Pulsed Electric Fields for Food Industry: Historical Overview

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Abstract

The current chapter gives an historical overview on the research works and applications of electricity and specifically pulsed electric fields in food processing. The practical applications of the continuous (DC) or alternating (AC) electric currents for heating of the foods and for killing of microbes in liquid foods have more than one hundred years history. The initial efforts had shown promising possibilities of application of electricity (electrical discharges, rapidly oscillating currents, DC and AC currents) for cooking, ohmic heating, canning, stimulation or killing of bacteria, and sterilization. In the middle of twentieth century the pulsed electric field (PEF) assisted processing of food has also attracted research interests. This interest was warmed up by discovery the phenomenon of electroporation in 1950s–1960s. Practically at the same time the different groups in Germany, Ukraine, and Moldova started their activity on AC/DC and PEF-assisted processing of food products. Two to three decades

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ago, applications of pulsed electric fields (PEF) for treatment of liquid and solid foods became more and more popular. Many important effects and mechanisms related with impact of PEF on bio, food, or agricultural products were discovered and elucidated for this period. At the same time concept of electroporation was continuously developing. The positive effects of PEE-assisted processing for inactivation of microorganisms, extraction, pressing, osmotic dehydration, drying, and freezing were observed. The final section in chapter covers a brief discussion on the recent advances with special emphasis on the producers of food-oriented commercial PEF-treatment apparatuses with different characteristics, power, and particular protocols.

Keywords
Electroporation • Pulsed electric fields • Electroplasmolysis • Historical overview

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Introduction

The practical applications of the continuous (DC) or alternating (AC) electric currents for heating of foods and for killing of microbes in liquid foods were started about one hundred years ago. In the middle of twentieth century the pulsed electric field (PEF) processing of foods was launched. The research interest to the PEF treatment of foods was warmed up by discovery of electroporation phenomenon in 1950s–1960s. Practically at the same time different groups in Germany, Ukraine, and Moldova started their activity on AC/DC and PEF treatment of food products. In 1970s–1990s the cell membrane electroporation concept was theoretically grounded. Starting from mid-1990s the application of PEF in food processing becomes more and more popular. For two recent decades the revolutionary changes in food, biorefinery, and environmentally oriented PEF applications have been occurred and various PEF-assisted techniques have been already tested.

This chapter briefly overviews the history of the continuous (DC), alternating (AC), and PEF studies in food and related industries, starting from early works published in the first half of the twentieth century and following by studies carried out during the period between 1940s and mid-1990s. The recent advances and up-todate efforts on various applications of PEF in food processing are shortly described with special emphasis on the producers of food-oriented PEF-treatment apparatuses.

Studies on Treatment of Foods by Electricity in the First Half of the Twentieth Century

The practical attempts on food application of electricity had been started at the beginning of the twentieth century. The different examples of application of DC and AC currents for microbial inactivation, cooking, ohmic heating, canning, stimulation or killing of bacteria, sterilization, etc. were demonstrated. For example, the applications of different forms of electricity (electrical discharges, oscillating currents, DC and AC currents) for disinfection of water, killing microorganisms suspended in liquids have been widely discussed. The killing of bacteria by electricity in the "electro-pure process" was explained by the heat produced by the electric current rather than to the electric current itself (Anderson and Finkelstein 1919). The important observations on electrical stimulation and noticeable increase in bacterial activity and yeast activity by weak electrical currents were also reported (Stone 1909).

For the other hand, the advantages of electricity application for cooking and joule heating have attracted continuous interest. In early studies the efficiency and low cost of electrical cooking has been generally recognized. Cooking with heat generation by food resistance was investigated and various types of cookers were described (Sater 1935). Practical examples demonstrating electrical equipment for the cooking of fruits, vegetables, and meats were also presented. During the first half of the twentieth century different types of equipment for direct resistance heating were developed in the food industry. Obtained results were explained by cell damage. Electrical resistance of the tissue decreased during the treatment and then was partially recovered after the current switching off.

Activity on Implementations of Electricity and Pulsed Electric Field in Food Industry in the Period Between 1950s and the Middle 1990s

The more active implementation of electricity and PEF for treatment of different foods was started in 1950s. During this decade the different groups in Germany, Ukraine, and Moldova started industrial research and industrial efforts on implementation of AC and DC currents and PEF treatment in food industry.

