exchanger with smaller cross section for water flow (Fig. 7).

Fig. 6. Old heat exchanger for control system transistor cooling

After these modifications Drexel University successfully performed a long run (8 hours) test of the system with 100% power.

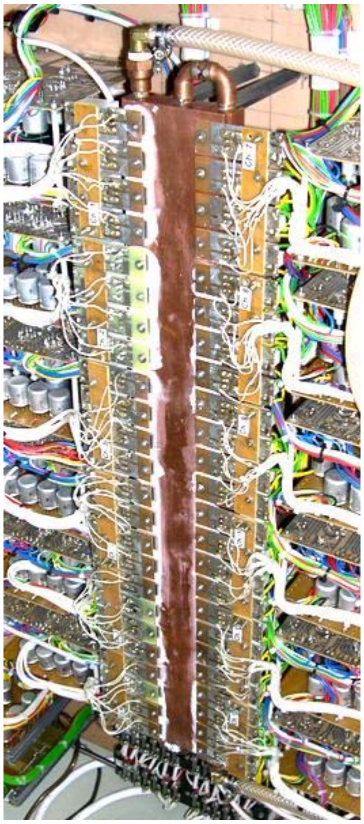
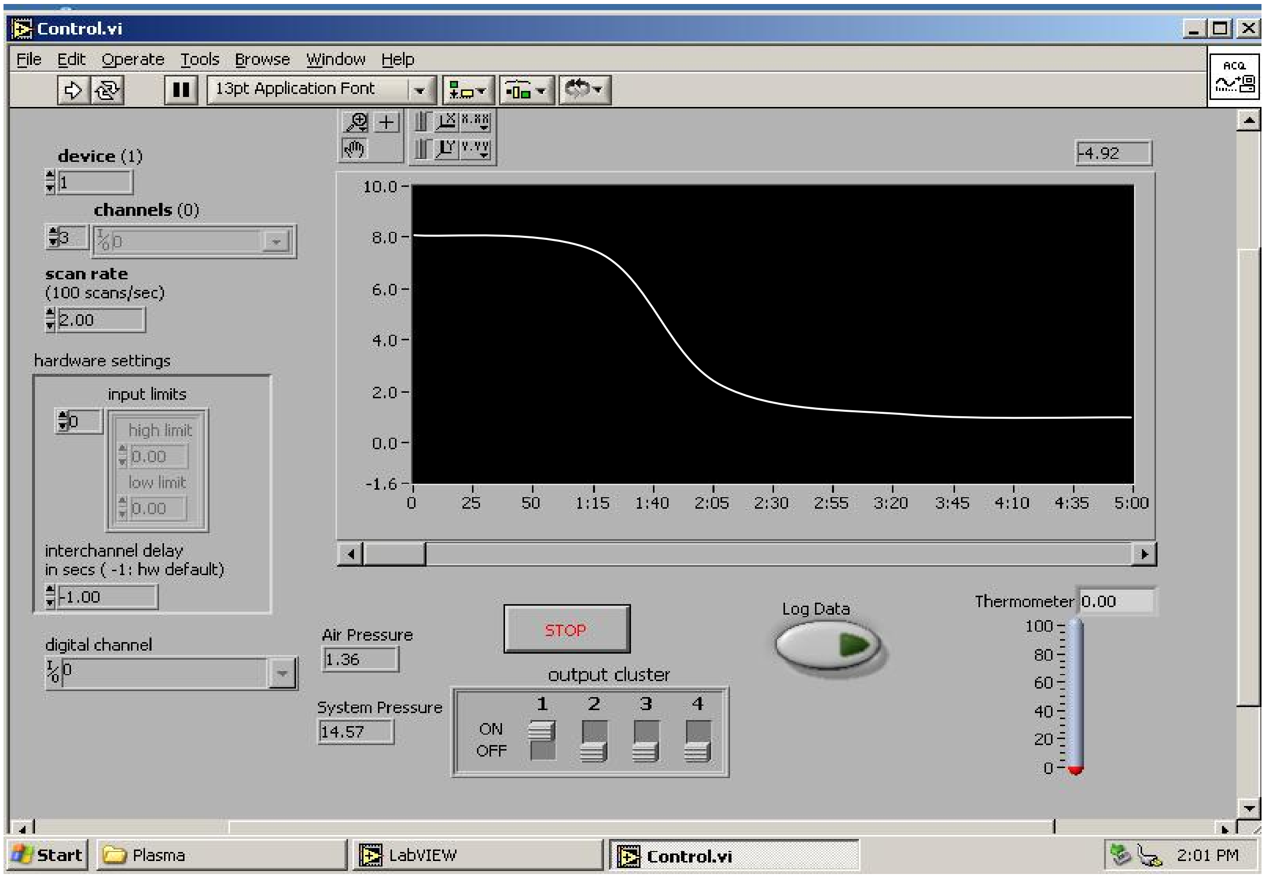


Fig. 7. New heat exchanger for transistor cooling in the control unit

Preliminary experiments demonstrated the necessity to make automatic control of the most parameters of the Pilot plant. Preliminary mathematical scheme of the system operation was developed in the framework of the previous project [8, 9]. In the framework of this project a real working system for data acquisition and representation was developed. All parameter were collected by PC and presented using LabView software (Fig. 8).



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hardware settings

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low limit: 0.00

interchannel delay in secs (-1: hw default): -1.00

digital channel: 0

Air Pressure: 1.36

System Pressure: 14.57

Thermometer: 0.00

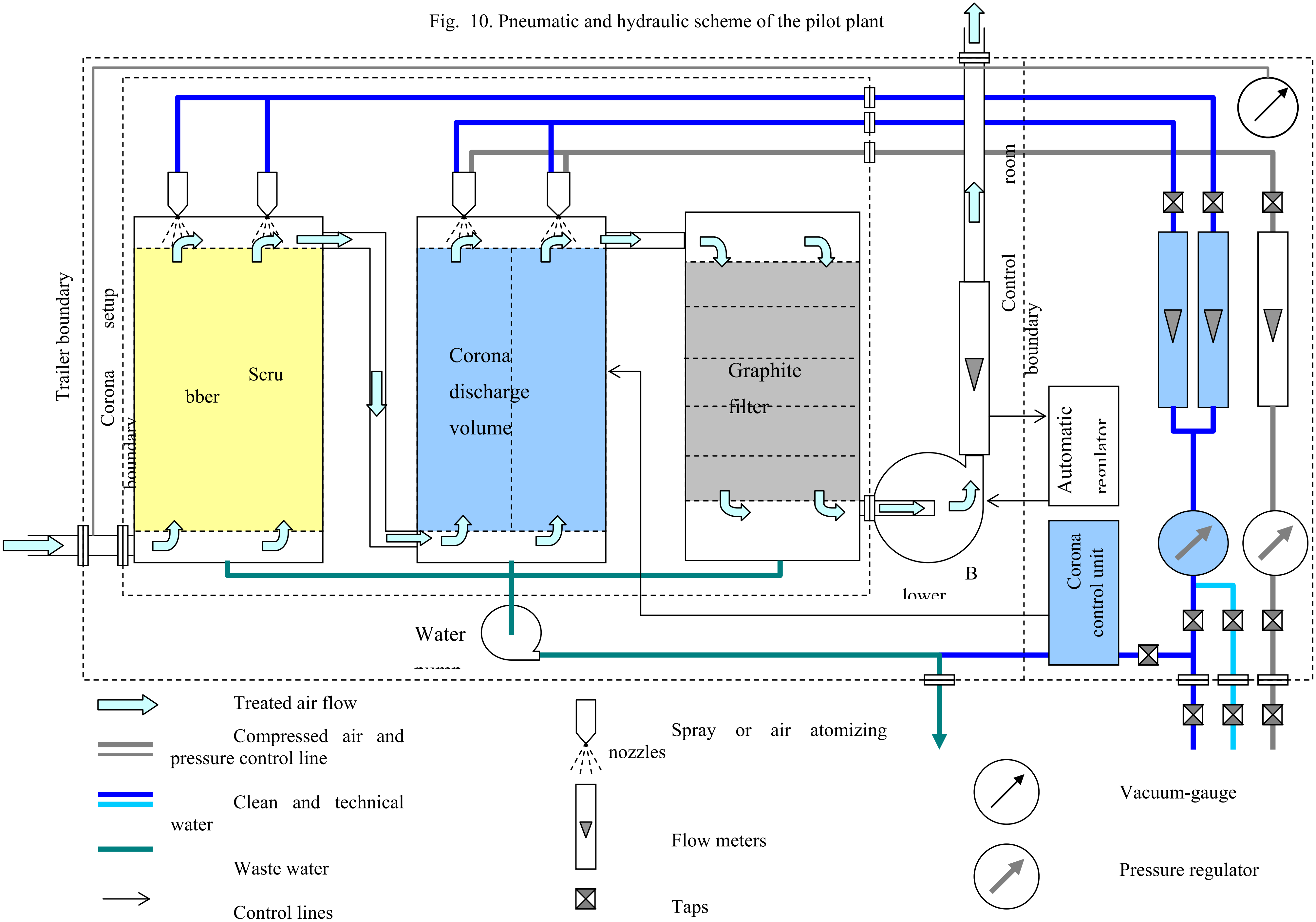
-4.92

Fig. 8. LabView screen for the Mobile Plasma Pilot Plant systems control.

The major data that the program shows is the time dependence of the total hydrocarbon concentration in the particular sample port measured by the California Analytical Model 300HFID/MHFID Heated Hydrocarbon Analyzer (Fig. 9), but also this software controls most of key elements of the Pilot Plant hydraulic (Fig. 10) and control schemes (Fig. 11).

Fig. 9. Heated Hydrocarbon Analyzer.

Fig. 10. Pneumatic and hydraulic scheme of the pilot plant



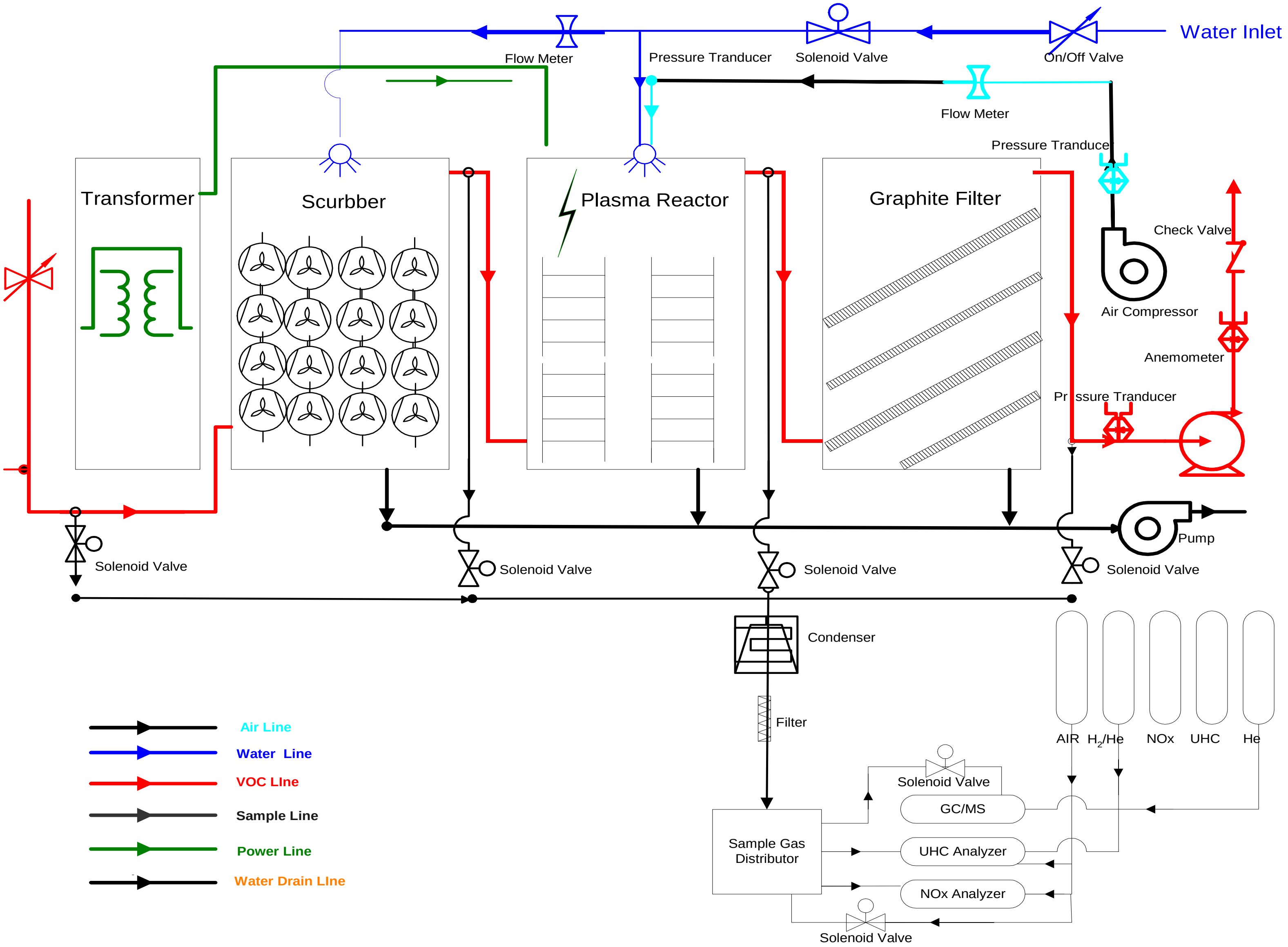


Fig. 11. Control Scheme of the Pilot Plant

Some modifications were made specifically to run experiments with simulated gas mixtures (see the following chapter). These modifications include, for example, extension of the inlet pipe (Fig. 12) to avoid pulsation of the VOC concentration in the test points. Large diameter of the inlet pipe results in formation of large turbulent eddies in the pipe, and admixing of VOC near the pipe inlet resulted in VOC concentration pulsation. Pipe extension solved this problem.

