A Fast Pulsed Power Source Applied to Treatment of Conducting Liquids and Air

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***Abstract*—Two pilot pulsed power sources were developed for fundamental investigations and industrial demonstrations of treatment of conducting liquids. The developed heavy-duty power sources have an output voltage of 100 kV (rise time 10 ns, pulse duration 150 ns, pulse repetition rate maximum 1000 pps). A pulse energy of 0.5–3 J/pulse and an average pulse power of 1.5 kW have been achieved with an efficiency of about 80%. In addition, adequate electromagnetic compatibility is achieved between the high-voltage pulse sources and the surrounding equipment.**

Various applications, such as the use of pulsed electric fields (PEF's) or pulsed corona discharges for inactivation of microorganisms in liquids or air, have been tested in the laboratory. For PEF treatment, homogeneous electric fields in the liquid of up to 70 kV/cm at a pulse repetition rate of 10–400 pps could be achieved. The inactivation is found to be 85 kJ/L per log reduction for *Pseudomonas fluorescens* and 500 kJ/L per log reduction for spores of *Bacillus cereus*.

Corona directly applied to the liquid is found to be more efficient than PEF. With direct corona we achieve 25 kJ/L per log reduction for both Gram positive and Gram negative bacteria. For air disinfection using our corona pulse source, the measured efficiencies are excellent: 2 J/L per log reduction.

***Index Terms*—Cold pasteurization, inactivation of microorganisms, membrane breakdown, pulsed corona, pulsed electric fields (PEF's), pulsed power.**

I. Introduction

THE USE of high-intensity pulsed electric fields (PEF's) in food applications such as milk and fruit juices has gained much popularity and is claimed to represent a most promising nonthermal alternative to conventional pasteurization methods.

Supposed mechanisms of inactivation of bacteria cells with PEF is perforation of the cell membrane due to high voltages across the membrane or due to current concentration in the pores. In a cell membrane, protein channels and pores are present [1], [2]. The opening and closing of many channels constituted by proteins depends on the transmembrane voltage difference [3], [4]. When PEF is applied, many voltage-sensitive protein channels may open, and when the voltage difference reaches 150–500 mV, the lipid bilayer breaks down.

Manuscript received May 13, 1999; revised October 27, 1999. This work was supported by the Dutch CPS, STW, and Novem research and funding programs.

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Publisher Item Identifier S 0093-3813(00)01385-0.

It is observed that when a cell membrane is exposed to an electric field larger than about 25 kV/cm, irreversible electric breakdown of the cell membrane occurs [5]. The extent of inactivation depends on the strength, duration, and form of the electric pulses [6]. Pulses with duration of 100–200 ns are reported to provide an efficient inactivation of microorganisms [7].

Nevertheless, the results with PEF published in literature show large differences in lethal effects and levels of energy [5], [8] under apparently similar conditions. The scatter in lethal effects may be due to different media, the condition of the bacteria [9], the treatment procedure, or the change with medium temperature of the susceptibility of the microorganisms to pulsed electric field [10].

If taste and food qualities are not the important issues, a more effective pulsed power method for inactivation of microorganisms is direct application of pulsed corona in the liquid. This pulsed corona method (PCOR) is based on the creation of inhomogeneous electric fields that are sufficiently high to generate corona discharges in the liquid. Discharge products such as radicals, ozone, aqueous electrons, and ultraviolet rays are produced directly in the liquid to inactivate the bacteria.

An airflow can also be treated with pulsed corona to kill or to remove microorganisms. Here, a similar interaction of discharge products and organisms is the supposed mechanism. A second possible mechanism in gases is electrostatic precipitation of bacteria. In this case, the collected dust of microorganisms would have to be collected in an extremely careful way to reach the required considerable reduction on a log scale.

Both PEF and PCOR require high voltages that are generated across a liquid load. To effectively apply high voltage to a conducting liquid, fast rise times and narrow pulses are needed to reduce the amount of dissipation. If the crucial effects to the liquid are limited to either high electric field or corona activity, it could be sufficient to maintain the pulse voltage only for a time that is on the order of the achievable rise time.

