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Removal of diesel soot particules using an esp supplied by a hybrid voltage

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Abstract. Electrostatic filtration is a process that has been studied for more than a century. One of the most recent applications is Diesel exhaust gas aftertreatment. More specifically, car manufacturers are very interested in using electrical discharge phenomena to remove the soot particles from exhaust gases. This process could be a feasible alternative to the Diesel particulate filter used at the present time. The aim of this paper is to investigate the effects of repetitive voltage impulses on the treatment efficiency on soot particles and to compare results with those achieved when a DC supply is used. The study was divided into two steps: in the first, a study of the modes of discharge which develop in an electrostatic precipitator allows us to optimize both the geometry of an ESP and a hybrid pulsed power/direct voltage supply. This study was performed without gas flow. In the second step, investigations concerning treatment efficiency were carried out under practical conditions using an engine test bench. Results show that the combination of direct voltage (–7 kV) and pulsed voltage (–14 kV, 3 kHz) provides treatment efficiency close to 75% using electrical power three times lower than that required using a DC supply.

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1 Introduction

Generally, the term "particles" denotes the aerosols created by dispersion in the air of solids and atomized liquids, powders or droplets and thus includes the terms dust, fume, soot and smog [1]. Particles can be generated by a large variety of physical and chemical processes, but the particles which interest us in this work and which are increasingly significant are the exhaust fumes of diesel car engines [2]. During combustion of the fuel/air mix, Diesel engines produce a variety of particles generally classified as diesel particle matter due to incomplete combustion. The physical and chemical characteristics of soot particles are complex because of the modifications which they constantly undergo while interacting with other elements present in the atmosphere. The diameter of the soot particles found in the exhaust fumes of diesel engines can vary from 0.01 μm to 1 μm. The largest are sufficiently heavy to settle quickly, but the smallest are difficult to collect because of their lightness [3].

While particulate emissions from diesel engines were first regulated in the United States, similar regulations have also been adopted by the European Union, most Asian countries, and the rest of North and South America. Increased use of diesel engines has prompted the development of various technologies for reducing soot particle emissions. One of these technologies consists in using a diesel particulate filter, called a DPF. The most common DPF is made of cordierite (a ceramic material) which provides excellent filtration efficiency. In addition to collecting the particles, there must be a method to clean the filter. Some filters are designed to burn off the accumulated particles, either through the use of a catalyst, or through an active technology, such as a fuel burner which heats the filter to soot combustion temperatures (600 °C). In spite of that, maintenance actions are essential to clean the filter.

This paper presents results of soot particle removal using an electrostatic precipitator (ESP) energized by negative voltage impulses and direct voltage. This device could be a feasible alternative to ceramic filters. Electrostatic precipitation is based on three mechanisms which are [4,5]:

- the creation of charges linked to the electrical discharge process;
- the ionisation of soot particles due to the impact between charges and particles;
- the drift of particles from the HV electrode to the collecting electrode due to the application of an electric field.

When negative DC voltage is used to supply the ESP, studies pointed out problems caused by back corona, in the case of particles of high resistivity, and entrainment, in the case of low resistivity particles, which is the case considered in our application. On the other hand,

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several experiments have pointed out the superiority of hybrid pulsed-power/direct-voltage precipitation [6,7]. The following are some of the advantages:

- it is possible to apply a higher peak voltage without sparks occurring and so to envision better particle charging;
- control of the mean current by varying impulse repetition rate and amplitude can be used to control the particle charging rate;
- the short duration of impulse voltage minimises the effects of gas and dust conditions on the discharge phenomena;
- a higher overall power input and improved precipitator efficiency can be achieved;
- the particle migration velocity is higher because of the stronger average electric field that can be sustained under pulsed conditions.

Other studies have examined the design of the ESP [8] but unfortunately, most research results published on the quantitative effects of pulsing on the performance of ESP are often inconclusive and contradictory.

As was shown by [9], there is a direct link between the efficiency of collection and the average current injected into the ESP. That is why this work began with a study without gas flow. The aim of this first study was to optimize both filter geometry and supply. This optimization relates only to the quantity of charges involved in the ESP. However this optimization work could not have been achieved without a physical study of the electrical discharges which develop in the filter and, more particularly, without characterizing Trichel type discharges. Optical and electrical analysis of these phenomena enabled us to analyze the physical processes (quantity of charge, recovery time, frequency limitation) associated with Trichel regimes in order to adapt a pulsed power source and the geometry of the HT electrodes.