Fig. 12. Inlet pipe extension for stabilization of VOC concentration in the test points.

Another modification was related to the tests with spray addition into the corona volume. According to theoretical estimations, pH of the solution sprayed can play an important role in the Destruction and Removal Efficiency (DRE) of VOCs in the pulsed corona discharge. Basic solution of KOH with pH=12 was prepared in the barrel installed over the reactor level (Fig. 13) and sprayed instead of water in some experiments. It is also possible to see in Fig. 10 connection of the Pilot Plant exhaust with ventilation system.

Fig. 13. Drum for basic solution and the Pilot Plant exhaust pipe.

TESTS WITH METPRO CORPORATION, SYSTEMS DIVISION, KULPSVILLE, PA

Pilot Plant Overview

Figures 10 and 11 illustrate the schematic diagrams of the pilot plant including sampling, measuring and calibration equipment. Basically the pilot plant process consists of three stages of gas treatment (see more details in [8, 9]):

1. Preliminary washing of the exhaust gas stream by a water shower for removing particulates and soluble VOCs such as methanol and acetone.

2. Exhaust stream treatment by dry or wet pulsed corona discharge for VOC oxidation.
3. Removal of the balance of ozone and VOC by self-cleaning adsorbent.

The first stage is similar to scrubbing. For maximum removal of soluble VOCs, the direction of the water flow is opposite to that of the gas stream. System and water flow rate were optimized to reach highest scrubbing efficiency of the soluble VOCs with expected gas flow rates and to prevent water droplets from being carried over by the gas stream. It was presented in the previous laboratory experiments and modeling that it was possible to remove nearly all the soluble VOCs using this technique [8 - 10]. The scrubber volume is about 1 m^3 and is filled with special low density-high surface packed bed material.

In the second stage, the gas stream is treated in the pulsed corona discharge plasma reactor, which includes an option of supplying a water spray flow into the discharge volume. Compressed-air atomizers are used for spray formation. The pulse corona discharge unit consists of 12 units (channels), and each of them includes high-frequency converter with an intermediate frequency of 25 kHz on the base of field (IGBT) transistors, pulse high-voltage transformers, work capacitance and special high-voltage self-firing discharge gap for high voltage pulse formation on the corona electrodes. Discharge power is regulated by stepwise changing of the pulse repetition frequency in the range 20-100% (20%, 40%, 60%, 80%, and 100%). The main parameters of the corona discharge are the followings: peak voltage is about 40 kV, pulse repetition frequency is up to 1 kHz, and pulse duration is of 200-250 ns. The structure of the pulsed corona discharge blocks (Fig. 14) consists of alternate rows of grounded and high-voltage electrodes. Such a structure provides transparency of the discharge volume for the water spray. Plasma discharge zone is formed by 12 corona blocks installed in three layers. Total discharge volume is about 3.6 m^3.

Fig. 14. Corona block

The last cleaning stage includes adsorption and oxidation of any remaining VOCs with filter. The filter is formed by activated charcoal particles of 3 mm size in layers of 2 cm thickness. Total area of the layers is about 2 m^2. This filter contributes to enhance complete removal of any remaining VOCs, ozone and nitrogen oxides.

The pilot plant has three sampling ports after the three cleaning stages for precise analysis of the removal efficiency. Soluble VOC and products of the plasma-chemical destruction may be removed by industrial wastewater. Additionally clean water flow is necessary for cooling electronic equipment (Figures 5 - 7) and oil of high-voltage transformers (Fig. 4).

Results and Discussion

Experiments with the Pilot Plant were performed together with MetPro Corporation, Systems Division, Kulpsville, PA, with average plasma power up to 3.6 kW. Different design of the laboratory and pilot plant pulsed coronas, as well as different analytical methods revealed many new peculiarities of the VOC abatement process. The work reported herein describes the experimental results for the VOCs removal efficiency with respect to energy consumption, residence time, water effect and initial concentration. In addition, generation of organic byproducts which are hardly removable by plasma is discussed.

Fig. 15 shows overall combination effect of scrubber and plasma on removal of methanol. Temperature of the plasma reactor is kept constant (room temperature). It is possible to reach desirable level of Destruction and Removal Efficiency (DRE) (for example 98%, according to the new U.S. regulations for paper and wood industry) by two ways: just by plasma power increase, or by combination of small plasma power level with scrubbing. If scrubbing and following water treatment is acceptable (as in paper mills), the second approach looks much more promising. If water discharge is not permitted (as in U.S. wood industry), plasma treatment should be applied without preliminary scrubbing, or additional water treatment system should be built. Plasma treatment of methanol is relatively expensive process, even for low concentrations, because as it was shown earlier [9, 10] energy cost of one VOC molecule oxidation by plasma rises enormously with VOC concentration decrease. Our results are a little better but comparable to that obtained with small 20 W system [8 - 10]: energy cost is about 300 eV per methanol molecule for 12 ppm initial concentration.

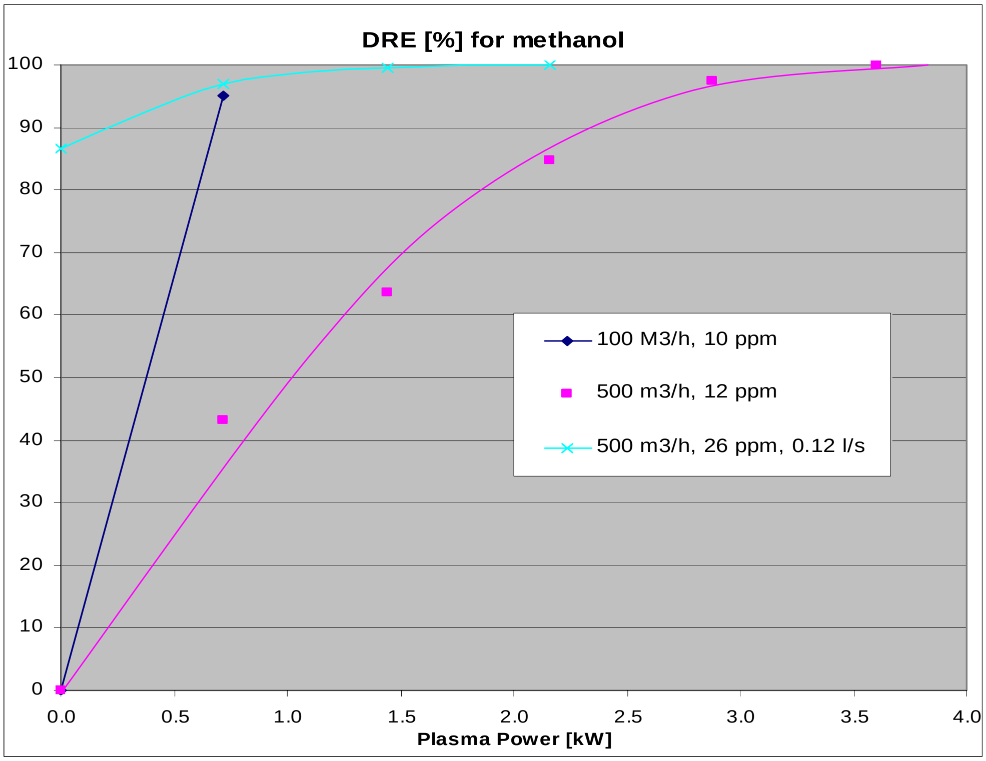


Fig. 15. Methanol destruction and removal efficiency depending on plasma power without and with water scrubbing under 0.12 l/s of water flow rate in scrubber (upper blue curve).

The main analytical tool at the pilot plant is a California Analytical Model 300HFID/MHFID Heated Hydrocarbon Analyzer (Fig. 9), in contrast to a gas chromatograph used in lab experiments [8 - 10]. Thus, instead of direct measurement of concentration for particular VOC we measured cumulative concentration of the initial VOC and all hydrocarbon byproducts.

Methanol oxidation (Fig. 15) in plasma is going without formation of any byproducts [8 - 10], so interpretation of these results is very simple. As it was demonstrated earlier [8 - 10] oxidation of dimethilsulfide (DMS, Fig. 16) in plasma is going faster than oxidation of methanol, but is accompanied by formation of byproducts – methanol and acetone. It is possible to distinguish two parts on concentration curves in Fig. 16: initially concentration of total hydrocarbons going down relatively fast (mostly DMS oxidation with energy cost about 200 eV per DMS molecule for 10 ppm initial concentration), and then much weaker dependence on power (compare with Fig. 15) that corresponds to oxidation of byproducts. It was shown earlier [9 - 10] that elimination of DMS in plasma is going considerably easier than elimination of methanol and much easier than acetone. Addition of NaOH solution spray (0.13 l/s, pH =11.5 and 12.1) into pulsed corona reactor does not change DMS oxidation process considerably.

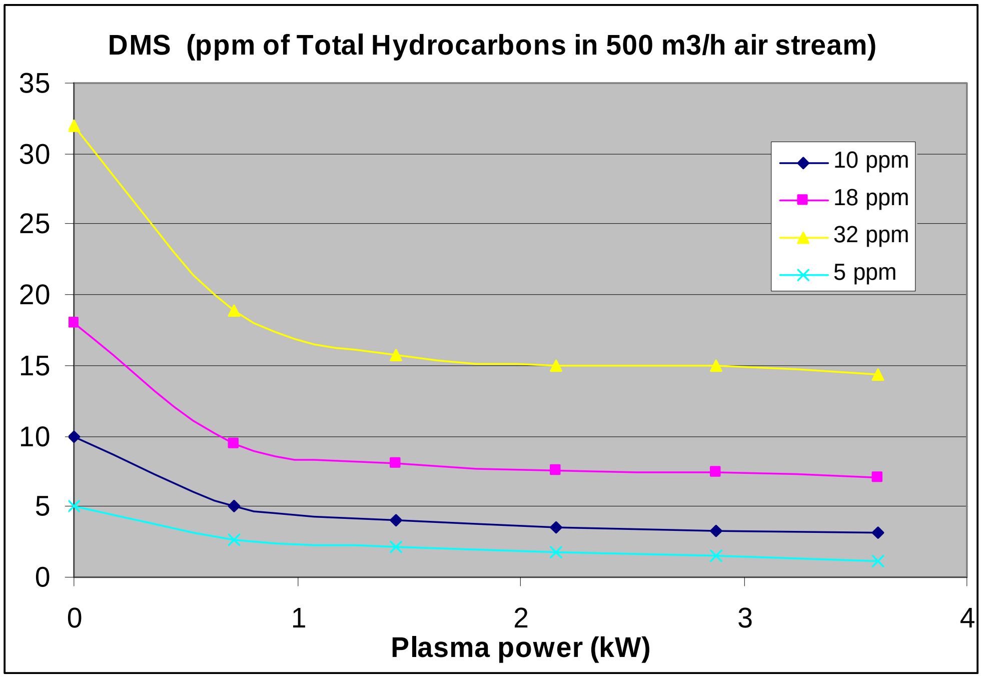


Fig. 16. Dimethylsulfide oxidation in plasma: concentration of total hydrocarbons depending on plasma power.

When we considered alpha pinene ($C_{10}H_{16}$) destruction, influence of by-products formation was not so obvious (Fig. 17) while we used relatively high concentration of alpha-pinene (note that 1 ppm of $C_{10}H_{16}$ corresponds approximately to 10 ppm of total hydrocarbons). Nevertheless, control of by-products using GS-MS (HP5890A gas chromatograph with HP5970 Mass Selective detector – Fig. 18) revealed high-molecular byproducts (like $C_{25}H_{46}$) than contained cyclopentane rings in molecular structure, which seems hardly to decompose, as these molecules can be considered as soot precursors. Strong influence of these by-products was found in experiments with low concentration of alpha-pinene (Fig. 19). This very specific picture hints us to suggest that there are two very different mechanisms of alpha-pinene interaction with plasma products: chain oxidation that starts by some radical and goes without formation of stable by-products; and decomposition by plasma particles (electrons, first of all) with following formation of soot precursors. It is necessary to test this suggestion, and if confirmed this leads to reconsideration of the optimal process organization scheme. Water spray in the corona reactor reduces efficiency of the alpha-pinene elimination process (Fig. 17). Energy cost is about 300 eV per alpha-pinene molecule for 2 and 7 ppm initial concentration (probably the most correct figure is for 2 ppm, see Fig. 19) and 40 eV per molecule for 64 ppm initial concentration. The last figure is in a good agreement with the data obtained using 20 W pulsed corona [8 - 10].