The liquid, considered as a combination of resistance and capacitance, responds to the pulse by means of characteristic *RC* time constants and voltage division over impedance ratios. Various subsystems in the liquid have different constants. The time constant of the liquid itself may vary from less than a nanosecond to 10 ns. Cell membranes have time constants in the same range.

The pulse source connected to this liquid system produces a waveform that also depends on the impedance (and inductance) of the source. We developed a pulse source with an impedance of 200 Ω that produces up to 1.5 kW of pulsed power in the load. The source can run continuously at a pulse repetition rate of up

to 1 kHz. The output voltage rating is 100 kV, and the pulse width is 150 ns. The source initially was developed for air treatment. For that application, the high output impedance of 200 Ω was found adequate. The combination of this source and a liquid treatment chamber leads to rise times of about 10 ns. In low frequency approximation the impedance division between source and load produces a considerable reduction in output voltage.

Further developments are needed to reduce the source impedance and to increase the load resistance and to effectively take advantage of time constants of subsystems. The result can lead to faster rise times and higher electric fields in the liquid. Part of this work needs to concentrate on the effect of shorter pulses ($\ll$150 ns) at a high repetition rate.

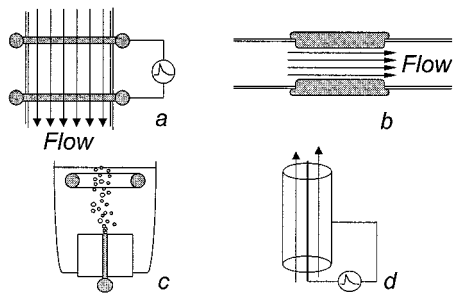

Fig. 1. Types of treatment chambers for inactivation of microorganisms by pulsed power: (a) perpendicular flow, (b) parallel flow, (c) bubbling needle, and (d) wire cylinder.

II. Treatment Chambers

Various types of treatment chambers have been designed and tested. Fig. 1 gives an overview of four basic layouts.

To apply PEF, the liquid cell is provided with electrodes. At least two electrodes are mounted either parallel [11] or perpendicular to the flow in the test cell. Since the high voltage applied across the electrodes can be up to 100 kV, the distance between them was kept sufficiently large to avoid discharge activity. Various shaping electrodes were added to avoid high local fields around the electrode structure. The test cell was immersed in transformer oil to avoid discharge activity on the external parts of the electrode structure. Inside the cell, the field is nearly homogeneous and reaches 70 kV/cm maximum. This should be sufficient to attack bacteria membranes.

The PCOR method can be applied in liquids as well as in air, e.g., in a wire-cylinder geometry. As an alternative, we used a liquid cell that has a hollow needle as central electrode and a remote ring-shaped conductor as second electrode in the liquid [12]. The hollow needle was fed with air or nitrogen to be bubbled through the liquid. High-voltage pulses were applied to the needle. During each pulse, intense corona discharges develop in the bubbles near the needle. The discharges disrupt the bubbles in many microscopic fragments and also lead to discharge products in the liquid.

For applications in air, we used the normal wire-cylinder geometry. The reactor has a length of 3 m and a diameter of 0.25 m.

III. Pulse Source

For most of our experiments, we used a heavy-duty pulse source developed during the past years. The unit produces 100-kV pulses (10 ns risetime, 150 ns wide) at a maximum rate of 1000 pulses per second (pps). An overall efficiency of up to 80% was obtained for the energy transfer from main's ac power to corona energy in gas flows at pulse repetition rates below 600 pps. The pulse energy can vary between 0.5–3 J/pulse. Failureless operation of this unit has passed the 400-h mark. The design has been patented [13].

Fig. 2 gives the basic principle of the pulse source. The circuit and the measuring circuits are described in detail in [14]. The circuit can be separated into a low-voltage and a high-voltage part. The low-voltage part consists of a rectifier, two resonant circuits that are switched by two thyristors, and the primary winding of the pulse transformer. The high-voltage part includes the secondary winding of the pulse transformer, an energy storage capacitor C_2, a triggered spark-gap SG for 32-kV switching, and finally a transmission-line transformer (TLT) to produce the 100-kV pulses. The high-voltage charging capacitor C_2 is resonantly charged to 32 kV in 50 μs. Then the low-inductance spark-gap (50 nH, coaxial with the high-voltage capacitor) discharges the capacitor into the TLT. The reliability of the spark gap is excellent; after 10^3 pulses (total transferred charge 200 kC), only minor electrode wear is visible. The gap has to be flushed continuously with air (30 Nm^3/h typically). The TLT is made of four coaxial cables, each 50 Ω and 12 m long (RG218).