Then, investigations concerning the removal of soot particles were carried out under practical conditions using an engine test bench on which entrance and exit exhaust gas characteristics are adjustable.

2 Optimisation of the quantity of electrical charge released into the filter without gas flow

The aim of this first experimental study was to optimize the mean charge injected into an ESP without gas flow. This optimization consisted in defining the geometrical characteristics of the ESP as well as the electrical characteristics of its power supply.

2.1 Experimental set-up

The experimental device shown in Figure 1 is composed of interchangeable power supplies (DC and hybrid supply) connected to an ESP. The mean current flowing through the ESP is measured at the grounded electrode with an ammeter A1. In addition, a point-to-plane arrangement is deported outside the ESP in order to analyse the discharge regime. Using this device, the light emission from the discharge is analysed by a UV photomultiplier (PM). The PM signal is both correlated to the instantaneous current through a 50 Ω shunt and to the average current value (ammeter A2). A high voltage probe (Northstar PVM5) is also used to measure the applied voltage.

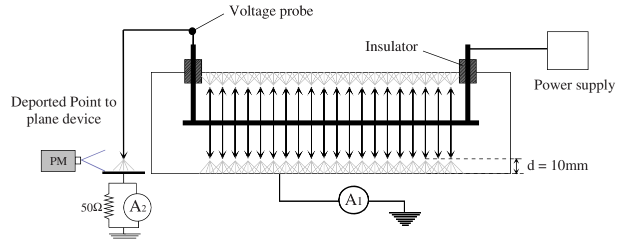


Fig. 1. Schematic design of the electrostatic filter associated to the electrical and optical devices.

2.1.1 Detailed description of the ESP

The ESP was previously designed [10]. The characteristics of the device were optimized by investigated the highest charge quantity produced in the filter. Finally the best ESP design was found to consist in a 500 mm length and 100 mm diameter grounded cylinder inside which an axial HV electrode is placed. The HV electrode is made of a rod on which 20 discharge disks are threaded with a 20 mm distance between each disk. Each disk is made of 16 tips which make it resemble a star. Consequently, the whole of this H.V. electrode presents 320 tips.

2.1.2 The power sources

Two different interchangeable power sources connected to the ESP present the following different voltage waveforms:

- A negative DC voltage is generated by a 50 kV–40 mA supply.
- A hybrid pulsed power/direct voltage supply was specifically developed for this study (Fig 2).

The switching device [11] is based on the series association of 24 thyristors 16TTS12. The chosen thyristor association makes it possible to apply long impulse voltage (impulse width of 120 μs). The capacitor C of 1 nF is used as a capacitor tank. The resistance R of 1 kΩ limits the current through the thyristors in case of output short circuit. The main characteristics of the output impulses are a voltage amplitude $U_{M(Thy)}$ up to 28 kV, a rise time of 250 ns, an impulse width as indicated above and a repetition rate up to 3 kHz.

Considering the ESP as an equivalent electrical circuit made of a 100 pF capacitance in parallel with a variable resistance, the conduction and turn-off times of the