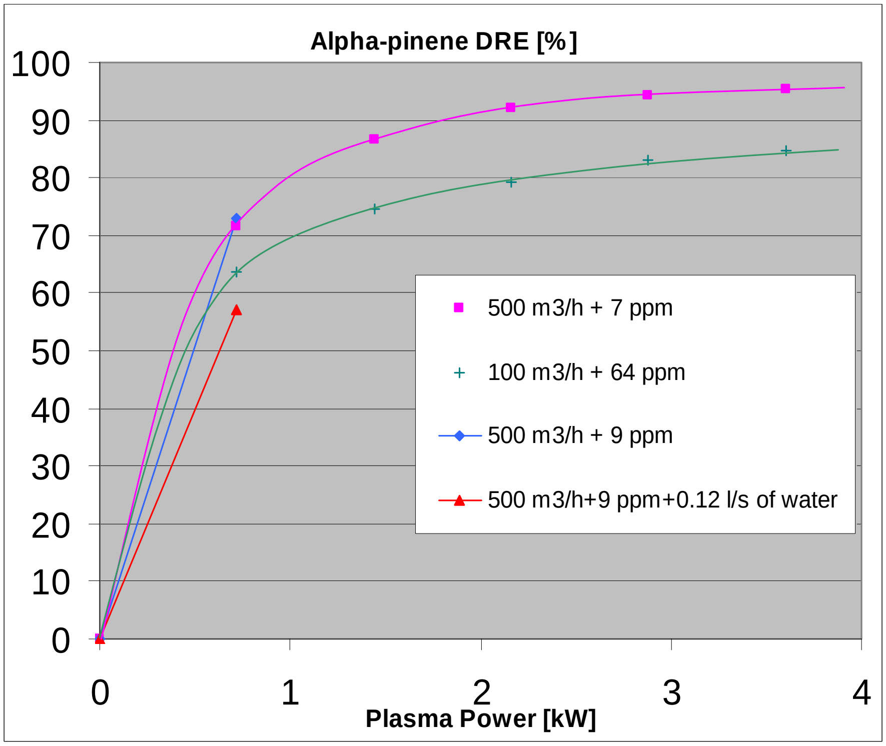


Fig. 17. Alpha-pinene destruction and removal efficiency depending on plasma power without and with presence of water spray in the corona reactor.

Fig. 18. HP5890A gas chromatograph with HP5970 Mass Selective detector

As it was mentioned earlier, energy price is strongly related to the initial concentration. For relatively low VOC levels, high energy price is required. This is due to the fact that not all the active species produced in the gas discharge can actually target VOC molecules, i.e. not all the electric energy to create active species is consumed for oxidation of organic compounds; some of these species undergo reactions with each other or lose their energy on walls. Reactions with VOC molecules are statistically more frequent if the concentration of VOC is relatively high; in this case, the fraction of energy spent for the purpose of removing the molecules is higher and the energy spent for the elimination of each single molecule decreases.

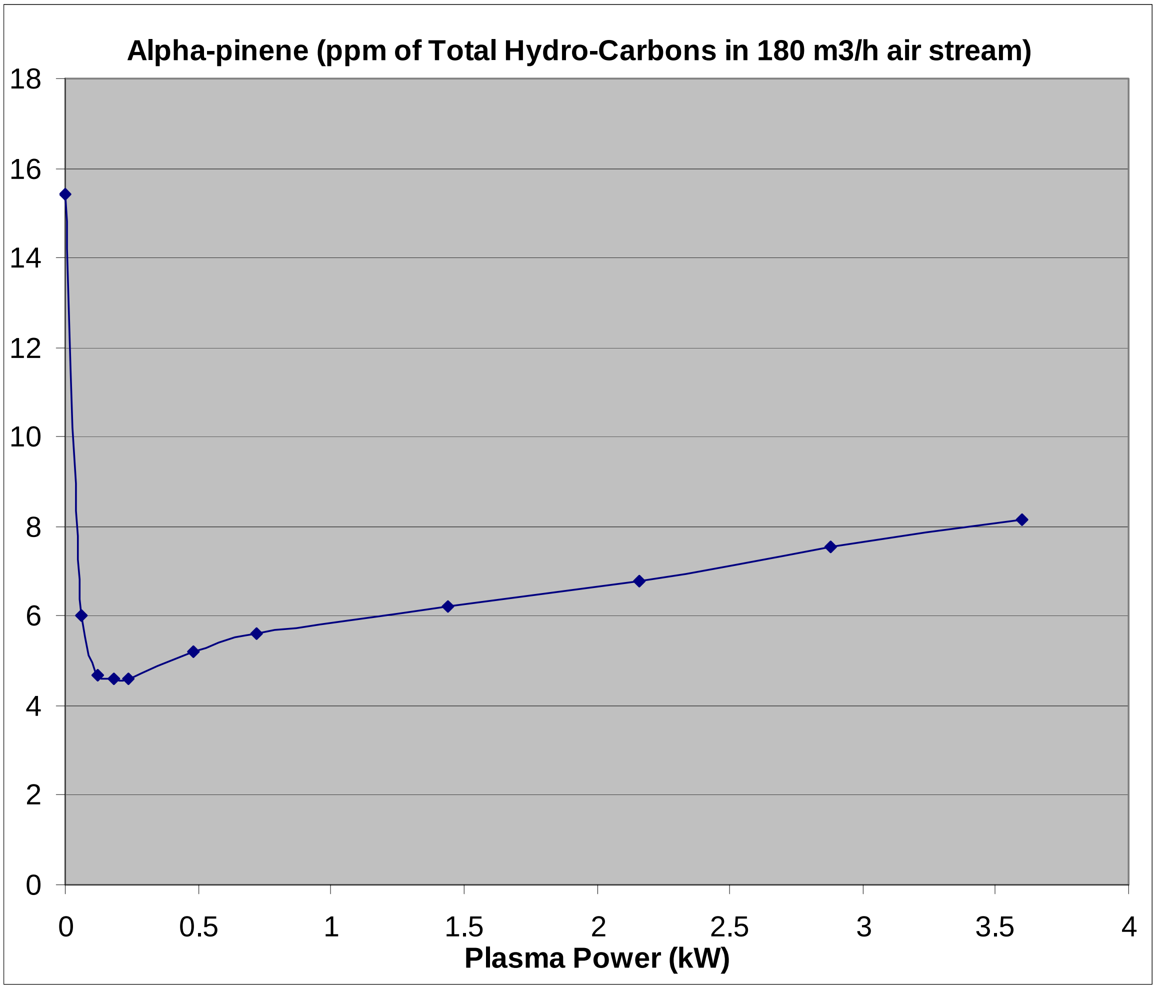


Fig. 19. Alpha-pinene oxidation process accompanied by production of stable by-products.

TECHNOLOGY EVALUATION

OSB Press Vent Cleaning

If to compare characteristic VOC concentration for the Brownstock Washer (BW) (especially “the worst case scenario”) and for Oriented Strandboard (OSB) press vent emissions, it is easy to see the significant difference: OCB press vent emission dos not contain the sulfur compounds, total VOC concentration is very low, and the only insoluble compounds are terpenes, concentration of which are also low. Also, because of “zero water discharge” policy in wood industry, the approach used for BW vent emission can not be used for OSB vent emissions.

	HVLC Brownstock Washer Vent Emissions		Oriented Strandboard Press Vent Emissions
	NCASI data	“The worst case scenario” suggested by GP	
Gas Compositions:			
Dimethyl Sulfide	-	20 ppm	-
Dimethyl Disulfide	2 ppm	1727 ppm	-
Methanol	83 ppm	2330 ppm	25 ppm
Acetone	3 ppm	-	1 ppm
Terpenes	209 ppm	62 ppm	4 ppm
Process Conditions:			
Temperature	103°F	150°F	100°F
Relative Humidity	100%	100%	70%

We suppose that the best approach in this case is two stage air cleaning: 1) Water scrubber with recirculated ozone-treated water and 2) Dry pulsed corona treatment. Scheme of the process is presented in the Fig. 20. The first stage is a well known technological process, that can easily clean stream from soluble compound to the level of 95%, so only about 1 ppm of soluble compounds together with several ppm of terpenes will come to the pulsed corona reactor.

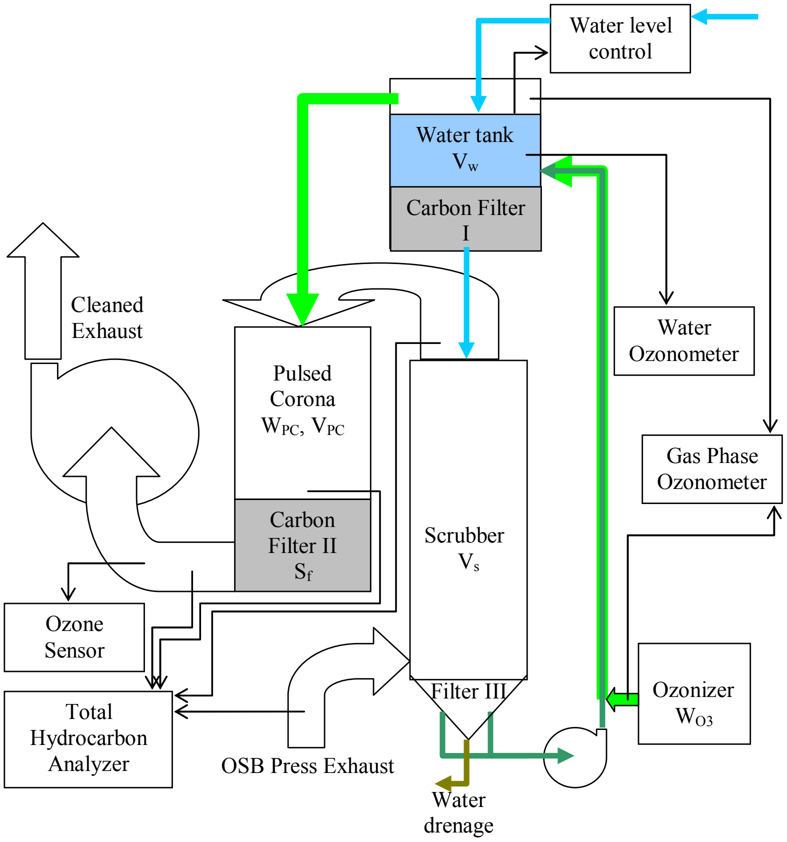


Fig. 20. Scheme of the proposed industrial process for OSB Press Vent emission treatment.

125,000 SCFM = 250,000 m^3/h vent stream contains 25 ppm of methanol, meaning about 6 m^3/h of gaseous methanol. To absorb this methanol from water with efficiency >95% it is necessary to have water stream 200 m^3/h (about 0.8 ml per 1 liter of gas according to [9]). Power consumption of the pump in this case is about 2 kW.

According to our estimation, to destroy methanol molecule in liquid phase (on the surface of a catalyst that absorbs methanol as well as ozone, active carbon, for example) it is necessary to spend 1-3 molecules of ozone. So, it is necessary to produce 6-18 m^3/h of O_3, meaning 7-20 kg/h of ozone. Efficiency of the modern ozone generators is about 20 kW*h/kg and the cost of powerful ozone generators is about $10,000 per 1 kg/h of ozone. It means that the ozone generator will have power 150-400 kW and cost $ 70,000 – 200,000 (Long and short term projection respectively).

Our Pilot Plant tests (made together with MetPro) with alpha-pinene contained air (Fig. 17), show that these amount of terpenes can be easily oxidized in the pulsed corona reactor with low power: about 2 W-h per m^3 to reach less then 1 ppm of alpha-pinene, meaning to reach less than 2 ppm of total VOC concentration.

So, we suppose that it will be necessary to spend 1-3 W*h per m^3 of treated gas to reach acceptable level of VOC concentration. So, power of the corona unit should be 250 – 750 kW, and its price $ 250,000 - $ 1,500,000 (long and short term projection respectively).

This information was presented to the Concurrent Technology Corporation (CTC), the company selected by DOE as a "third party" evaluator (Project No. 01021.02.01). CTC has prepared a couple of surveys: one for Georgia Pacific about available RTO technology and another for Drexel University about Plasma Technology. These surveys contain some questions related to the equipment erection, like price of the base, etc. Drexel University with the help of MetPro filled out all data related to the plasma technology; MetPro also filled out the data related to the RTO technology, as MetPro is a vendor of this kind of technology and equipment. All these data were submitted to CTC for their evaluation. This data are presented in the Attachments 1 and 2. Recently CTC sent to Drexel University a draft of their report to DOE [7]. They use data for RTO presented by G-P but not by MetPro through Drexel: "Drexel also supplied information on the RTO, but CTC believed, since this information differed significantly from that supplied by GP, that it was best to use the GP-supplied RTO data, since the RTO is owned and operated by GP." CTC evaluation conclusion is positive for the plasma technology: "Using information provided to date by Drexel and GP, the results of the cost analysis performed by CTC show that with regard to treatment of the offgas from the OSB press vent at the GP Brookneal, Virginia facility, conversion from the baseline RTO to the alternative PCR would result in a cost savings. This would be dependent upon realization of the estimated $171,439 annual savings based on the data supplied. The majority of this annual cost savings is from reduced utility costs and an estimated materials cost reduction."

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10. M. G. Sobacchi , A. V. Saveliev , A. A. Fridman, A. F. Gutsol, L. A. Kennedy, “Experimental Assessment of Pulsed Corona Discharge for Treatment of VOC Emissions”, Plasma Chemistry and Plasma Processing, Vol. 23, No. 2, 2003, p. 347-370.

ATTACHMENT 1

Pulse Corona Reactor (PCR) for Off-Gas Treatment from the Oriented Strandboard (OSB) Press Vent
Georgia Pacific (G-P) Facility, Brookneal, Virginia

Cost Analysis Questionnaire
Developed by Concurrent Technologies Corporation (*CTC*)
Filled out by Drexel University team in co-operation with MetPro

Alternative Process: Pulse Corona Reactor (PCR) for OSB Press Vent Off-Gas Stream, G-P, Brookneal, VA

Please answer the following questions, filling in the gray, shaded areas as possible. All costs should be reported in U.S. dollars, on an annual basis (fractions may be used if some items occur at less than annual frequencies). If the topic does not apply to the process under investigation, please place an "X" over it to illustrate this.