The output high voltage is measured by means of a capacitive sensor, and the output current is measured by means of a single-turn Rogowski coil. From these signals, the delivered power and energy are calculated. During an experiment, the high voltage, current, power, and energy are monitored continuously.

With respect to electromagnetic compatibility, methods have been developed to effectively suppress interference, in a systematic and reproducible manner, by appropriate guidelines and rules for the layout [15]. Sensitive electrical equipment can operate reliably close to the pulse source. Computers and networks in close vicinity and in the surrounding buildings remain undisturbed.

For the experiments with pulsed corona discharges directly in the liquid, a different pulse source of 50 W, 20 kV was used. It has a longer pulselength (6 μs) and can run at up to 50 pps. This pulse source will be described in Section VI.

IV. Typical Values for Applications in Conducting Liquids with Bacteria

If homogeneous high fields are applied, an important field enhancement across the membranes can occur due to inhomogeneities in the material constants ε and ρ, the dielectric permittivity, and the specific resistivity. The membranes will have properties that differ considerably from those of the surrounding water. The value of ε of the membrane is assumed to be $1/\alpha_1$ ($\alpha_1 = 10$–40) times its value in the water, whereas the resistance will be α_2(10–40) times its value in water. However, as a result, the time constants $\tau = \varepsilon\rho$ of the media membrane and liquid both are in a range around 1 ns.

If the actual time constants are close together, we have a difficulty in attacking membranes in liquids. Suppose that we have a

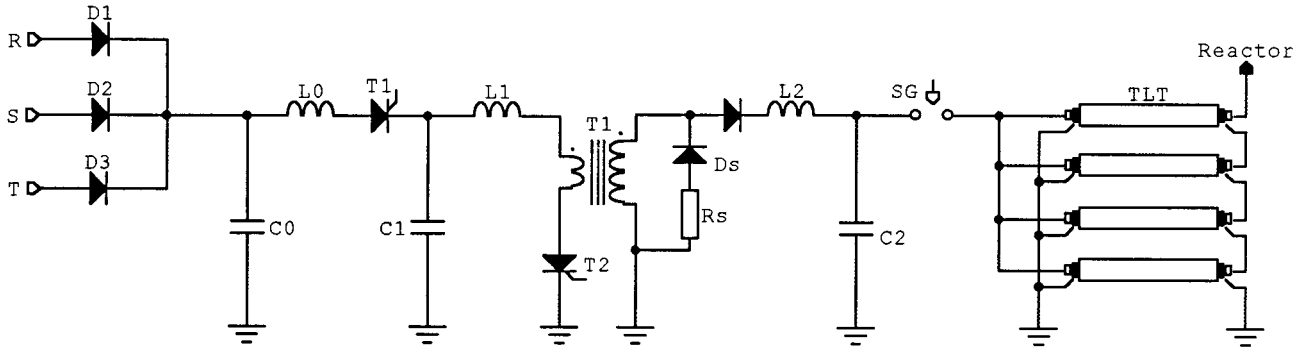

Fig. 2. Schematic overview of the high-voltage pulsed power source.

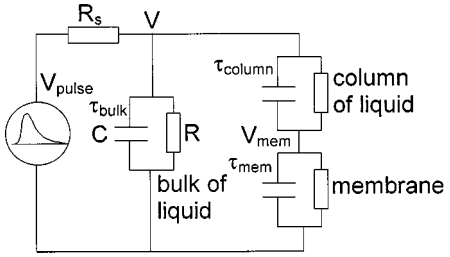

Fig. 3. Electrical model of membrane in a liquid.