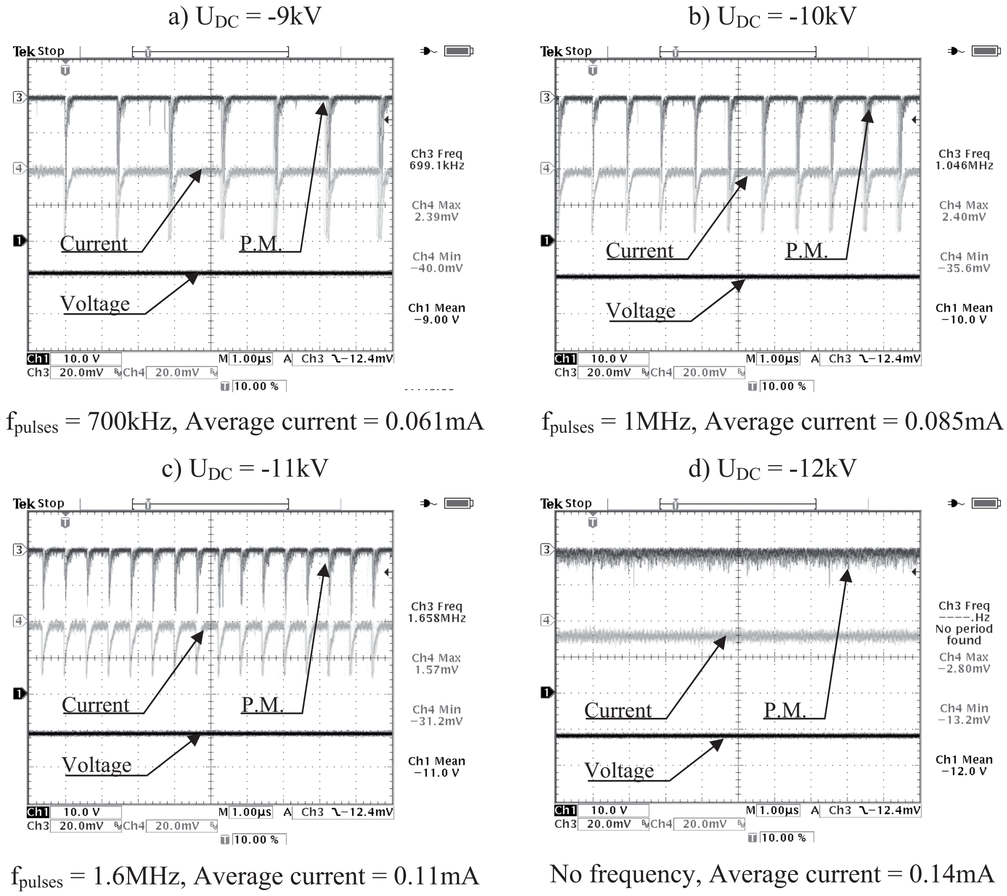


Fig. 3. Current and light impulses (PM) records when the single point is supplied by different values of negative direct voltage U_{DC}.

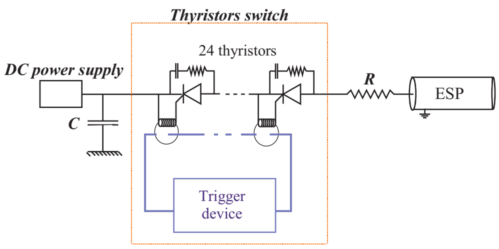


Fig. 2. (Color online) The thyristor switch used to generate hybrid pulsed power/direct voltage impulses.

thyristors increase [11]. Consequently, when the impulse frequency reaches a few hundred hertz, the voltage level generated by the switching device never sets to zero leading to the generation of a continuous voltage component. The maximum DC background generated for a repetition rate of 3 kHz is about –7 kV.

2.2 Results and discussion

2.2.1 Using negative DC voltage

It is well known that under this type of voltage a specific discharge regime appears under a point to plane device: the Trichel discharge [12–14]. As is shown in Figure 3, instantaneous current is composed of impulses, whose amplitude decreases and repetition rate f_{pulses} increases with the applied voltage, and of a continuous background current which increases with applied voltage. It is important to note that the repetition rate of the current impulses is higher than 1 MHz for high DC voltage. When the applied voltage level is close to the breakdown value (about 12 kV in our configuration), the current impulses disappear and the current is only continuous. The quantity of charge released is then optimum. As shown in Figure 3, the mean current increases from 0.06 mA (for $U_{DC} = -9$ kV) to 0.14 mA (for $U_{DC} = -12$ kV).

This discharge mode involves a charge quantity which will be the reference for all the later comparisons.

2.2.2 Improvements using the hybrid pulsed power/direct voltage supply

This study was carried out in two parts: instantaneous observation of the physical phenomenon developing from the point located outside the filter and study of the average current flowing into the filter.