1. Complete the shaded areas of the table below regarding capital or one-time costs, for a 125,000 standard cubic feet per minute (SCFM) PCR system. Costs should include all components necessary from the exit point of the OSB press vent building. (If any of the components separately listed below are included in cost of the PCR Unit, please clearly indicate this).

Component	**Specifications**	**Quantity**	**Supplier or Source of Estimate**	**Estimate ($K)**
125,000 SCFM PCR Unit	530 kW unit consists from about 360 channels with Power Supply and Controls	1	Ecos, Quinta	530
Pulse Power Supply & Controls	Included into PCR Unit			
Insulators	Included into PCR Unit			
Ductwork & Exhaust			MetPro	250
Fans	Probably the same as for RTO, For 125,000 SCFM, Pressure drop > 3" H2O	1	MetPro For 100,000 CFM, 20' DP fan (from PNNL report)	55
Sensors/Controllers	Ozone Sensor	1	Air-Zone.com	0.3
Monitors/Analyzers	Total Hydrocarbon Analyzer, Liquid Ozone Monitor, Gas Ozone Monitor Computer Control system	1 1 1 1	California Analytical Medozone Medozone Drexel University	11.7 3.5 3.5 5
Ozone Generator	253 kW ozone Generator with Oxygen generation system		Ecos, Quinta	215

Water Pump	9 kW water pump with 10 m water head and 265 m3/h flow rate	1	MetPro	15
Water Tank	22 m3 tank for water and Filter I	1	MetPro	15
Scrubber	440 m3 scrubber	1	MetPro	125
Carbon Filter/Catalyst	15 m3 water carbon filter I 7.5 m3 gas carbon filter	1 1	MetPro MetPro	30 20
Foundations			MetPro	50
Support Structures			MetPro	50
Exhaust Stack			MetPro	100
System Installation/Startup			MetPro	250
Filter for solids	Self-cleaning net filter III for wood chips separation from water	1	MetPro	75
TOTAL	--	--	--	**1024**

2. Complete the shaded areas of the table below regarding one-time labor costs, for training for operation of a 125,000 SCFM PCR system.

How many operators would be trained to conduct this process?		no. of operators
How many hours of training would be required for each?	0	hours
What is the operators’ pay rate?	0	$/hour
How many total hours of trainer's time would be used to conduct above training for all operators?	0	hours
What is the trainers' pay rate?	0	$/hour

3. Complete the shaded areas of the table below regarding operation and maintenance costs for parts for a 125,000 SCFM PCR system, assuming 24/7 operation. List other parts or components that may likely need replacement over a 15 year period in addition to PCR unit, power supply, and/or high-speed switches.

Part or Component	**Specifications**	**Estimated Annual Replacement Schedule**	**Supplier or Source of Estimate**	**Estimate ($K per year)**
PCR Unit	-			
Power Supply	-			
High-Speed Switches	360 Spark gaps	Ones per year	$50 per gap (Ecos)	18
Active Carbon	22.5 m3	Ones per 5 years	$50 K	10

4. Complete the shaded areas of the table below regarding annual utility consumption of a 125,000 SCFM PCR system, assuming 24/7 operation, and site-specific utility cost range.

Utility	**Estimated Annual Consumption**	**Units**
Electricity	6.61	10^6 kW-h

Natural Gas	-	cu feet
Propane	-	cu feet
Water	20	1,000 gal

5. Complete the shaded areas of the table below to provide information related to annual labor costs for a 125,000 SCFM PCR system, assuming 24/7 operation.

How many operators are required to conduct this process per shift?	1	persons/shift
What is the operators' pay rate?	20	$/hour
How long does a shift last (e.g., 8 hours)?	8	hours
How many shifts are operated per day?	3	shifts/day
How many days per year is the process conducted?	365	days/year
Does the above information include the labor required to carry out waste management and reporting activities?	Yes	Please circle one

6. Complete the shaded areas of the table below to provide information related to waste streams and disposal activities for a 125,000 SCFM PCR system, assuming 24/7 operation. These costs may be a portion of costs related to operation of a larger system.

List any waste streams associated with this process, its rate of production and total annual volume, and indicate whether it is hazardous (H), non-hazardous (NH), or a combination of the two (CB)? Include appropriate units. (ex. wastewater, 5 gpm, 2.63 mg/yr, (H)).	1. Barrel per day of drain water with wood chips (NH) 2. 3.
Indicate how each waste stream above is managed, and any annual transportation, disposal, or treatment fees associated with each waste stream listed above. Include appropriate units. (ex. onsite wastewater treatment, $200,000/year).	1. Water should be evaporated 2. 3.

7. Complete the shaded areas of the table below to provide information regarding annual costs related to environmental issues for a 125,000 SCFM PCR system.

Does this process require any permits (e.g., air emissions, related regulations, etc.)?	No	Please circle one
If yes, please list the permits required with the associated annual cost next to each.	1. 2.	
Does this process require sampling and analysis to comply with the permits listed above, to provide operational data, and/or to provide data for management of waste streams?	No	Please circle one
If yes, please indicate the media (air, water, etc.), and the associated annual cost associated with sampling and analysis activities next to each.	1. 2. 3.	
Are there any reporting requirements associated with this process (e.g., annual air emission reports, etc.)?	No	Please circle one
If yes, please list the reporting requirements associated with this process.	1. 2.	
Also, if yes, do the process operators complete these reports? If no, please include the title of the person required to do so.	No	Please circle one and complete "No" option, if necessary

If the operators do not complete the reports, so that their cost is not captured in operation of the process, please indicate the associated cost of the reporting requirements listed above.	1. 2. 3.

8. Complete the shaded areas of the table below to provide information regarding annual costs related to health and safety issues for a 125,000 SCFM PCR system.

Are the operators required to receive annual medical exams to operate this process?	No	Please circle one
If yes, please indicate the cost associated with one of these annual medical exams for one operator.		$
Are the operators required to attend annual health and safety training in support of this process?	No	Please circle one
If yes, please indicate the cost associated with annual health and safety training for one operator.		
Are the operators of this process expected to wear personal protective equipment (PPE)?	No	Please circle one
If yes, please write down all the pieces of PPE that are required to operate this process with the number of units annually provided to each operator in parentheses (e.g., safety boots (2)), and associated cost.	1. 2. 3. 4.	

Additional Information for PCR

Using the space below, or additional pages as needed, please list/explain any other information you believe is important and should be considered in the alternative process cost evaluation, or indicate below that no other information is deemed necessary.

	OSB Press Exhaust	Ozonizer	Pulsed Corona	Scrubber	Water tank	W. Filter I	Water pump	Gas Filter II	Water Filter III	The Sum	Per Year
Hours											8.76E+03
Air Flow Rate											
SCFM	1.25E+05							1.25E+05			
m3/hr	2.65E+05			2.65E+05				2.65E+05			
Methanol (+acetone)											
ppm	2.60E+01		0.26	2.07E+04							
m3/hr	6.89E+00		0.07	6.82E+00							6.04E+04
kg/h	9.84E+00		0.1	9.74E+00							
Henry constant	5.00E+03										
Terpens											
ppm	4.00E+00		3.21	4.80E+00							
m3/hr	1.06E+00		0.85	2.10E-01							
kg/h	6.44E+00		5.16	1.27E+00							
Henry constant	1.20E+00										

Total Carbon (ppm)	6.60E+01		32.4					6.68E+00			
Total VOC (ppm)	3.00E+01		3.47					9.02E-01			
Necessary molecule ratio O3/VOC		1.0									
Ozone fraction loss		0.001									
Henry constant		0.3									
Ozone Flow Rate (m3/h)		7.03			7.13E-03						
Ozone Concentration in Gas Phase (volume fraction)		0.07			7.10E-05						
Ozone Concentration in Water (volume fraction)					2.13E-05						
Oxygen flow rate m3/hr		100			1.00E+02						
Generation efficiency (kg O3/kW-h)		0.07									
Power (kW)		215	530				9.02E+00			754	6.61E+06
Mass per kW (kg)		13	40								
Mass (1000 kg)		2.8	21								
Price per kW ($)		1000	1000								
Price ($1000)		215	530								
Volume per 1 kW (m3)		0.03	0.15								
Volume (m3)		6.46	79.5	4.42E+02	7.36E+00	1.47E+01		7.36E+00			
Acceptable gas velocity (m/s)				1.00E+00				3.00E-01	0.3		
Cross section (m2)				7.36E+01				2.45E+02	0.245		
Hight (m)				6.00E+00				3.00E-02			
Energy for 80% Terpen removal (W-h/m3)			2.0								
(Necessary) residence time (sec)			1.08	6.00E+00	1.00E+02	1.00E+02					
Necessary liquid/gas ratio (m3/m3)				1.00E-03							

Water flow rate (m3/h)				2.65E+02	2.65E+02		2.65E+02		265		
Head of water (m)							1.00E+01				
Efficiency							8.00E-01				
Filter Porosity						5.00E-01					
Cleaning time (s/day)									3		
Water drenage (m3/day)									0.221		8.06E+01

Please contact Bill Benusa, 412-992-5366 with any questions. Once you have completed this questionnaire, please return it to the attention of Bill Benusa either through email or via FAX.

Email – benusab@ctc.com • FAX – 412-992-5360

ATTACHMENT 2

Regenerative Thermal Oxidation (RTO) for Off-Gas Treatment from the Oriented Strandboard (OSB) Press Vent
Georgia Pacific (G-P) Facility, Brookneal, Virginia

Cost Analysis Questionnaire
Developed by Concurrent Technologies Corporation (*CTC*)
Filled out by MetPro

Current Process: Regenerative Thermal Oxidation (RTO) for OSB Press Vent Off-Gas Stream, G-P, Brookneal, VA

Please answer the following questions, filling in the gray, shaded areas as possible. All costs should be reported in U.S. dollars, on an annual basis (fractions may be used if some items occur at less than annual frequencies). If the topic does not apply to the process under investigation, please place an "X" over it to illustrate this.

1. Complete the shaded areas of the table below regarding capital or one-time costs, for a 125,000 standard cubic feet per minute (SCFM) RTO system. Costs should include all components necessary from the exit point of the OSB press vent building. (Note: Capital cost may be zero if the current RTO system is purchased, installed, and operating).

Component	**Specifications**	**Quantity**	**Supplier or Source of Estimate**	**Estimate ($K)**
125,000 SCFM RTO Unit (including media)		Two (2) RTOs Two beds each.	Met-Pro	1300
Ductwork & Exhaust			Met-Pro	Site dependent
Fans	Induced draft fan	One (1) per RTO	Met-Pro	Included
Foundations			Met-Pro	105
Support Structures			Met-Pro	Included
Exhaust Stack	40' high	One (1) per RTO	Met-Pro	Included
System Installation/Startup			Met-Pro	250
TOTAL	--	--	--	**1655**

2. Complete the shaded areas of the table below regarding one-time labor costs, for training for operation of a 125,000 SCFM RTO system. (Note: One-time labor costs may be zero if the current RTO system is up and running with trained operators).

How many operators would be trained to conduct this process?	3	no. of

		operators
How many hours of training would be required for each?	4	hours
What is the operators’ pay rate?	25	$/hour
How many total hours of trainer's time would be used to conduct above training for all operators?	4	hours
What is the trainers' pay rate?	35	$/hour

3. Complete the shaded areas of the table below regarding operation and maintenance costs for parts for a 125,000 SCFM RTO system, assuming 24/7 operation. List other parts or components periodically replaced, or that may need replacement in a 15 year period, in addition to RTO unit, media change-out, and/or valve replacement. Fractions may be used for annual replacement schedule

Part or Component	**Specifications**	**Estimated Annual Replacement Schedule**	**Supplier or Source of Estimate**	**Estimate ($K)**
RTO Unit			Met-Pro	20
Media			Met-Pro	10
Valves			Met-Pro	10

4. Complete the shaded areas of the table below regarding annual utility consumption of a 125,000 SCFM RTO system, assuming 24/7 operation, and site-specific utility cost range.

Utility	**Estimated Annual Consumption**	**Units**	**Estimated Site-Specific Cost Range Next 15 Years (Provide Min-Max)**	**Units**
Electricity	3,500,000	kwh	0.04-0.07	$/kwh
Natural Gas	125,000	cu feet	6-7	$/MM Btu
Propane	n/a	cu feet		$/cu feet
Water	n/a	1,000 gal		$/1,000 gal

5. Complete the shaded areas of the table below to provide information related to annual labor costs for a 125,000 SCFM RTO system, assuming 24/7 operation.

How many operators are required to conduct this process per shift?	1	persons/shift
What is the operators’ pay rate?	25	$/hour
How long does a shift last (e.g., 8 hours)?	8	hours
How many shifts are operated per day?	3	shifts/day
How many days per year is the process conducted?	355	days/year
Does the above information include the labor required to carry out waste management and reporting activities?	Yes OR [✓ No]	Please circle one

6. Complete the shaded areas of the table below to provide information related to waste streams and disposal activities for a 125,000 SCFM RTO system, assuming 24/7 operation. These costs may be a portion of costs related to operation of a larger system.

List any waste streams associated with this process, its rate of production and total annual volume, and indicate whether it is hazardous (H), non-hazardous (NH), or a combination of the two (CB)? Include appropriate units. (ex. wastewater, 5 gpm, 2.63 mg/yr, (H)).	1. 2. 3. 4.
Indicate how each waste stream above is managed, and any annual transportation, disposal, or treatment fees associated with each waste stream listed above. Include appropriate units. (ex. onsite wastewater treatment, $200,000/year).	1. 2. 3. 4.