homogeneous membrane without pores and a homogeneous cell interior with properties equal to those in the surrounding water. An electrical model connected to this picture of membrane, capacitance, and resistance resembles the picture of a void in a dielectric fluid (Fig. 3). If the membrane is a disk perpendicular to the electric field, the high-frequency field enhancement in the membrane is α_1. This occurs for times shorter thanτ_{water} (with $\tau_{\text{water}} < \tau_{\text{membrane}}$). On a longer time scale, it is the resistivity that determines the field enhancement. The enhancement in this case is α_2. In the simple case that $\alpha = \alpha_1 = \alpha_2$, the division ratio of the membrane over the liquid is constant and equals $\alpha d.E/V$. Here, E is the undisturbed electric field in the liquid, V is the applied voltage, and d is the thickness of the membrane. The voltage across the membrane is $\alpha\, dE$. It is often assumed that 1 V across the membrane will lead to inactivation [5]. For typical values of $d = 2 \cdot 10^{-6}$ cm and $\alpha = 20$ we find that the applied E field needed to reach 1 V across the membrane is 25 kV/cm. To calculate the needed source voltage, the reduction due to source over liquid impedance also has to be taken into account. A typical value would be a reduction of two. For an electrode distance of 1 cm, the applied voltage source therefore should produce 50-kV pulses.

V. PEF Treatment in Water

The treatment cell [shown in Fig. 1(a)] has a diameter of 40 mm and is placed in series with a closed-loop circulating flow system of 0.5 L total volume. The liquid is water with a resistivity of 35 Ω·m. The flow is 200 L/h, the energy per pulse is 1.85 J, and the repetition rate is 215 pps. The electrodes are perpendicular to the flow, and the distance between them is 16 mm [11]. The electrodes are connected to the output of the 100-kV pulse source shown in Fig. 2.

Pseudomonas fluorescens B337 was grown overnight in nutrient broth at 30 °C. During this incubation, concentrations of 10^9 colony forming units (cfu's) per milliliter were reached. In order to prepare spore suspensions, sporulation of *Bacillus cereus* P5 was achieved on nutrient agar plates containing 7 mg/L manganese. After incubation for seven days at 30 °C, spores were washed from the surface with sterile distilled water. The final concentration of the suspension was 10^8 spores per milliliter. The levels of the spores were checked by plate counting on plate count agar containing 1% of skim milk (PCMA).

Bacterial or spore suspensions were diluted in sterile distilled water to obtain an initial inoculum level of 10^5–10^6 mL^{-1} to carry out the experiments. This level was checked by surface streaking on PCMA.

The samples taken during the experiment were cooled in ice water. The levels of vegetative bacteria surviving the treatment were determined by plate counting on PCMA. To count the concentration of spores, a heat treatment of 10 min at 80 °C was carried out to inactivate vegetative bacteria and to only detect the spores. Following this heat treatment, the samples were also plated on PCMA. The log reduction is calculated as the concentration of microorganisms or spores initially present (log cfu of spores per milliliter) minus the concentrations surviving the treatment (log cfu or spores per milliliter).

Experimental results with this chamber are promising. Fig. 4 shows the results of an experiment carried out at an electrical field strength of 66 kV/cm. It gives a plot of the log reduction versus the input energy (kJ/L). The input energy was measured as the sum of the energies of the applied pulses. The samples for microbial investigations were taken at intermediate time steps after start of the pulse source. At a temperature of 32 °C both *Pseudomonas fluorescens* and *Bacillus cereus* spores were inactivated, respectively, by more than 3 and by 0.8 log reduction. The maximum energy input was up to 430 kJ/L. The resulting efficiency to inactivate is 85 kJ/L per log reduction for *Pseudomonas fluorescens* and some 500 kJ/L per log reduction for *Bacillus cereus* spores.