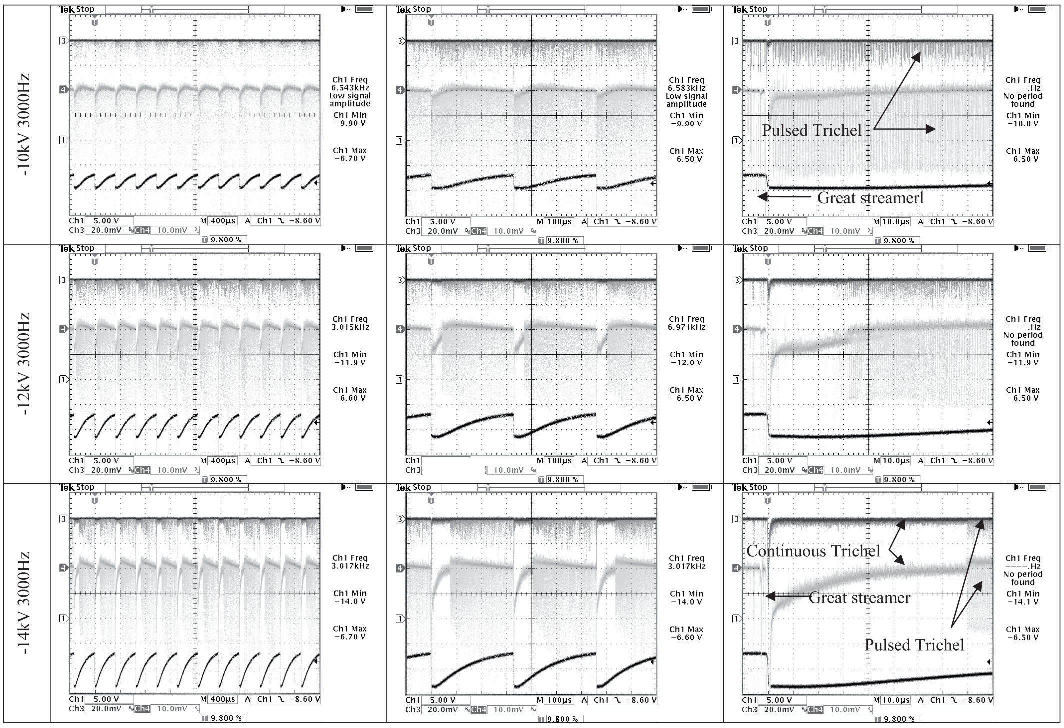


Fig. 4. Applied voltage (signal ①), UV light emission (signal ③) and instantaneous current (signal ④) records when the ESP is supplied by the thyristors switch ($F = 3$ kHz).

a. Physical phenomenon developing from the point

These observations were made under 3 kHz pulse repetition frequency. All the recordings performed in this configuration are presented in Figure 4. The records located on the same line of the table are obtained under the same conditions of voltage and frequency. Only the time scale is modified in order to detail the phenomena developing during the voltage impulses. On each oscillogram is plotted the applied voltage, the time behaviour of the current flowing through the point to plane device and the signal delivered by the photomultiplier. On the emitted light and current recordings of the right-hand side column (enlargement of an impulse), a stable and fast impulse mode corresponding to the Trichel mode appears. This mode is less observable on current recordings because the optical equipment used is faster and more sensitive than the equipment used for current measurements.

Before analyzing recordings, it can be said that for any given voltage impulse repetition rate, and whatever the maximum voltage amplitude, the level of continuous background is always the same: the discharge mode between each voltage impulse is thus identical.

When combined voltage delivered by the thyristor switch is applied to the point, the complete sequence is thus as follows: a great streamer appears during the voltage pulse rise time (when for example using short time duration impulse voltage), then a pulsed Trichel mode is established due to the long duration of the applied voltage impulse. This second phase develops when the absolute value of the impulse voltage decreases and it presents two aspects:

– If $|U_{max}| < 10$ kV, the continuous discharge mode does not appear. A stable impulse mode develops which is characterized by a high repetition rate and low amplitudes. Then, when the absolute voltage value decreases from $|U_{max}|$ to the background value, the amplitude of the Trichel impulses increases and the frequency is stabilized.
– If $|U_{max}| > 10$ kV, the continuous Trichel mode appears after the maximum amplitude of the voltage. Then, when the absolute value of the impulse voltage decreases until it drops below 10 kV, the phenomena become identical to those described for $|U_{max}| < 10$ kV. The development of a continuous Trichel mode makes it possible to improve the value of the average current. The duration of the continuous Trichel mode being constant for each repetition rate tested, increasing the functioning frequency of the generator leads to increased charge injection into the ESP. We will now compare the average current injected under combined voltage and continuous voltage into the ESP (without gas flow).

b. Average current study

Average current values measured inside the filter when it is energized by continuous and combined voltage are thus compared in Figure 5. This figure shows clearly that hybrid supply makes it possible to obtain very interesting values of average current. On the other hand, whatever the pulse repetition frequency of the hybrid supply, the average current remains always lower than that obtained under DC voltage. Nevertheless, the decrease in the breakdown

Table 1. Characteristics of the engine operating levels.