Germany

In the 1950s and 1960s there were reports on abrupt capacitor discharges which lead to killing effects of microorganisms in fluids and to cracking of composite materials. Very high electric field strengths are applied pulsatingly using capacitor discharges

Fig. 1 Heinz Doevenspeck (1917–1993)

which create electric arcs and quickly expanding plasma. Ultraviolet light, electrochemical reactions, and, mainly, a shock wave of up to 5000 bar were identified responsible for bacteriocidal effects. This process, then titled “electrohydraulic treatment,” is nowadays used, for example, by the German Institute of Food Technology in Quakenbrück, Germany, to change the structure of ham.

The generation, application, and impact of pulsed electric fields (PEF) on cell membranes were reported for the first time by the German engineer Heinz Doevenspeck who therefore can be declared intellectual father of the PEF technology. The actual contribution describes Doevenspeck’s own research projects between 1958 and 1985 (as far as they are known to the authors) and their common work from then on until Doevenspeck’s death in 1993.

Heinz Helmut Doevenspeck was born on the 15th of August 1917 in Bremen, Germany, where he died on the first of July 1993 (Fig. 1). He served his apprenticeship as a locksmith at AG Weser in Bremen, and during the years of World War II he trained as machine constructor and finished his education as a mechanical engineer. Due to missing documents it is not clear from which institution he definitely got his engineering degree. During World War II he was injured and from then on working for the Organisation Todt in different countries which were occupied by the German Wehrmacht in these years. Looking for quick and pragmatic solutions for technical problems was his job. This ability, he always was admired for, resulted in the first patent applications in the 1940s. During the turmoil of the postwar era, Doevenspeck had several jobs also working for the British military government in the City of Bremen. His smartness and his aspiration for independence resulted early after the war in his self-employment as a consulting engineer.

The present documents do not show when and how Doevenspeck exactly got the idea to use pulsed electric fields for different applications. It is not even clear without any doubt that it was his own invention. Only in one of his progress reports from the 1970s he mentioned that he was inspired in 1958 by a publication of Sven Carlsson on the influence of electric current on growth of microorganisms.

Knowing about Sven Carlson's publications he started his own experiments in 1958. In his opinion, Carlson's mistake was to change the physical properties of the treated materials in a way that particularly a targeted electric field strength could not be adjusted during the whole duration of treatment. According to Doevenspeck, defined portions of electric charges determined by the size of a capacitor have to be used to overcome this problem. From this time on he was obsessed by the idea to influence substance systems by pulsed electric fields. Doevenspeck was an autodidact and not a scientifically educated person. He fiddled as an interested nonprofessional with physical, chemical, and – in this case – biological details to understand how the material systems he was working with were constructed and how "his" pulses could impact these materials.

He converted the basement of his one-family house in Minden, Germany, to a professional laboratory, containing pulse generators, experimental equipment made of glass, microscopes, centrifuges, filters etc. In spite of his limited financial and scientific possibilities and his very empirical approach he soon came to astonishing conclusions which he described in 1960 in his first patent application (Doevenspeck 1960) on a "process and device for gaining different phases from dispersed systems."

In detail he identified that PEF shows the following advantages compared to existing technologies: extensive suppression of electrolysis, wide prevention of temperature increase, high profitability by low energy consumption, mild treatment of raw materials and preservation of biological activity, and killing of pathogenic germs.

Doevenspeck postulated already in this patent application that surface charges of inorganic and organic substances can be influenced by PEF. Thus unwanted ingredients in wastewater can be flocculated and separated and oil/water emulsions can be divided into their components. Doevenspeck was living near to the coast, he was an enthusiastic sailor and made contact to fish processing companies in his region. There in the early 1960s he did several trials and found out that wastewater ("stickwater") could get rid of its suspended proteins by means of electroflocculation during PEF treatment. More important however were his observations concerning cell cracking. During his experiments he noted that one could get cell contents like oils or fats from animal raw materials. He described in 1960 that when applying PEF muscle fascicles contracted and cell containing liquids were set free. The same happened to oil containing deposit cells of fish.

In cooperation with the German company Baumgarten Fischindustrie in Bremerhaven, in the early 1960s Doevenspeck produced fishmeal and fish oil from poor stinking herring offal by cracking the cells with pulsed electric fields before separating solids and liquids by using a screw press. The original correspondence between Doevenspeck and his partners shows that the experts on site especially noticed that contrary to expectations the whole process was very low odor.