The input energy also is a measure of the duration of the real treatment time, that is, the time that each fluid element has been

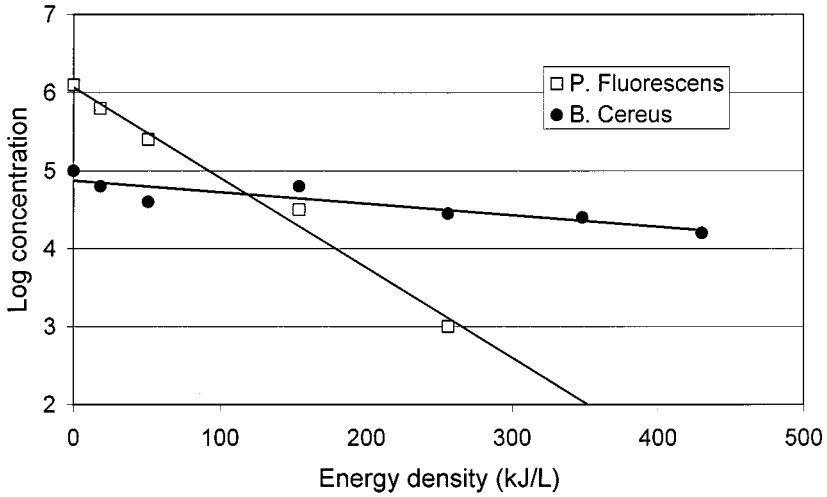

Fig. 4. Inactivation of bacteria and spores in tap water by 66 kV/cm PEF at 215 pps and a pulselength of 150 ns.

in the cell while the pulse source was running. The real treatment time in seconds is the input energy (in kJ/L) divided by 20 (in kJ/L/s). The number of 20 is given by the energy per pulse (in kJ) times the repetition rate (in pps) divided by cell volume (in L). Therefore, in our case, 430 kJ/L means a real treatment time of 21.5 s.

VI. PCOR Treatment in Water

In this experiment, we used a culture of Gram positive and Gram negative bacteria instead of *Pseudomonas fluorescens* and *Bacillus cereus* vegetative cells and spores that were used in Section V. An energy input of 14–19 W by 16–44 pps pulsed corona is applied to the cell with the bubbling hollow needle. The treatment cell is shown in Figs. 1(c) and 5. Air or nitrogen is fed to the needle at a rate of 39.5 mL/min. The cell is connected to a closed-loop flow system with a pump in series. The liquid is water with a resistivity of 15 Ω·m. The total volume is 430 $\pm$70 mL. The active corona volume is a small area near the needle tip. The liquid was pumped at 100 L/h in the closed loop.

The important parameter is the energy density in kilojoules per liter of the entire liquid volume. This parameter was deduced from the time-resolved measurements of voltage and current and from the average value of volume and pulse repetition rate. The applied voltage is either $-$10 or $+$20 kV, and the pulse width is 6 μs (at 50% peak value). The pulse source is of a different type here: a spark gap that discharges a capacitor directly onto the needle (see Fig. 5). The capacitor is dc charged, continuously via a resistor. In this configuration, the repetition rate is set by the values of charging voltage, gap setting, and resistor value.

The microbial population was prepared from the accumulation of a pure culture of Gram negative and Gram positive bacteria. The culture was diluted into standard samples of 50 mL of water. One to five minutes before the start of an experiment, a standard sample was injected into the water ($\cong$430 mL) in the corona treatment chamber. The resulting initial total counts in the unprocessed liquid are in the range of 10^6–10^7 counts per milliliter. After PCOR treatment, samples were extracted from the processed liquid and the setup was decontaminated. The samples were analyzed microbiologically by surface plating on nutrient agar. Following incubation at 30 °C, the plates and the surviving bacteria were counted.

The results of the tests are given in Fig. 6 for the inactivation of the entire bacterial population: the sum of Gram positive and Gram negative bacteria. A near log 3 reduction can be obtained for energy densities of 75 kJ/L. The microbiological properties of the present flow system are insufficient to obtain better reduction rates.

The results of variation of voltage and polarity show that the effects of these parameters are not considerable. It is mainly the energy density that is the key factor for the inactivation effect. The type of gas flown through the needle also has some influence. Air leads to an efficiency of 25 kJ/L per log reduction, whereas N2 needs 32 kJ/L per log reduction. This could mean that apart from aqueous discharge products, also ozone and oxygen radicals might play a role.

VII. PCOR Treatment in Air

An airflow of 197–967 m^3/h was fed to a 147-L wire-cylinder treatment chamber. The reactor of Fig. 1(d) is connected to the pulse source of Fig. 2. The air was environmental air from the building. The corona power during all experiments was 612 W average. The pulse voltage is 100 kV, the repetition rate 600 pps, and the pulse width 150 ns (at 50% peak voltage).