Number of engine operating	Gas speed in the filter ($m.s^{-1}$)	Rotation speed ($tr.min^{-1}$)	Couple (N.m)	Gaz flow rate before the filter ($kg.h^{-1}$)	Gas Temperature before the filter (°C)	Gas Temperature after the filter (°C)	Load (purcentage of max load)
1	14	2000	40	97	210	180	0
2	20	2250	80	123	285	243	25
3	25	2500	100	182	325	285	50
4	55	3750	40	310	310	285	75
5	105	40000	204	–	510	–	100

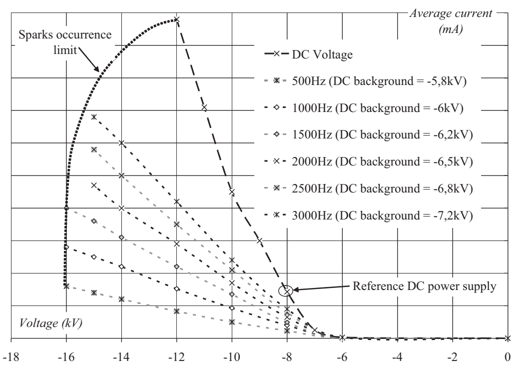


Fig. 5. Behaviour of the average current injected into the filter versus the applied voltage (DC voltage or combined voltage).

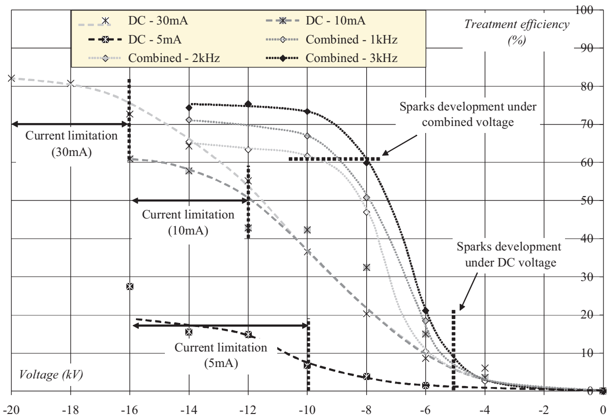


Fig. 6. Treatment efficiency behaviour as a function of applied voltage (Engine speed n°1).

voltage value due to an increase in the gas temperature (real conditions of diesel exhaust gas filtration) will be more penalizing for operation under continuous voltage. So the combined voltage provides high charge quantities only during a short time avoiding the breakdown of the gap.

3 Tests using an engine test bench

A partnership with a French car equipment manufacturer enabled us to test our ESP energized by our repetitive impulse voltage generator under practical conditions using an engine test bench. As a soot generator, a turbo-diesel engine equipped with an oxidation-type catalytic converter was used. This motor has been intensively used in Peugeot cars. Tests are performed using the five different engine operating levels presented in Table 1.

The ESP is placed in the exhaust line of the engine bench between two gas analysis probes. They allow the calculation of the treatment efficiencies. Measurements of the soot particle concentration were achieved via an AVL system. For each experimental configuration, a coefficient η representative of the treatment efficiency is calculated as follows: three concentration measurements M_{up} are made upstream of the ESP and three downstream from the ESP (M_{down}). The efficiency of treatment is given by the relationship:

$$\eta = \left(1 - \frac{\langle M_{down}\rangle}{\langle M_{up}\rangle}\right) \times 100.$$

The aim of this study is to characterise the particle treatment efficiency according to the engine bench speed and the two types of power supply used (continuous and combined).

The following abbreviations are used in the figures:

– "DC-XmA": DC power supply with a current limitation corresponding to XmA.
– "Combined-YkHz": combined voltage working with pulse repetition frequency of YkHz.

3.1 The first engine operating level

3.1.1 Influence of the applied voltage

A representation of filter treatment efficiency variations according to applied voltage is presented in Figure 6. A DC power supply is used using three different values of current limitation (5, 10 and 30 mA). The three curves correspond to results achieved with the hybrid power supply functioning with different pulse repetition frequencies (1, 2 and 3 kHz). The x-axis corresponds to the values of the preset continuous level with no-load, that is to say when the ESP is not connected to the supply. There is obviously a difference between the preset values and those really measured on the HV electrode. These differences are due to the speed flow and temperature of the gas which modify the electric properties of gap space.