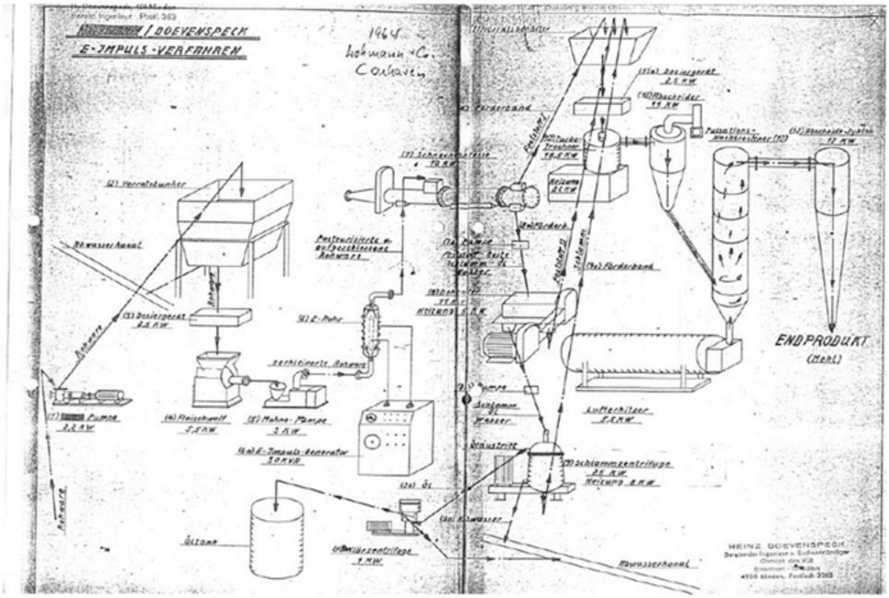

Fig. 2 Production line for fishmeal and oil from herring (Original diagram from Doevenspeck 1964)

Also together with the German fishmeal producing factory Lohmann & Co. in Cuxhaven, he experimented on fish processing. Figure 2 displays an original flow diagram from 1964 drawn by Doevenspeck personally. One can see a typical fishmeal production line as it is still being used nowadays. The only difference is the PEF system instead of a conventional cooking system.

Original reports and the correspondence between Lohmann and a participating feed producing company show that Doevenspeck's fishmeal was of high quality and had a long shelf life. The vitamin A content did not change essentially during 6 months storage. Additionally there was almost no oxidation of the residual oil in the final fish meal. Feeding experiments with laying hens showed that "Doevenspeck" fishmeal produced from poor, low protein containing raw materials was much better than conventional fish meal from Peru in respect to feed conversion rate. Moreover independent experts certified that the eggs produced by the abovementioned laying hens tasted distinctively more palatable than the eggs from hens fed with conventional meal.

Doevenspeck realized that the impact of electric pulses on biological matter strongly correlates to the electric field strengths being applied. During experiments with *E. coli* bacteria in his own lab in 1962/63, he discovered that cultures being treated with field strengths below 3 kV/cm seemed to increase their growth rates whereas those being treated with field strengths above this value showed reduced growth velocities. And very high field strengths obviously killed microorganisms. Motivated by these observations he extracted microorganism containing corn mash from a technical scale fermenter and applied electric pulses with a field strength of about 2.4 kV/cm. As a result he could measure a distinct acceleration of the fermentation process. In cooperation with the sewage plant operators of the German city of Nienburg, Doevenspeck achieved a 20% increase of methane yield by using PEF. In 1967 he applied a patent together with a well-known big German brewery in Dortmund. Subject of their common invention was a low temperature (25 °C) conservation method for beer with the positive side effect of almost no changes of color and taste during the subsequent storage phase. At the end of the 1970s and the beginning of the 1980s, Doevenspeck was in contact with the Institute of Biophysics of the University of Hannover (Glubrecht, Niemann) and the Institute of Microbiology of the Hannover Medical School (Hülsheger, Potel) where his working hypothesis on germ killing was confirmed and scientifically examined for the first time.

Until 1983, Doevenspeck conducted many trials with interested companies, communities, and research institutes. He took part in symposia and was able to inspire people being in touch with him. But in the end with respect to a remarkable financial success of his new process he failed after 20 years of intense work.

Doevenspeck's chance came up in the early 1980s due to the ban of perchlorethylene as a solvent for the extraction of oils and fats from animal raw materials in rendering plants. Krupp Industrietechnik GmbH, a German company for plant construction and engineering, located in Hamburg, was very successful in selling this type of extraction plants for many years. In this critical phase, Ernst Wilhelm Münch (Fig. 3) the area manager of the abovementioned extraction plants at Krupp company became acquainted with Doevenspeck.