7. Complete the shaded areas of the table below to provide information regarding annual costs related to environmental issues for a 125,000 SCFM RTO system.

Does this process require any permits (e.g., air emissions, related regulations, etc.)?	[✓ Yes] OR No	Please circle one
If yes, please list the permits required with the associated annual cost next to each.	1. air - $15,000 2. 3. 4.	
Does this process require sampling and analysis to comply with the permits listed above, to provide operational data, and/or to provide data for management of waste streams?	[✓ Yes] OR No	Please circle one
If yes, please indicate the media (air, water, etc.), and the associated annual cost associated with sampling and analysis activities next to each.	1. air - $10,000 2. 3. 4.	
Are there any reporting requirements associated with this process (e.g., annual air emission reports, etc.)?	[✓ Yes] OR No	Please circle one
If yes, please list the reporting requirements associated with this process.	1. CO 2. VOC 3. NOx 4.	
Also, if yes, do the process operators complete these reports? If no, please include the title of the person required to do so.	Yes OR [✓ No] No EHS Mgr	Please circle one and complete "No" option, if necessary
If the operators do not complete the reports, so that their cost is not captured in operation of the process, please indicate the associated cost of the reporting requirements listed above.	1. $5000 2. 3. 4.	

8. Complete the shaded areas of the table below to provide information regarding annual costs related to health and safety issues for a 125,000 SCFM RTO system.

Are the operators required to receive annual medical exams to operate this process?	Yes OR [✓ No]	Please circle one
If yes, please indicate the cost associated with one of these annual medical exams for one operator.		$

Are the operators required to attend annual health and safety training in support of this process?	Yes OR [✓ No]	Please circle one
If yes, please indicate the cost associated with annual health and safety training for one operator.		
Are the operators of this process expected to wear personal protective equipment (PPE)?	[✓ Yes] OR No	Please circle one
If yes, please write down all the pieces of PPE that are required to operate this process with the number of units annually provided to each operator in parentheses (e.g., safety boots (2)), and associated cost.	1. Site specific 2. 3. 4.	

Insert flow diagram of RTO – Sent separately

Additional Information for RTO

Using the space below, or additional pages as needed, please list/explain any other information you believe is important and should be considered in the baseline alternative process cost evaluation, or indicate below that no other information is deemed necessary.

Please contact Bill Benusa, 412-992-5366 with any questions. Once you have completed this questionnaire, please return it to the attention of Bill Benusa either through email or via FAX.

Email – benusab@ctc.com • FAX – 412-992-5360

ATTACHMENT 3

METHOD AND APPARTUS FOR VENTILATION STREAM CLEANING USING LOW-TEMPERATURE PLASMA

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to the field of exhaust ventilation stream cleaning. In particular the invention relates to a more efficient way to treat an exhaust ventilation stream using low-temperature plasma.

2. Description of the Related Technology

Volatile Organic Compounds are a class of air pollutants that has been addressed by environmental regulations in the past few decades due to their toxicity and their contribution to the global warming mechanism. In the paper industry, they are mainly contained in solvents, chemical binders, bleaching chemicals for paper production; they are also contained in the wood itself and released into the exhaust gases during the processing of the wood paste.

Currently Regenerative Thermal Oxidizers (RTO) are used for VOC treatment in the paper industry ("The Technical and Economic Feasibility of Using Low-Temperature Plasma to Treat Gaseous Emissions from Pulp Mills and Wood Products Plants", John B. L. Harkness and Alexander A. Fridman, NCASI Technical Bulletin No. 795, September 1999.) These devices are very good for a high level of contamination, when VOC oxidation provides a substantial amount of energy, otherwise a lot of natural gas should be used for RTO operation. Other disadvantages of RTO are SO_2 emission in the typical case of sulfur-contained VOC and cyclic operation resulting in cracking of the ceramic parts of RTO. Other disadvantages include high capital requirements and operation expenses.

Low-temperature, non-equilibrium plasmas (also called "non-thermal" plasmas) are an emerging technology for abating diluting volatile organic compounds (VOC) emissions. These plasmas can be produced by a variety of electrical discharges or electron beams.

The basic feature of plasma technologies is that they produce plasma in which the majority of the electric energy (more than 99%) goes into production of energetic electrons, instead of heating the entire gas stream. These energetic electrons produce excited species (free radicals and ions) as well as additional electrons through electron impact dissociation, excitation, and ionization of the background molecules. These excited species, in turn, oxidize, reduce, or decompose the pollutant molecules.

This mechanism of VOC removal is in contrast to the mechanism involved in thermal processes (such as plasma torches or furnaces, regenerative thermal oxidation (RTO) and several chemical techniques) that require heating the entire gas stream in order to destroy pollutants. In addition, the low-temperature plasma technology is highly selective and has relatively low maintenance requirements. Its high selectivity results in relatively low energy costs for emissions control while low maintenance keeps annual operating expenses low. Furthermore, these plasma discharges are very uniform and homogeneous, which results in high process productivity.

RTO is more effective at high concentrations of VOC. Plasma is normally used at lower concentrations of VOC and in the cases where combustion is not effective, such as removal of nitrogen oxides (NO_x) or sulfur-containing compounds. Scrubbing of exhaust gases with water might be required for both techniques, but some plasma reactors can be designed as a single unit with a scrubber to reduce the equipment cost.

A Corona is a self -sustained electrical gas discharge that occurs only when the electric field is sharply non-uniform. The field near one or both the electrodes must be stronger than in the rest of the gap. This situation typically arises when the characteristic size *r* of the electrode to which the high voltage is applied, is much smaller than the inter-electrode distance *d*. If one considers a wire-into-cylinder configuration, the electric field in the space between the coaxial cylinders of radii *r* (internal cylinder) and *R* is given as a function of the radial coordinate x as:

$$E = \frac{V}{[x \ln\left(R/r\right)]}$$

where V is the voltage between the cylinders.

There is always some ionization in the atmosphere due to high-energy particles coming from space. Existing electrons are accelerated by the electric field. The existing electrons can ionize more molecules of the gas. New electrons are accelerated in the field, and so forth. Corona discharge occurs only when the value of the maximum electric field exceeds the breakdown field. For coaxial cylinders, the critical electric field of corona ignition in air is expressed by an empirical formula suggested by Peek (1929)

$$E_e = 31\delta\left(1 + \frac{0.308}{\sqrt{\delta r}}\right)[kV / cm]$$

where δ is the ratio of air density to the density in standard pressure and temperature. It is clear that a constraint is imposed on the maximum field, which occurs on the surface of the sharp electrode, that is the high field or “corona carrying” electrode.

The formulae given above describe fairly well the physics of the corona with DC or slowly changing fields, such as in gas phase corona reactors (GPCR). For these applications, to be sustained at non-equilibrium state, the discharge can acquire only small power. Higher power would cause sparking and eventually lead to thermal arc formation.

Natural power limitations of DC corona technology gave rise to the development of the pulsed corona technology. In a pulsed corona discharge, voltage is applied to the sharp electrode as a series of fast rising pulses. Incoming pulses generate a number of micro-discharges (streamers); the faster the pulse, the more streamers are produced per unit length, increasing the power input per unit gas volume.

The width of the applied pulse must be minimized in order to avoid formation of spark discharge or thermalization of the streamers. For most geometries, then, the pulse rise time must be on the order of few nanoseconds and the duration of the pulse on the order of 100 ns.

The electron energy, in fact, depends on both the intensity of the electric field (i.e. on the voltage) and the mean free path. For a fast rising pulse, the mean electric field is very high (since the peak voltage is high), allowing the electrons to gain enough energy for the discharge to take place; however, since the duration of each pulse is much smaller than the interval between pulses, the mean required power is low (e.g., it is in the order of a few Watts per liter) even though the actual power of each single pulse is very high (up to 100 MW for the system with average power of 10 kW). The existing equipment predetermines the positive polarity.

A DC corona usually is a uniform discharge. In contrast, a pulsed corona locally is highly non-uniform. All the discharge power is localized in streamers. To describe the physics of the discharge, one must consider a phenomenon of a streamer as a whole. The electromagnetic model of physics in streamers must be coupled with the chemistry of excited species, and with internal particles (electrons, photons) transport. This coupling is very difficult because of enormous amount of computational work. Simplified models were developed, but they are still not adequate for the purposes of trustworthy chemistry prediction. Many parameters are known without a great degree of certainty, such as cross-sections of electron-molecule reactions.

There are numerous methods for treatment of waste gases from volatile organic compounds (VOC) with the help of electrical discharges, and particularly with the help of the pulsed corona discharge [Malik et al., *Chinese J. Chem. Eng.*, 7(4)(1999)]. To remove one large VOC molecule with the help of such methods it is necessary to produce several active radicals like OH. The energy price of one radical production is very high — about 50 eV per radical. As a result, the total price of one VOC molecule removal (transformation of VOC molecule into H_2O and CO_2) is also very high - about 300 eV. It is possible in this case to satisfy the industry demand to spend not more than about 10 W-hour/m^3 of the waste gas only if VOC concentration is not higher than about 30 ppm. Real industrial waste streams such as that of the papermaking, metal cleaning and plating, and plastics manufacturing industries have VOC contamination levels that are several times higher (e.g., about 100 to about 6000 ppm), so usual plasma methods for VOC removal are not applicable.

Another known method for abatement of VOCs in an exhaust gas stream comprises passing an exhaust gas stream through a pulsed corona discharge chamber in the presence of a spray of water droplets or a flowing film of water to form one or more oxidation products that dissolve in the water spray droplets or film and provide an effluent water stream and an effluent gas stream. The ratio of the water spray rate to the exhaust gas flow is about 0.2 to about 2 grams per liter (Mario G. Sobacchi , Alexei V. Saveliev , A. A. Fridman, A. F. Gutsol, Lawrence A. Kennedy, “Experimental Assessment of Pulsed Corona Discharge for Treatment of VOC Emissions”, Plasma Chemistry and Plasma Processing, Vol. 23, No. 2, 2003, p. 347-370.)

A key problem of any plasma cleaning process is that on one hand, it can be energetically effective only in the case of low concentration pollutants, and on the other hand, the cleaning process efficiency drops significantly with a decrease of pollutant concentration, and decrease of residence time. Therefore there remains a need for a more efficient way to treat an exhaust ventilation stream using low-temperature plasma.

3. SUMMARY OF THE INVENTION

The invention utilizes Plasma Ion Cluster Chemical (PICC) processes for exhaust gas treatment when water use is restricted. Plasma ion clusters are very small droplets that are formed around charged particles – ions. The main advantage of these clusters is that they can be formed even when water vapor pressure is below the dew point. So, formation of plasma in “dry” exhaust streams will result in formation of ion clusters, and the treatment process in the presence of these clusters will be similar to that in the presence of large water droplets, meaning that molecules of soluble volatile organic compounds (“VOCs”) will be absorbed together with ozone molecules, and then interaction between all these molecules will result in VOC oxidation

These and various other advantages and features of novelty that characterize the invention are pointed out with particularity in the claims annexed hereto and forming a part hereof. However, for a better understanding of the invention, its advantages, and the objects obtained by its use, reference should be made to the drawings which form a further part hereof, and to the accompanying descriptive matter, in which there is illustrated and described a preferred embodiment of the invention.

4. BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a schematic of Plasma Ion Cluster Chemical (PICC) processes of VOC oxidation

FIG. 2 shows a schematic of multiple stage plasma system for air cleaning

FIG. 3 shows a schematic of re-circulation of ventilation gas in the industrial zone

FIG. 4 shows experimental data regarding Energy Cost for the treatment of VOCs with the pulsed corona discharge

FIG. 5 shows experimental dependence of the logarithm of alpha-pinene concentration on power.

5. DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The invention utilizes Plasma Ion Cluster Chemical (PICC) processes (Fig. 1) for exhaust gas treatment when water use is restricted. Plasma ion clusters are very small droplets that are formed around charged particles – ions. The main advantage of these clusters is that they can be formed even when water vapor pressure is below the dew point. So, formation of plasma in "dry" exhaust stream will result in formation of ion clusters, and treatment process in the presence of these clusters will be similar to that in the presence of large water droplets, meaning that molecules of soluble VOCs will be absorbed together with ozone molecules, and then interaction between all these molecules will result in VOC oxidation.

In the cases when VOC radicals are inclined to polymerization, that is typical for most of organic molecules, we propose to stage plasma treatment (divide total plasma energy input in time) or to increase considerably the power of the plasma system. After the first stage of plasma product (active particles, for example OH radicals) interaction with VOC molecule (R-H)

$$\text{R-H} + \text{OH} \Rightarrow \text{R-} + \text{H}_2\text{O} \qquad (1)$$

the organic radical R- can be oxidized to final products (water and CO_2 molecules) by a number (n = 5-10) of other OH radical;

$$\text{R-} + n\ \text{OH} \Rightarrow \text{products} \qquad (2)$$

or in the complex chain process of interaction with molecular oxygen.

$$\text{R-} + \text{O}_2 \Rightarrow \text{R-O-O-}$$
$$\text{R-O-O-} + \text{R-H} \Rightarrow \text{R-O-O-H} + \text{R-}$$
$$\text{R-O-O-H-} \Rightarrow \text{R}_1\text{-} + \text{R}_2\text{-}$$

…………………………..