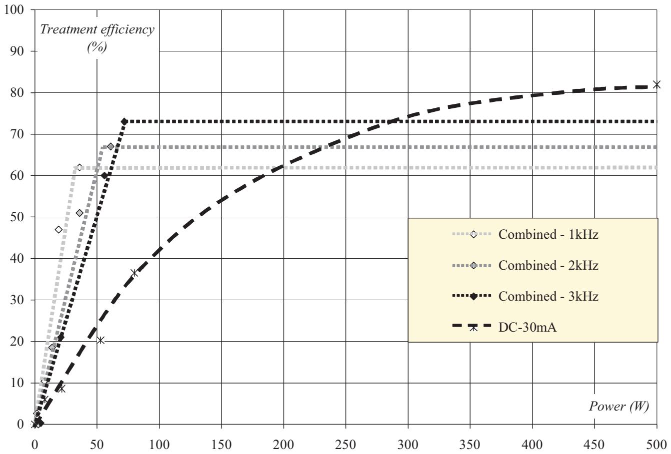


Fig. 7. Treatment efficiency behaviour versus the electrical power provided to the ESP (Engine speed n°1).

On the curves, breakdown voltage levels are indicated. Under DC voltage, as soon as sparks occur, it is no longer possible to measure the average current injected, except when the current limitation of the power supply is reached. Under combined voltage, the DC power supply never works in current limitation mode. The mean current injected into the ESP was measured up to spark development.

a- Operation under DC voltage

These curves present a saturation effect when the current limitation of the power supply is reached. As long as this limitation is not reached, it is possible to increase the maximum voltage value even if sparks occur in the inter-electrode gap. For example, for $U_{DC} = -14$ kV, the applied voltage to the H.V. electrode reached, between two sparks, approximately –8.3 kV. If we increase the preset voltage ($U_{DC} = -18$ kV), the applied voltage between two sparks also increases (about –10.8 kV) as long as the power supply is able to provide the current.

Consequently, as long as the current limitation of the power supply is not reached, these results emphasize that the treatment efficiency always increases with the applied voltage and the current provided by the power supply. Under DC voltage, it can be concluded that the development of sparks in the ESP is not a disadvantage for the removal of Diesel soot particles.

b- Operation under combined voltage

Whatever the impulse repetition rate, increasing the applied voltage leads to an improvement in the treatment efficiency until sparks occur (Fig. 6). Above the voltage level corresponding to spark ignition, the treatment efficiency saturates (contrary to the case with DC voltage). It can be seen that the breakdown voltage levels decrease when the pulse repetition frequency increases. Consequently, a shift of the threshold saturation level can be noted. Figure 6 also shows that the higher the pulse repetition frequency, the higher the treatment efficiency.

3.1.2 Influence of the electrical power involved

In order to analyze the electrical power involved in the ESP, it is necessary to refer to Figure 7. The power indicated on the x-axis on this figure is the product of the preset voltage value with no-load and the average current value measured during operation. It corresponds to the power available to achieve a given treatment efficiency that is to say to the cost of the DC power supply necessary for the gas treatment.

a- Operation under DC voltage

The first five points (power lower than 100 W) were obtained without sparks. As indicated previously, it is not possible to measure the mean current in sparks mode except when the current limitation of the DC power supply is reached. In this last case, the electrical power involved can be calculated (the point corresponding to $P = 500$ W). The curve presented in Figure 7 under DC supply corresponds to the extrapolation between all these six points. Consequently, these results indicate that a power of 500 W makes it possible to achieve a treatment efficiency of about 80% when the ESP is energized using a DC supply.

b- Operation under combined voltage

We also considered the presence of two zones of operation under this kind of supply: a functioning of the ESP with or without sparks. In the first zone (without sparks), the treatment efficiency increases with the applied electrical power. In the second zone, the treatment efficiency is nearly constant whatever the value of the applied electrical power. That is the reason why in our representation of Figure 7, we chose to maintain the power involved at a constant value as soon as sparks develop.