Münch realized the possibilities of Doevenspeck's new technology which could be an alternative for the old (banned) solvent extraction process. In 1985, he engaged

Fig. 3 Münch (CEO, *left*), Sitzmann (Head of R&D, *right*, standing), and diploma student Stempel

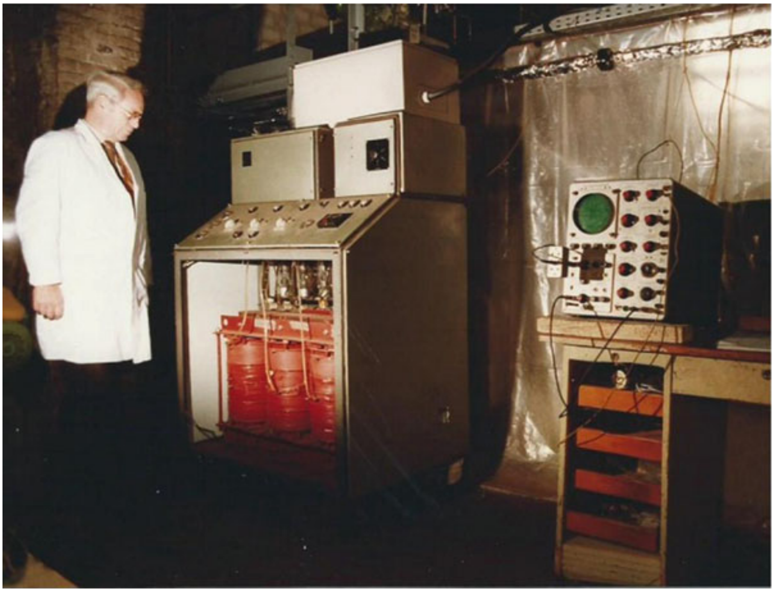

Fig. 4 Doevenspeck and his pulse generator (Krupp pilot plant 1985)

him as a consultant. In the R&D center of Krupp company in Hamburg, a PEF pilot plant was erected and taken into operation in 1985.

The main component of this plant was Doevenspeck's 80 kW pulse generator (Fig. 4). Frequencies in a range from 1 to 16.7 Hz and capacities of 5, 10, 15, 20, 25, 30, and 35 μF could be adjusted; the maximal charging voltage U_0 was 8 kV. The generator could only be used for "trial and error" experiments. It was nearly impossible to set repeatable electric parameters and thus to really reveal the interaction between cause (for example, the field strength) and impact (for instance, the cell cracking or the killing of germs) of the process. Krupp was mainly interested in gentle cell cracking of animal and herbal materials. During 1986 and 1990, Sitzmann's task as Head of R&D department was to investigate different products with respect to their processability, to research the mechanism of action of PEF and to make the results available to a scientific public (Sitzmann and Münch 1989). In order to protect Doevenspeck's ideas several patents were applied and Krupp company registered the trademarks ELCRACK© and ELSTERIL©.

Sitzmann visualized for the first time Doevenspeck's ideas regarding low temperature cell cracking of fish material. An irreversible damage was obviously the consequence of adequate high field strengths. Surprisingly it also could be found that the fish proteins were coagulated by PEF at low temperatures of about 30 °C. In Krupp's continuously operating pilot plant the material throughput could be varied between 100 and about 250 kg/h. The distances of the discharge electrodes were 50 and 70 mm, respectively. There have been several tests regarding different electrode geometries and raw materials being carried out in the pilot facility. The positive results in the technical facility in the 1980s encouraged Krupp company to finally present their new technology to the international public. This was firstly done at the ACHEMA fair in Frankfurt in 1985. During 1986 and 1994 as Head of R&D at Krupp company and later on between 1994 and 1996 as founder and CEO of the consulting company NaFuTec Sitzmann's main tasks were to investigate different products with respect to their processability, to research the mechanism of action of PEF, and to make the results available to a scientific public.

Leading figures in food engineering like Barbosa-Canovas, Washington State University, and Knorr, Technical University of Berlin, were very interested in Sitzmann's work and the lessons learned up to then on PEF technology. They visited Krupp's pilot plant in the late 1980s and first common investigations were realized. In the following years it was primarily their merit to initiate research projects and to disseminate the knowledge on this new emerging technology worldwide. Based on the work which has been done at Krupp company, PEF technology was made available not only to a scientific but also to an industrial public. Main results of Krupp's R&D work were mathematical models for describing the discharge curves and the killing effects of germs depending on electrical parameters of the materials to be treated, a better understanding of the operating principle of pulsed electric fields, and a way to quantify cell cracking effects by using the impedance of the materials as a measure.