Achieved reductions of bacteria, spores, and yeast in the applied environmental airflow are estimated by means of PCA and OGY sampling. Total counts of PCA and OGY (total microorganisms including yeasts) before and after processing are presented here. The sampling technique was performed using a rotating collector during 8 min in the air flow. Instrumentation was the RCS Airsampler of Biotest, Germany.

In the 967 m^3/h flow, we achieved at least one log reduction at an energy density of only 2 J/L. The reduction efficiency may very well prove to be higher when more detailed measurements are done.

Particle charging in a corona discharge is a well-utilized effect in electrostatic precipitators. The charged particles are subsequently transported by the electric field and collected at the walls of the discharge chamber. To investigate whether the ob-

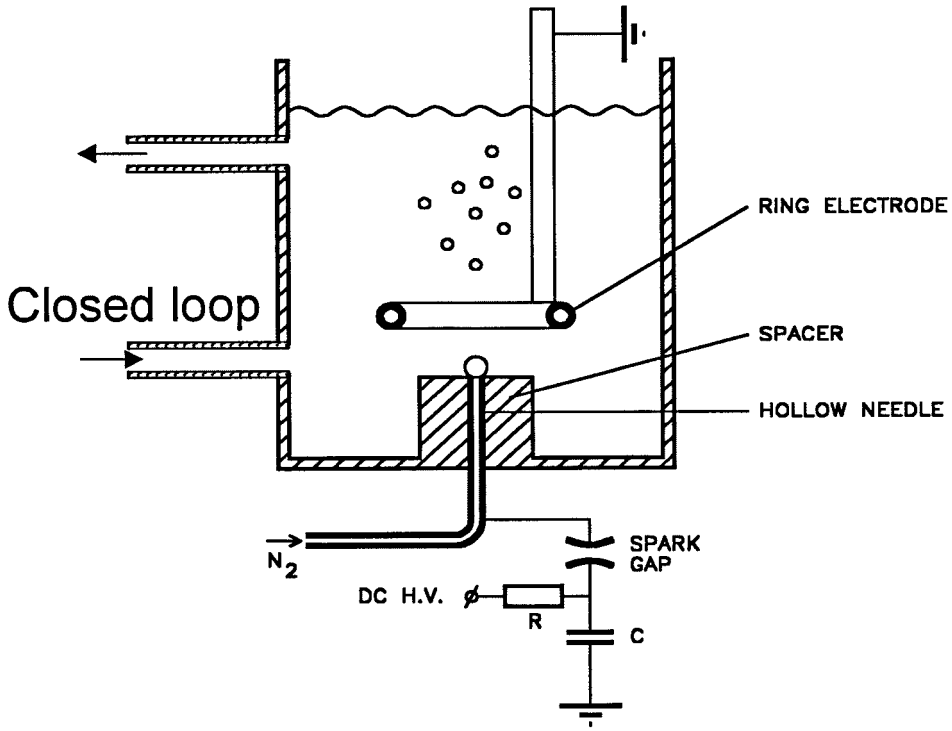

Fig. 5. Setup with the bubbling needle for PCOR treatment of microorganisms in water. The flow is pumped in a closed loop containing the treatment chamber. The high-voltage electrode in this chamber is the needle.