This complex process can be described with significant simplification as

$$\text{R-} + m\text{O}_2 \Rightarrow \text{products} \qquad (3)$$

The other pathway for organic radical transformation is polymerization:

$$\text{R}_i\text{-} + \text{R}_j\text{-} \Rightarrow \text{P-H} \qquad (4)$$

The polymerized organic molecules (for example soot) are usually much more stable to oxidation than the initial molecules, so the process;

$$\text{P-H} + \text{OH} \Rightarrow \text{P-} + H_2O \qquad (5)$$

is going slower than (1).

To spend energy the most efficient way, formation of a high concentration of radicals should be avoided because that leads to intensive polymerization according to reaction (4). Conditions should be formed where reaction (3), that is energy “free”, is faster than reaction (2), that is very energy “expensive”, as we “pay” for each step about 30 eV (typical energy price of OH radical formation in plasma). That is why the most energy efficient way to generate a low concentration of OH radicals (small energy input), is to wait some time for the completion of reaction (3), and repeat this step as many time as necessary for desirable Destruction and Removal Efficiency (DRE). In this case a relatively low concentration of VOC radicals will be produced in each stage, and the process of polymerization will be very slow as the rate of this process is proportional to the square of the radical concentration.

As a result of research experiments scientist usually obtain the Energy Cost value for destruction of a particular VOC in the particular type of discharge (Fig. 10). For most of the experimental conditions, data on the Destruction and Removal Efficiency (DRE) can be closely curve-fitted by a negative exponential curve as a function of the specific energy input (SEI):

$$DRE = A \cdot \left(1 - e^{-\left(SEI/\alpha\right)}\right) \qquad (6)$$

Energy Cost for the destruction of a given VOC is the amount of SEI equal to the coefficient α. Values of the Energy Cost can be defined only for those initial concentrations of VOC such that complete destruction is not obtained at least for the smallest power supplied. Experimental data (see Fig. 4) shows the presence of a threshold concentration for VOCs (concentration that is actually different for each VOC, but approximately equal to 200 ppm for all the compounds): above this threshold value, the Energy Cost becomes fairly constant, meaning that in these conditions the concentration of VOC is not a limiting factor for the reactions with the active species produced in the plasma. The value of Energy Cost in this range of concentrations is on the level of 20-60 eV/molecule depending on the type of VOC, for example for a pulsed corona discharge the Energy Cost was 30-40 eV/molecule for alpha-pinene and 18 eV/molecule for dimethyl sulfide.

It is important to understand that the Energy Cost is defined for efficient treatment according to the reactions (1) and (3). To reach the same Energy Cost values for high DRE it is necessary to use a staged plasma treatment. This approach leads to a total residence time increase and equipment size enlargement. Therefore, there is a trade-off between the capital costs and the operating costs.

It is possible to use another way to reach high DRE – to increase SEI so high that the most important reactions become (1) and (2), and polymerization according to the reaction (4) does not have high yield because of high rate of reaction (5). In this scenario, in order to perform the energy calculation energy costs for removal of the polymerized products should be taken into account (Fig. 5). Fig. 5 shows the experimental dependence of the logarithm of alpha-pinene concentration on the power. The slopes of the curves are inversely proportional to the Energy Cost of the process. Change of slope is caused by formation of large molecules due to polymerization.

The present invention comprises a process and device for efficient treatment of exhaust ventilation gases that contains not only VOC, but also organic and inorganic particles and droplets. Efficient cleaning is possible because of the combination of different processes into one apparatus. The processes that should be combined in this apparatus include all or part of the followings sub-processes:

1. Scrubbing of a gas stream by water or another solvent.
2. Electrostatic precipitation of solid and liquid particles.
3. Plasma treatment of gas flow, including the Plasma Ion Cluster Chemical (PICC) processes, making this treatment optimal, depending on the kind of VOC, its concentration and inclination to polymerization.
4. Plasma treatment of a gas flow in the presence of liquid phase of solvent.
5. Solvent mist separation from the gas flow on active surface and/or electrostatic precipitator.
6. Recirculation and/or multiple use of solvent in the apparatus.
7. Solvent cleaning from insoluble particles.
8. Plasma and/or chemical treatment of solvent for reuse.
9. On-line control of gas and solvent cleaning process efficiency.
10. Repetition of different stages and/or their combinations in serial and/or in parallel with different specific plasma energy inputs and residence times.
11. Partial recirculation of the ventilation gas in the whole system that includes apparatus and the industrial zone.

Below, the method of efficient use of each of the sub-processes mentioned above is described. The efficiency of the whole process will be rational combination of effective use of the sub-processes.

1. If the stream contains soluble organic substances (like methanol in an Oriental Strandboard (OSB) press vent stream) and/or organic particles (like small wood fibers in wood industry streams), then it is not rational to send this stream to a plasma system, such as the pulsed corona discharge, or one of the plasma systems. Energetically expensive active chemical radicals produced by the plasma will be spent for oxidation of these particulate substances that could be easily removed by a scrubber with water or another effective solvent. So, the scrubbing stage is effective in this case.
2. A small amount of solid and/or liquid organic and/or inorganic particles could be effectively removed from the gas stream in the apparatus part that is combination of a pulsed corona and electrostatic precipitator. Then these particles could be removed by the solvent flow on the precipitation surface.
3. Plasma treatment of gas flow, including the Plasma Ion Cluster Chemical (PICC), processes should be staged to reach effective VOC oxidation and to avoid VOC polymerization. Alternatively, the specific energy input should be considerably increased.
4. Sometimes plasma treatment is more efficient in the presence of a solvent that absorbs intermediate products of VOC oxidation. In such cases, the solvent can be added as a spray or a liquid film inside the pulsed corona discharge and soluble by-products will be removed from the discharge.
5. The use of solvent in combination with the plasma treatment provides a lot of advantages. One of them is the possibility to separate mist of the solvent from the gas flow, and this mist will contain absorbed pollutants (like VOC) and active species (like ozone). An active surface will provide additional residence time for reaction of pollutants with

plasma active species.

6. Sometimes, as in the wood industry, it is not possible to use considerable exhaust flows of cleaning solvent, like water. In such cases the only effective way to use water or other liquid solvent in combination with plasma treatment is recirculation and/or multiple use of the solvent. For example, solvent can be used in the initial stages of gas cleaning, where the pollutant concentration is high, after preliminary use in the latest stages, where pollutant concentration is low, or the nature of pollutants is another (for example, after absorption of low concentration of plasma treatment byproducts inside the corona discharge or immediately after the discharge, the solvent can be used for methanol and particles absorption in the beginning of the process). This is deemed multiple use of solvent. The dirty solvent can be cleaned and used again. This is deemed reuse of solvent.
7. If solvent is used for particles absorption, the particles should be cleaned from the solvent before reuse. This solvent cleaning process can include but is not limited to magnetic separation, skimming with or without flocculating agents, sedimentation, centrifugal separation and other separation methods.
8. Before solvent reuse, the absorbed soluble components should be cleaned from the solvent. This cleaning may include chemical treatment of soluble components (like oxidation of VOC by a strong oxidation agent, or chemical transformation of inorganic soluble components to insoluble substances and precipitation), electrochemical treatment of the solvent; or plasma cleaning (non-equilibrium plasma produces radicals that can oxidize VOC in liquid phase). All cleaning methods are more effective when concentration of the pollutant is higher. That is why the solvent should be chosen and treated by a process that can absorb more pollutants, and it should be treated preferably after multiple uses.
9. To make all sub-processes the most efficient, on-line control and feedback should be used to change corona power, solvent or chemicals flow rates, etc. For example, conditions of the solvent can be controlled with a pH-meter, colorimeter etc. Corona (plasma) treatment efficiency can be monitored with the ozone sensor. A high concentration of ozone after the corona treatment means the excess of specific power on the particular stage. Closing a feedback loop on these process sensors, which varies the power levels and activated corona and scrubber stages – will enable power and other criteria optimization in order to minimize fixed, variable and capitalization costs associated with the system
10. It is envisioned that the industrial application of this apparatus should consist of multiple stages. For example (Fig. 2), after the first stage of scrubbing, a second stage follows with high specific power and low residence time of corona treatment combined with the electrostatic precipitation in the presence of solvent; the third stage is corona treatment with lower specific power and higher residence time; the forth stage is a scrubber; the fifth stage is a low specific power corona in the presence of solvent mist that is following by the final stage of mist separation. The solvent from the mist separation stage is moving to the beginning of the process and used in all appropriate stages. After the first stage the solvent is passed through the conditioning (solvent cleaning) stage, where it is cleaned, reaches appropriate pH and is ready for return to the process.
11. A proposed approach for providing a power efficient and cost effective design is to employ treated gas flow recycling (feedback) and modularity (series/cascaded repetition of plasma or plasma/scrubber stages). This will permit customization of the system size

and complexity to meet the needs of a required application. This will minimize the consumed power for operation and decontamination, and via modularity – enable low cost, off the shelf, system design and manufacturing. In many cases the exhaust ventilation flow stream intensity is defined not from the necessity of personnel protection, but from other conditions, like removing humidity or excess heat. In such cases, the technology described herein (in contrast, for example, to Regenerative Thermal Oxidation (RTO), that uses a considerable amount of oxygen from the ventilation flow and transforms it to CO_2) can be perfectly combined with the industrial process itself, resulting in considerable reduction of the total ventilation exhaust. Preferably, part of the whole exhaust stream after partial, or total cleaning can be re-directed (re-cycled) to the industrial zone (Fig. 3), and only a small amount of additional clean air might be necessary to ventilate the working area around the industrial zone. In that case the total exhaust flow will be decreased considerably, and plasma energy will not be ineffectively spent to clean the almost clean total flow. This small amount of exhaust gas can be released without cleaning if the regulations demand reduction of total pollutant release, or the small amount of exhaust can be cleaned separately. In this method, most of the gas stream participates in recirculation with a higher pollutant concentration leading to more effective and efficient treatment.

The appropriate combination of the sub-processes described above can make plasma treatment of an exhaust ventilation stream very efficient and affordable for industry.

It is to be understood, however, that even though numerous characteristics and advantages of the present invention have been set forth in the foregoing description, together with details of the structure and function of the invention, the disclosure is illustrative only, and changes may be made in detail, especially in matters of shape, size and arrangement of parts within the principles of the invention to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed.

6. ABSTRACT OF THE DISCLOSURE

The invention utilizes Plasma Ion Cluster Chemical (PICC) processes for exhaust gas treatment when water use is restricted. Plasma ion clusters are very small droplets that are formed around charged particles – ions. The main advantage of these clusters is that they can be formed even when water vapor pressure is below the dew point. So, formation of plasma in “dry” exhaust streams will result in formation of ion clusters, and the treatment process in the presence of these clusters will be similar to that in the presence of large water droplets, meaning that molecules of soluble VOCs will be absorbed together with ozone molecules, and then interaction between all these molecules will result in VOC oxidation.