During the years 1988–1990, Krupp initiated together with the Technical University of Hamburg-Harburg, Germany, an EU project on continuous sterilization of juices and milk in a pilot plant. Within Grahl's doctoral thesis (Grahl 1994) the influence of PEF on food components like vitamins, enzymes and flavor carriers was investigated for the first time. Two industrial scale plants (a 10 t/h plant for producing rendered fats from slaughterhouse by-products in Duisburg, Germany, and a 22 t/h plant in Egersund, Norway, for low temperature production of high grade fishmeal and fish oil from herring) were engineered and commissioned in these years.

Two more plants for processing slaughterhouse offal and bones were designed but never realized. There were many difficulties during the start-up phase which could not be solved within appropriate time. Forced by short-term economical success the clients decided to stop the commissioning. The plants had to be dismantled and replaced by conventional technology.

These – preliminary – failures, however, did neither discourage Doevenspeck who continued his work (extraction of wool fat from sheep wool and cleaning the wastewater with PEF) in New Zealand until he died in 1993 nor Sitzmann who as a consultant founded NaFuTec GmbH and who gave a first historic overview on pulsed electric fields in 1995 (Sitzmann 1995). In cooperation with TU Berlin where Sitzmann's generator was placed he investigated until 1996 several possible applications. For example, cell cracking of fruits in order to increase the yield of juices or – in cooperation with a big German starch producing company – the cracking of potato cells aiming at low residual water contents after the consecutive pressing step and at sterilizing the wastewater.

Ukraine and Moldova

Two Ukrainian food engineering scientists Zagorul'ko and Flaumenbaum started their activities on implementation of electricity in the food industry in 1949. Anatolii Zagorul'ko (Fig. 5) graduated from the chemical department of Kharkiv University in 1946 continued his activity in different sugar factories and laboratories in Ukraine.

He took a great interest on application of electricity to intensify the extraction of sugar from sugar beet. Later on he wrote that his work was stimulated by experiments on the action of DC on sugar beet, which were performed by famous sugar technologist Jaroslav Dedek (1890–1962) in 1947 (Zagorul'ko 1958). In Dedek's experiments, the voltage of 100 V was applied to the tissue cylinder with diameter of 30 mm and height of 25 mm. The initial electric current was rather low (≈10 mA). However, in the course of electric treatment the value of I increased and above 100 mA the noticeable increase of temperature was also observed. It was speculated that this observation can reflect the damage (killing) of sugar beet cells and process was named by Dedek as "electrocution."

The different constructions of continuous electrotreatment apparatuses (so-called electroplasmolyzators) were tested and patented by Zagorul'ko with coworkers starting from 1949 (see, e.g., Mil'kov and Zagorul'ko 1949). Figure 6 shows the principal scheme of electrotreatment apparatus of belt type. Electricity was applied between two rotating metallic belts (electrodes) 1 and 2. It was stated that proposed

Fig. 5 Anatolii Ya. Zagorul'ko (1920–1983)

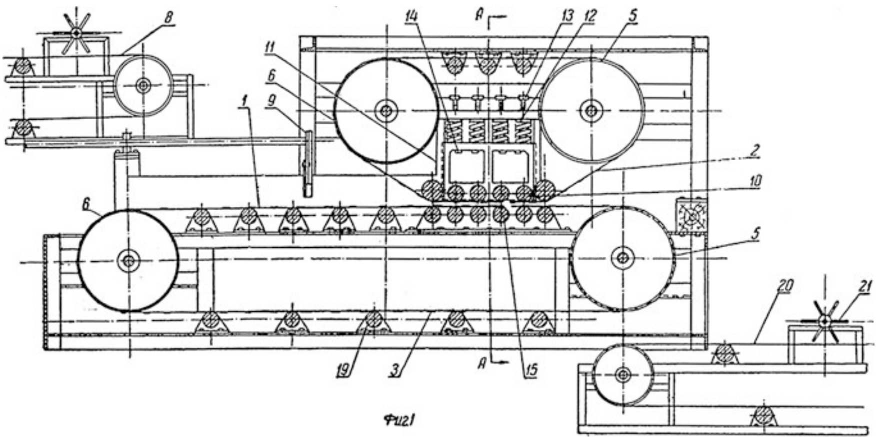

Fig. 6 Continuous electrotreatment apparatus of belt type. Here the main components: *1* and *2* are the rotating metallic belts (electrodes), *3* are contact riffles, *5* and *6* are drums, and *10* are the pressing rollers (Zagorul'ko 1958)

methods are nonthermal and increase of the temperature during treatment was about 0.5 °C during the treatment for a time of 0.001 s.