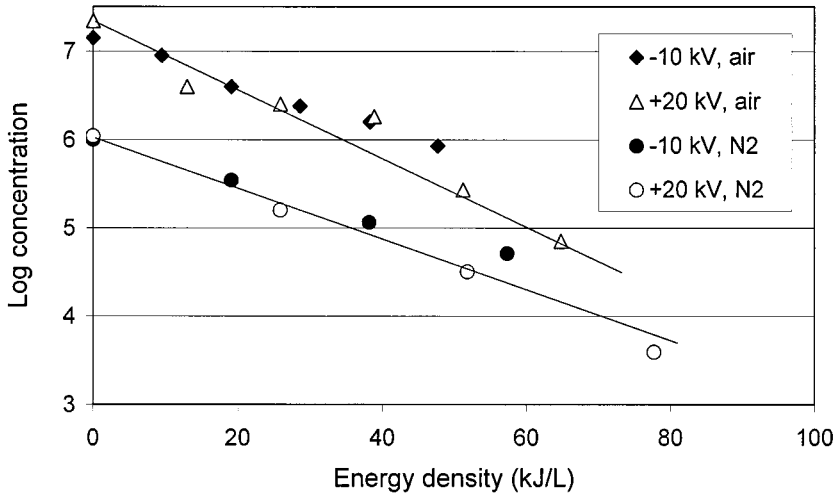

Fig. 6. Inactivation of gram negative bacteria by PCOR in a needle versus ring configuration. The hollow needle is flushed with air or nitrogen. The pulses are –10 kV, 44 pps, 14 W; or +20 kV, 16 pps, and 19 W. The pulselength is 6 μs.

served reductions in air are a direct consequence of the lethal effects of corona discharges or are the result of charging and precipitation, we also measured the particle collection efficiency of the pulsed discharges. We found that particles of more than 5 μm diameter are removed for more than 90% in a flow of 967 m^3/h. In a flow of 197 m^3/h, this figure is near 100%. Most of the considered microorganisms, however, are in the next smaller size range of 0.5 μm <size <μm. For particles in this size range, the precipitated fractions are only 25% and 34%, respectively. Since the inactivation of microorganisms is much higher, it is not the particle collection but more probably the direct lethal effect of corona discharges that is responsible for the observed reductions.

VIII. Discussion

Various types of pulsed power treatment of microorganisms in water and in air were investigated. Efficiencies were expressed in terms of energy density per log reduction and are summarized in Table I.

For liquids, PEF treatment remains preferred if food is to be pasteurized. Parameters for PEF inactivation were estimated for

TABLE I
SUMMARY OF EFFICIENCIES OF VARIOUS TESTED METHODS ON INACTIVATION OF MICROORGANISMS

Medium	Treatment type	Efficiency (kJ/L per log reduction)
Air	PCOR, wire-cylinder	0.002
Water	PCOR, needle - air bubbles	25
Water	PCOR, needle - N_2 bubbles	32
Water	PEF, bacteria	85
Water	PEF, spores	500

a test cell with homogeneous electric field. A voltage of 1 V across the membrane would coincide with a bulk E-field of some 25 kV/cm. This value may vary by a factor of two, depending on actual values of material parameters. The effect would be similar for bacteria and spores. However, experiments show that spores are inactivated only at much higher energy densities. We need to compare the supposed mechanism with another possibly important effect: the current concentration in the pores of organisms in the high E-field. Local heating in the pores could transform the pores into lethal perforations of the membrane. Spores would suffer much less from this effect, which might be one possible hint for their hardness against PEF.

To arrive at industrial applications, reliable pulse sources such as the one demonstrated here have to be further developed and made more powerful with longer proven life time. High energies are needed even for direct corona treatment. Further developments are needed to improve the efficiencies to values below 10 kJ/L per log reduction.

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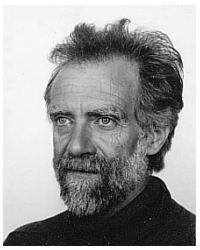

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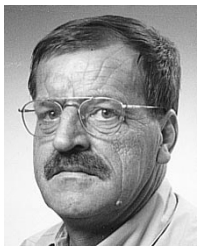

Geert Jan Zanstra was born in Groningen, the Netherlands, in 1944.

Since 1968, he has been active as a Food Technologist in the agrobusiness. Due to his interest in environmental problems, in 1986, he became a consultant for food production and environment. Among his activities are a design for biomass digestion and for protein recovery in waste water. He became Director of the engineering company CONVEX in 1994.

Peter de Jong was born in Utrecht, the Netherlands, in 1965. He received the B.Sc. and Ph.D. degrees in chemical engineering from the University of Technology Delft, the Netherlands, in 1986 and 1996, respectively.

Since 1987, he has been with NIZO Food Research, the Netherlands, and has been leading the New Technology Group since 1996. This group is active in the field of predictive computer models and new processes, such as PEF.