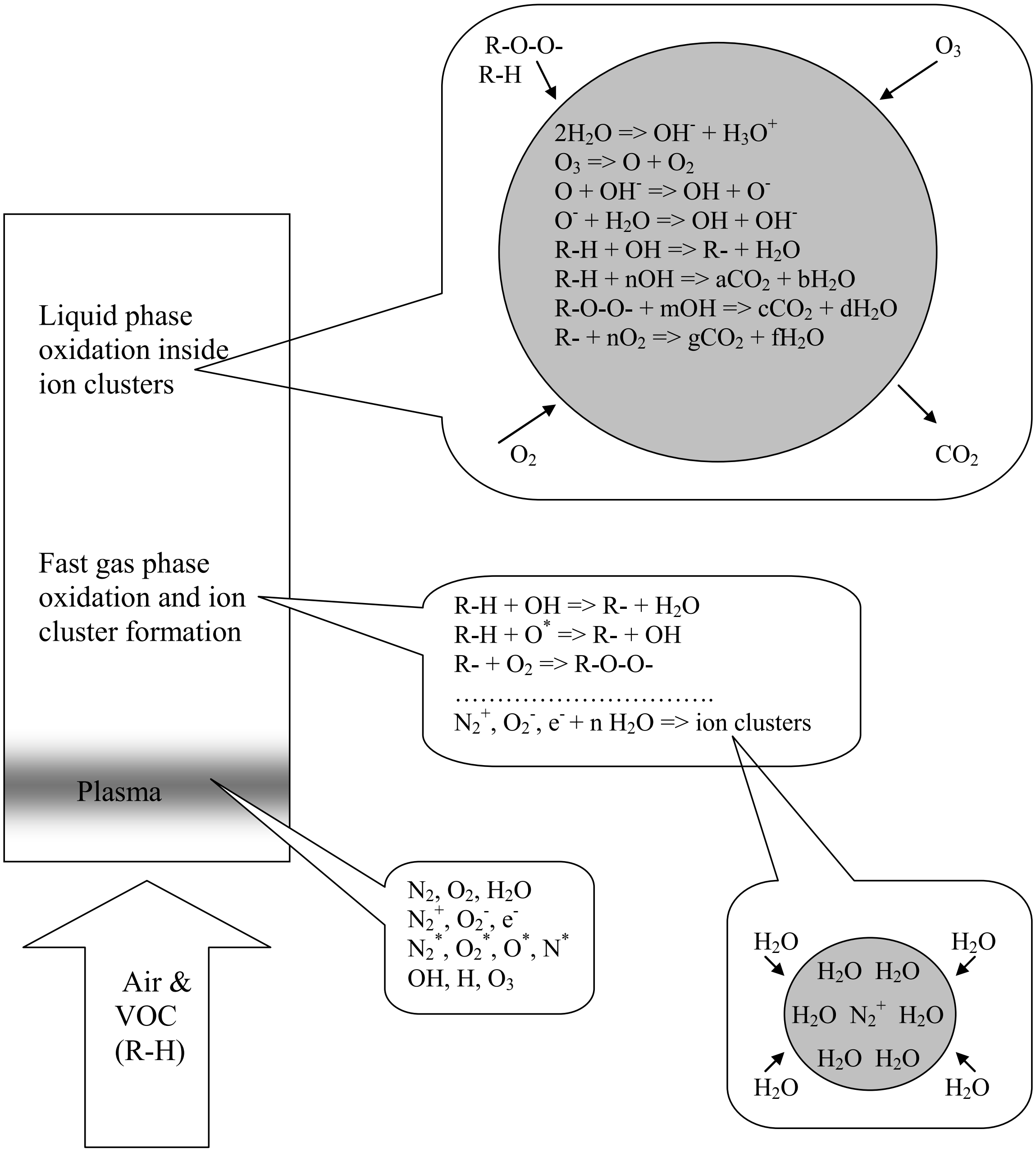

R-O-O-
R-H
O_3
$2H_2O \Rightarrow OH^- + H_3O^+$
$O_3 \Rightarrow O + O_2$
$O + OH^- \Rightarrow OH + O^-$
$O^- + H_2O \Rightarrow OH + OH^-$
$R\text{-}H + OH \Rightarrow R\text{-} + H_2O$
$R\text{-}H + nOH \Rightarrow aCO_2 + bH_2O$
$R\text{-}O\text{-}O\text{-} + mOH \Rightarrow cCO_2 + dH_2O$
$R\text{-} + nO_2 \Rightarrow gCO_2 + fH_2O$
O_2
CO_2
Liquid phase oxidation inside ion clusters
Fast gas phase oxidation and ion cluster formation
$R\text{-}H + OH \Rightarrow R\text{-} + H_2O$
$R\text{-}H + O^* \Rightarrow R\text{-} + OH$
$R\text{-} + O_2 \Rightarrow R\text{-}O\text{-}O\text{-}$
…………………………
$N_2^+, O_2^-, e^- + n\, H_2O \Rightarrow$ ion clusters
Plasma
N_2, O_2, H_2O
N_2^+, O_2^-, e^-
N_2^*, O_2^*, O^*, N^*
OH, H, O_3
Air & VOC (R-H)
H_2O
H_2O
$H_2O\ H_2O$
$H_2O\ N_2^+\ H_2O$
$H_2O\ H_2O$
H_2O
H_2O

Fig. 1

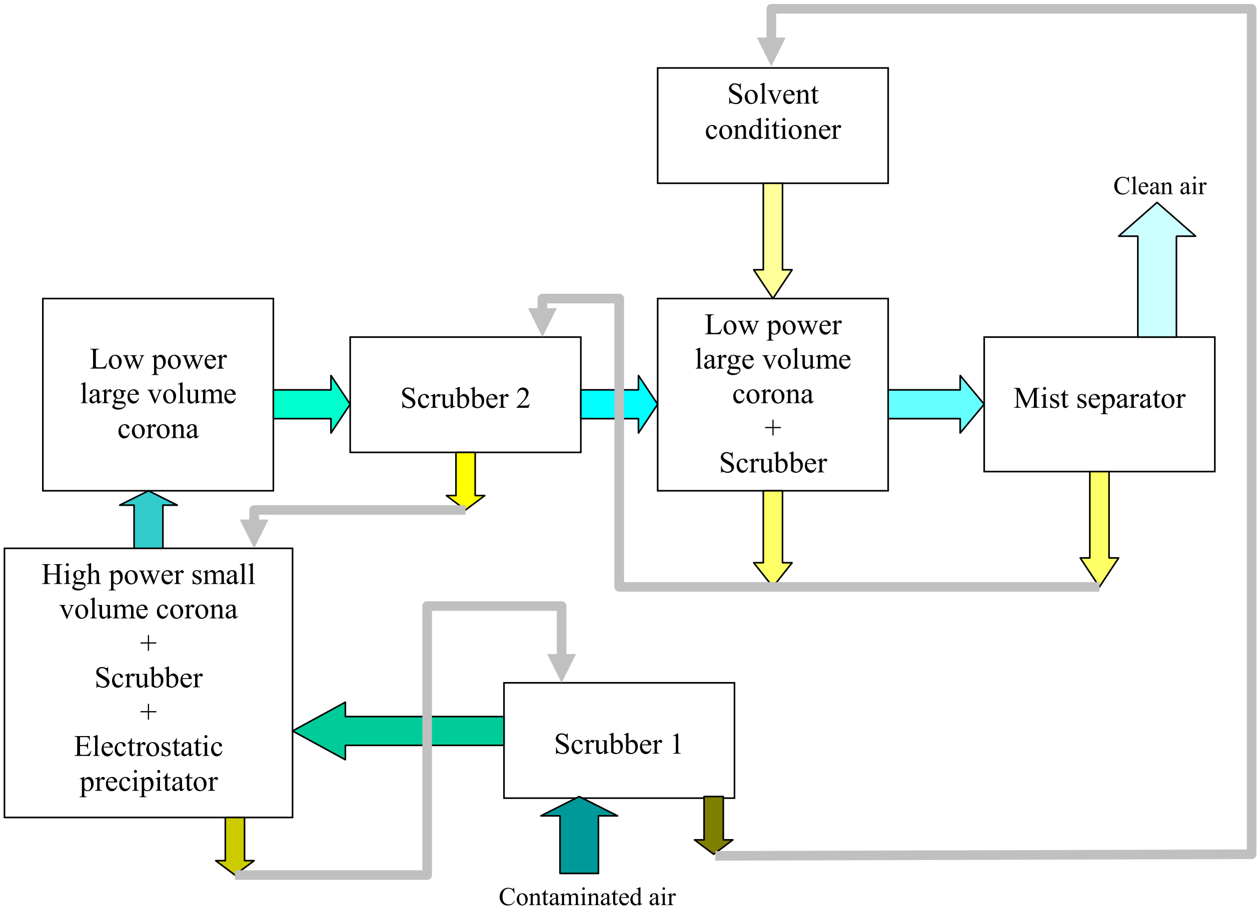

Solvent conditioner
Clean air
Low power large volume corona
Scrubber 2
Low power large volume corona + Scrubber
Mist separator
High power small volume corona + Scrubber + Electrostatic precipitator
Scrubber 1
Contaminated air

Fig. 2

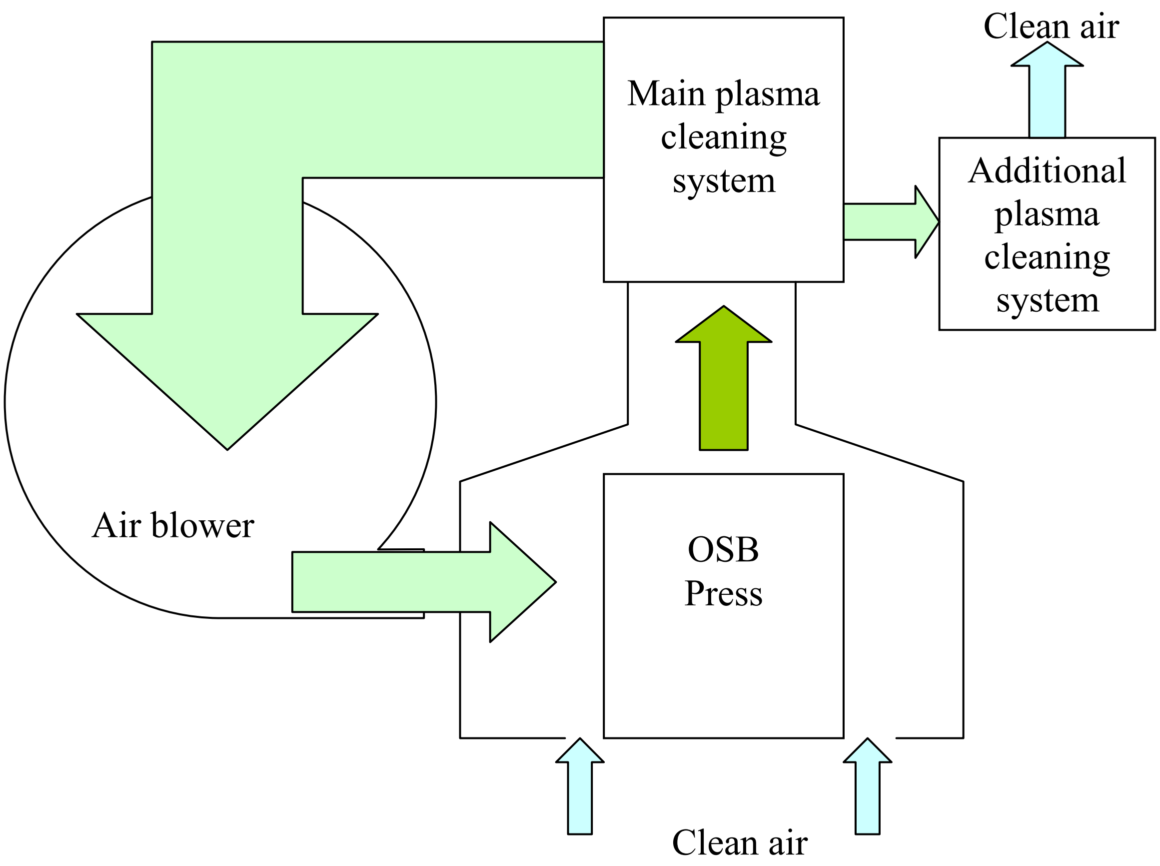
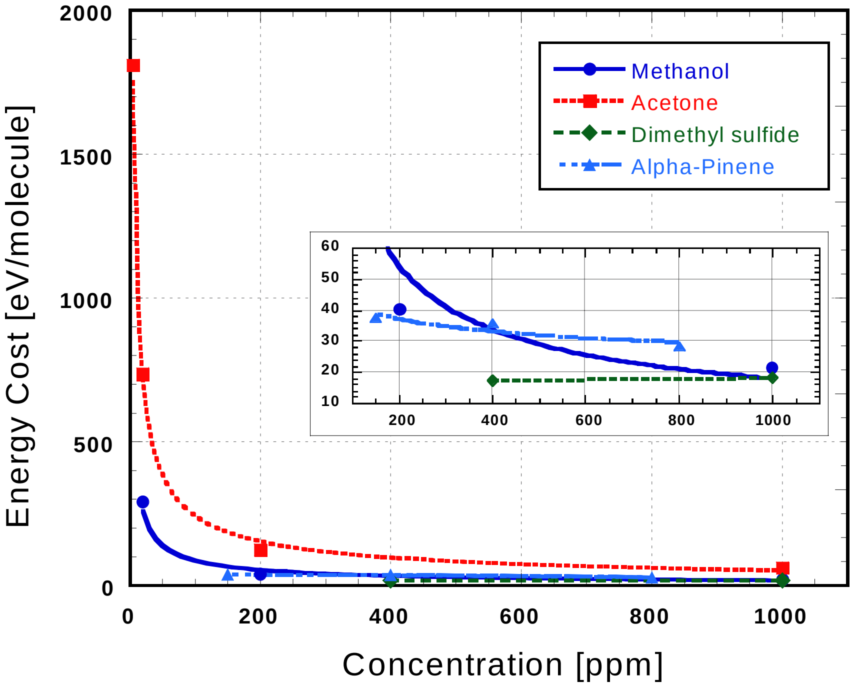
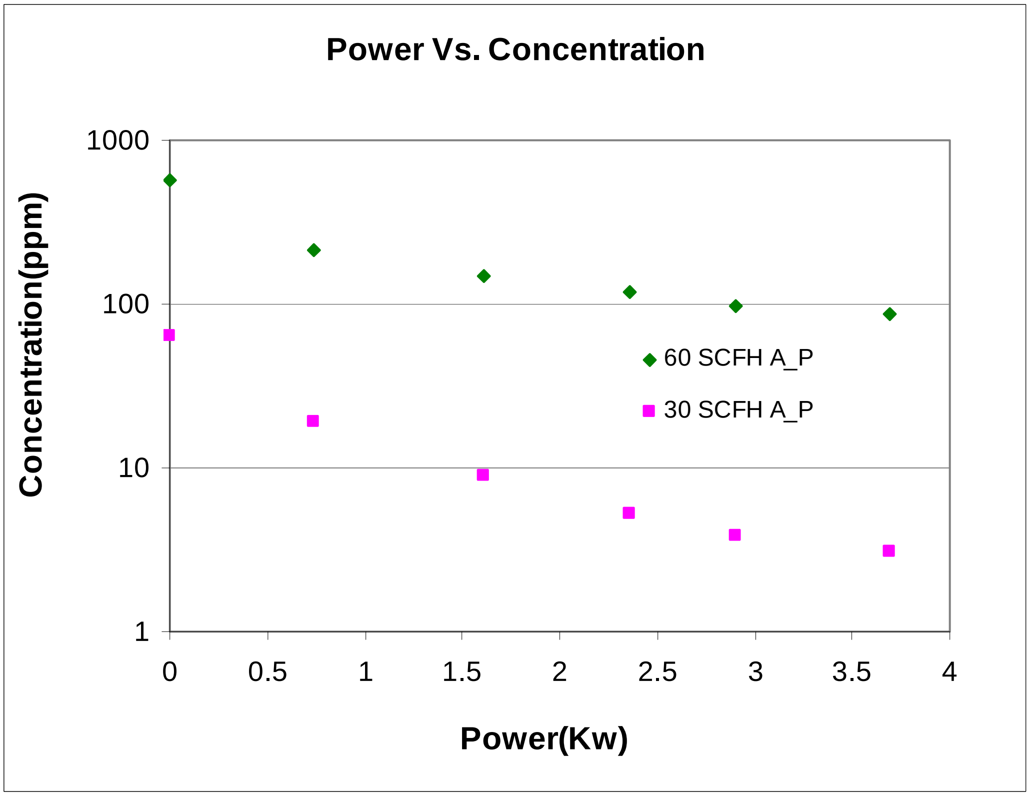

Clean air
Main plasma cleaning system
Additional plasma cleaning system
Air blower
OSB Press
Clean air

Fig. 3



2000
1500
1000
500
0
Energy Cost [eV/molecule]
0
200
400
600
800
1000
Concentration [ppm]
Methanol
Acetone
Dimethyl sulfide
Alpha-Pinene
60
50
40
30
20
10
200
400
600
800
1000

Fig. 4



Power Vs. Concentration
1000
100
10
1
Concentration(ppm)
0
0.5
1
1.5
2
2.5
3
3.5
4
Power(Kw)
60 SCFH A_P
30 SCFH A_P

Fig. 5

ATTACHMENT 4

DEVICE FOR GENERATION OF PULSED CORONA DISCHARGE

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates to the field of environmental control technology. In particular the invention relates to a method and system for the generation of high voltage, pulsed, periodic corona discharge.