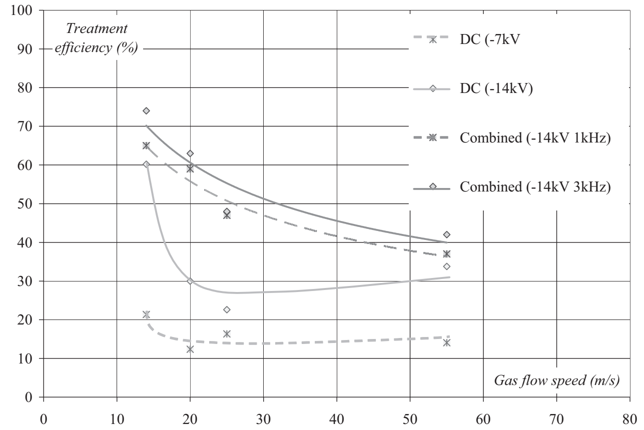
Consequently, Figure 7 shows that, using combined voltage, interesting levels of treatment efficiency are reached for low power levels. For example 60% effectiveness is reached with approximately 30 W with combined power supply functioning with a repetition rate of 1 kHz, (50 W with 2 kHz and 60 W with 3 kHz) whereas it is necessary to apply approximately 180 W to reach the same effectiveness under DC voltage.

Moreover, it can be noted that, the more the frequency increases, the weaker the η/P slope. This result indicates that, for a constant power value, efficiency decreases when the frequency increases, but, on the other hand, the highest frequency allows the highest performance of treatment. This result is very important because the volume and the price of the supply are essential parameters if one wishes to adapt the device in a car.

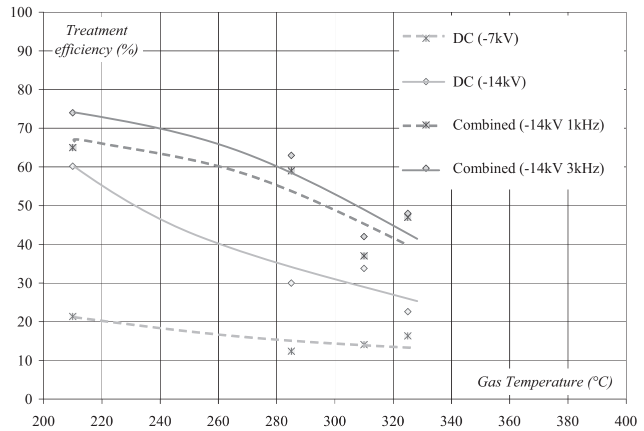
All the remarks and observations made using engine operating level n°1 are valid on the other studied operating levels as we will see in the following section.

3.2 Results using the other engine operating levels

Figure 8 presents the behaviour of filtration efficiency as a function of engine bench characteristics (flow speed and



(a) Parameter: Gas flow speed



(b) Parameter: Gas temperature

Fig. 8. Treatment efficiency measured for several configurations of power supplies according to engine bench speed characteristics.

gas temperature) according to the applied voltage. For operations under combined voltage, the maximum of the pulsed voltage is –14 kV and the repetition rates are 1 kHz and 3 kHz. For operation under DC voltage, two curves are also presented: one corresponds to the same level of maximum applied voltage (–14 kV), the other corresponds to a DC voltage of –7 kV.

Gas temperature and speed flow do not vary regularly when the exhaust gas characteristics are modified (Tab. 1). For example, the behaviour from engine speed n°1 to engine speed n°2 leads to an increase in temperature of 65 °C (210 °C to 285 °C) and an increase in gas flow rate of 6 $m.s^{-1}$ (14 $m.s^{-1}$ to 20 $m.s^{-1}$). The transition from engine speed n°3 to engine speed n°4 leads to a temperature reduction of 15 °C (325 °C to 310 °C) and a gas speed increase of 30 $m.s^{-1}$ (25 $m.s^{-1}$ to 55 $m.s^{-1}$).

The main results in this study show that, whatever the type of supply, the effectiveness of treatment decreases when the temperature and/or the exhaust gas speed increase. This behaviour is consistent with the well-known results which show that the modes of discharge are a function of both the temperature and the flow rate of the gas. Moreover, the best treatment efficiency is always achieved when the combined voltage is used.

4 Conclusion

The aim of this study was to optimize the design of an ESP and to develop a hybrid pulsed power/direct voltage supply. This device could be use to remove diesel soot particles from exhaust gas. The results described above show that the superposition of impulses on DC voltage makes it possible to achieve a treatment efficiency higher than that obtained when the ESP is energised by DC voltage, and use less electric power. Consequently, this system could provide a feasible alternative to ceramic filters.

Moreover, it was shown that the higher the pulse repetition frequency, the higher the treatment efficiency. Consequently, when the aim is only to optimize the treatment efficiency, the highest frequency is recommended. However, an increase from 1 kHz to 3 kHz of the impulse repetition rate leads to a significant increase in the power consumption whereas the treatment efficiency only increases slightly. A power/efficiency trade-off remains to be defined.

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