2. Description of the Related Technology

Pulsed corona discharge based systems are among the most promising approaches in the field of environmental control technology. Such systems are used for the cleaning of water, air, furnaces, fuel and vent gases. The systems are also used as electro-precipitators with pulsed power supplies, as well as for ozone generation. Further development of these systems is limited by the lack of cost-effective and reliable power supplies that can generate short high voltage pulses and that have the necessary characteristics for industrial applications. Methods for matching these power supplies with a non-linear load of pulsed corona discharge are also lacking. This matching is desirable in order to achieve reasonable energy input efficiency into the pulsed corona discharge.

Today most of the methods for pulsed corona discharge generation are based on the use of thyratrons, which are gas-filled hot-cathode electron tubes in which the grid controls only the start of a continuous current thus giving the tubes a trigger effect, or triggered spark gaps (with a third electrode or rotating electrodes). These methods have the following drawbacks: Industrial thyratrons, as well as triggered spark gaps, are relatively expensive and have a short life time as generators of short pulses. Moreover, use of thyratrons or triggered spark gaps demands additional power for thyratron cathode heating, or for the formation of control pulses (triggering) or the rotation of electrodes. This reduces the overall energy efficiency of the pulse generator.

The use of untriggered spark gaps that have the best time characteristics when generating single pulses in conventional methods with ballast (serial) resistors results in very large energy losses during charging of the discharge capacitor (Ohmic heating loss can be more than 50%). Furthermore, the typical untriggered spark gap cannot provide the high frequencies of pulse generation (1000 Hz and higher) that are necessary for commercial applications of the pulsed corona discharges such as gas cleaning, or ozone generation.

Russian patent no. 2144257 discloses a device that was developed for generation of short pulses of high voltage for ignition of pulsed-periodic electric discharges like pulsed corona discharges or pulsed barrier discharges. The device can generate high voltage pulses with extremely short rise times (up to 5-10 ns) with high pulse repetition frequencies (about 2000 Hz) and with a maximal energetic efficiency of the device (COP on the level of 90%). The device comprises a high voltage power supply, a discharge capacitor, and a high voltage commutation switch that connects a discharge capacitor and a load. The high voltage power supply comprises a main rectifier, a semiconductor converter, and one or more pulsed high voltage transformers that provide charging of the discharge capacitor by small portions that form in each operation of the converter, so that the frequency of charging pulses of the discharge capacitor is at least three times larger than the frequency of the high voltage communication switch operation. The high voltage communication switch is made as an untriggered spark gap in which one or both electrodes are made in the form of one or several pins, threads, needles, blades or other components with sharp edges, so that corona discharge appears on these edges when the voltage between the gap electrodes is still below the breakdown voltage.

The method used in this above device has one important drawback: The residual high voltage exists on the electrodes of the pulsed corona chamber between corona pulses. This voltage corresponds to an extinguishing voltage of a corona discharge. Because of this drawback this device cannot be used for the generation of a corona discharge in the presence of droplets of water (e.g. spray, fog) or other conductive liquids in the discharge chamber. This option is extremely important for most commercial applications of the pulsed corona discharge for gas cleaning to enable hetero-phase plasma chemical reactions.

Therefore, there exists a need for providing a method and system for the generation of high voltage, pulsed, periodic corona discharges capable of being used in the presence of conductive liquid droplets.

5. SUMMARY OF THE INVENTION

Accordingly, it is an object of certain embodiments of the invention to provide a method and system for the generation of high voltage, pulsed, periodic corona discharges capable of being used in the presence of conductive liquid droplets.

For a better understanding of the invention, its advantages, and the objects obtained by its use, reference should be made to the drawings which form a further part hereof, and to the accompanying descriptive matter, in which there is illustrated and described a preferred embodiment of the invention.

6. BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a diagram of a system for supplying pulsed electric power to a pulsed corona discharge chamber.

FIG. 2 shows a diagram of the electrodes of the pulsed corona discharge chamber.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

The instant invention provides a method and system for the generation of high voltage, pulsed, periodic corona discharges capable of being used in the presence of conductive liquid droplets, while maintaining high-energy efficiency. The invention can be used, for example, in different devices for cleaning of gaseous or liquid media using pulsed corona discharges.

The result of the method and system is the formation of high voltage pulses with an extremely short rise time, for example, up to 5-10 nanoseconds, and with high pulse repetition frequency, for example, up to 1000 - 2000 Hz. The high voltage pulses facilitate maximum efficiency plasma chemical oxidation of detrimental impurities, and increase the range of stable discharge operations in the presence of droplets of water or other conductive liquids in the discharge chamber.

It is possible to achieve this using a device comprising a high voltage power supply 18 with limited output current (i.e. a high voltage rectifier provided with current limitation), a discharge capacitor 14, an untriggered spark gap 12 and a pulsed corona discharge chamber 16 with electrodes that are connected to inductor 10. Anode 22 may be fabricated as a bunch of conductive rods and cathode 24 may be a plate with flat surface.

Electrodes 20, shown in Fig. 2, are connected to the discharge chamber by inductor 10, shown in Fig. 1. In this method, inductor 10 removes the residual voltage from electrodes 20 of pulsed corona discharge chamber 16 and generates a current pulse that effectively switches off untriggered spark gap 12 that results in an increase of the system operation stability.

As shown in Fig. 2, discharge chamber electrodes 20 are designed to increase stability of pulsed corona discharge generation. Electrodes 20 are made as alternate rows of parallel plates 26 with sharp cogs and rods 28, or, alternatively, as round rods. This electrode system is almost transparent for liquid spray or fog droplets and minimizes formation of continuous rivulets or streamlets of conductive liquid that may short-circuit the discharge, or spark gap 12.

The electrical device may be made according to Fig. 1. In a specific embodiment, the average corona plasma power may be 450 W, the capacitance (C) of capacitor 14 may be C= 5 nF, and the inductance of inductor 10 may be L=50 mkH. The electrical efficiency of energy transfer from the charging capacitor 15 to the impulse corona discharge chamber 16 is 95%. The gap between electrodes 20 is $d = 25$ mm; the distance between cogs a_1 on the positive electrode is equal to the width of the cogs a_2 and is equal to 1 cm; while the thickness of the positive electrode plates is $\delta \geq 2.5$ mm.

Generally, inductance should be chosen according to the equation:

$$100 \text{ ns} < (LC)^{1/2} < 1000 \text{ ns}$$

and the sizes of electrodes 20 should obey the following rules:

The thickness of the positive electrode is $\delta \geq 0.1\ d$; distance between the plates of electrodes is $D > d$; the "saw" period $(a_1 + a_2)$ is $> 0.5\ d$.

It is to be understood, however, that even though numerous characteristics and advantages of the present invention have been set forth in the foregoing description, together with details of the structure and function of the invention, the disclosure is illustrative only, and changes may be made in detail, especially in matters of shape, size and arrangement of parts within the principles of the invention.

7. ABSTRACT OF THE DISCLOSURE

The invention is a method and system for the generation of high voltage, pulsed, periodic corona discharges capable of being used in the presence of conductive liquid droplets. The method and system can be used, for example, in different devices for cleaning of gaseous or liquid media using pulsed corona discharge. Specially designed electrodes and an inductor increase the efficiency of the system, permit the plasma chemical oxidation of detrimental impurities, and increase the range of stable discharge operations in the presence of droplets of water or other conductive liquids in the discharge chamber.

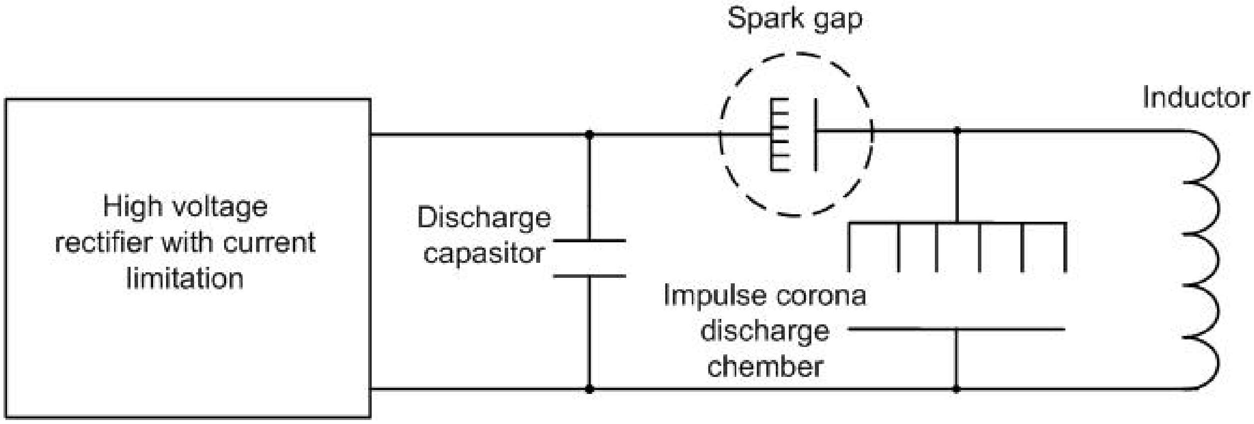


Fig. 1. Diagram of a system for supplying pulsed electric power to a pulsed corona discharge chamber.

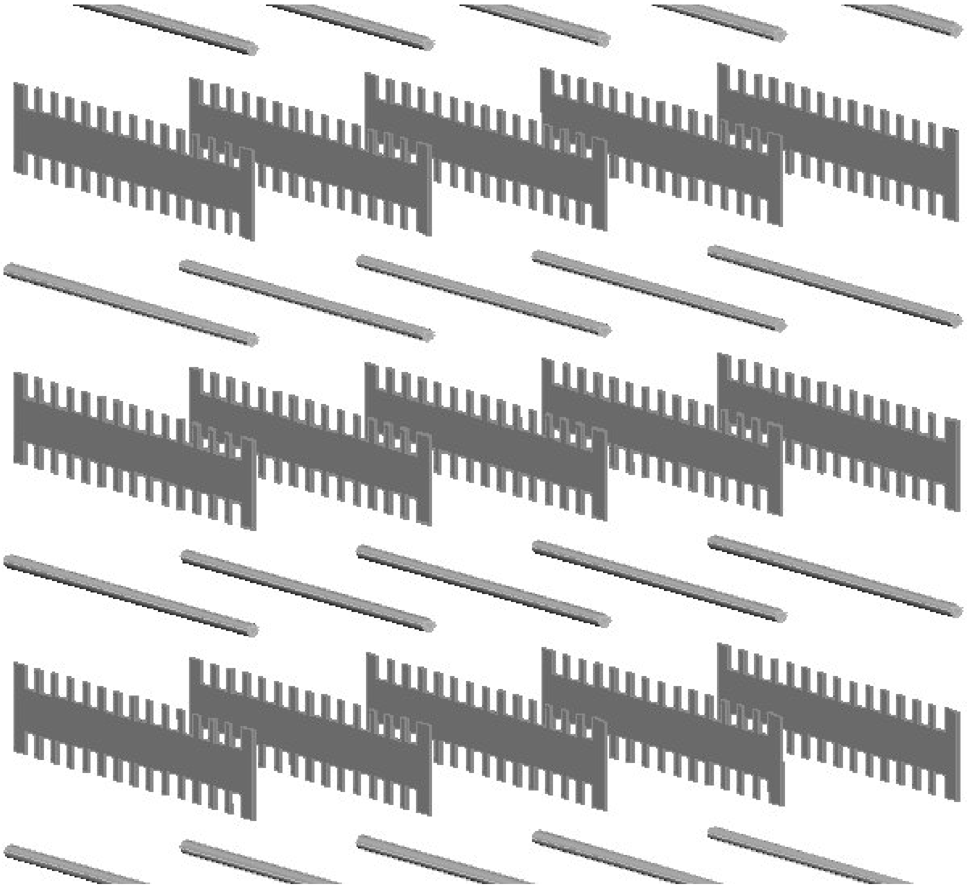


Fig. 2. Diagram of the electrodes of the pulsed corona discharge chamber.