In 1949–1953, Zagorul'ko performed the pioneering laboratory studies on impact of AC and DC currents on the structure of sugar beet tissue. He observed the breaking down of cell membranes by electric current and called this phenomenon as electroplasmolysis. The electric-assisted processing of sugar beets allowed obtaining the colorless diffusion juice at "cold" (room) temperatures and it was a revolutionary discovery at that time. The estimated energy consumptions were extremely low, of order of 4–5 kJ/kg. Analytical estimations of the electrical potential on the plasmatic shells u_m were done and it was shown that $u_m \approx 0.953u$, i.e., the external potential applied to sugar beet u was localized mainly on low conducting of plasmatic shells (membranes). Their electrical conductivity was estimated as 10^{-6} S/cm. The breaking down of the cell membranes by electric current was explained by selective overheating the plasmatic shells without significant heating of surrounding media. That is why this type of plasmolysis was defined by him as a selective.

In 1953–1957, Zagorul'ko proposed to use the PEF treatment for the purpose of electroplasmolysis. The scheme of his pulse generator is presented in Fig. 7. The generator produced exponential pulses with duration of 20 μs and allowed PEF treatment at electric field strength of $E = 20$ kV/cm. He had speculated about possible mechanism responsible for pulsed electroplasmolysis. He argued that the high electric field pulses with short duration (of order of microsecond) can provoke exceptional electroosmotic jerking resulting in damage of plasmatic shells. The principal difference between thermoplasmolysis and electroplasmolysis was noted. The thermal plasmolysis causes disruption of cell walls and is followed by diffusion

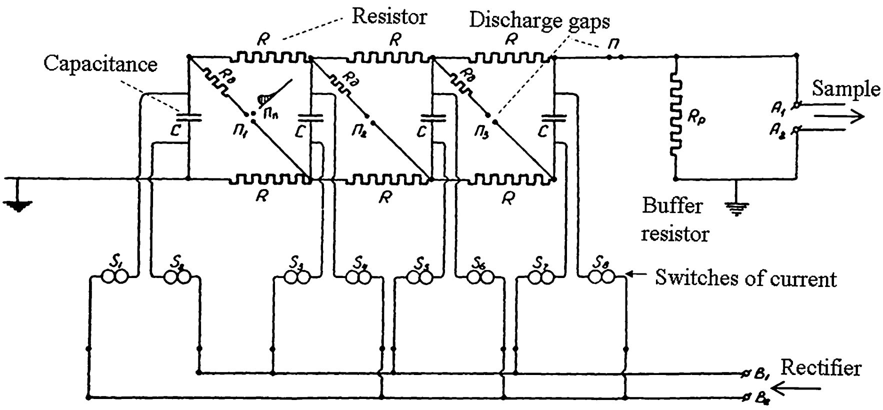

Fig. 7 Electronic scheme of pulse generator constructed by Zagorul'ko in 1955–1957 (Zagorul'ko 1958)

of pectin substances in a juice, while the electroplasmolysis only pierces plasmatic shells with insignificant damage of cell walls.

At the same period in the Kiev branch of all-Union Central Research Institute of the Sugar Industry, the investigations of the effects of electroplasmolysis on extraction of sugar by pressing and by preliminary pressing followed by diffusion extraction had been performed (Kartashev and Koval' 1956). The electric treatment was done at field gradient of 2 kV/cm. The separation of slices and juice after pressing was realized using a centrifuge.

Figure 8 presents the obtained dependence of juice yield versus the temperature of sugar beet slices for pressing of plasmolyzed (1) and untreated (2) slices. For the cold slices the preliminary electroplasmolysis increased the juice yield by two to three times. It was also concluded that current flow through sugar beet causes not only electroplasmolysis but also electroosmotic processes.

In 1958, Zagorul'ko defended in Kiev his PhD thesis "Obtaining of diffusion juice with the help of electroplasmolysis" (Zagorul'ko 1958). In this thesis he had analyzed the different effects of electricity on sugar beet tissue, PEF-assisted processing of sugar beet, and he had developed the concept of cold and selective electroplasmolysis for the first time. To avoid the ohmic heating he used the interrupting mode of PEF treatment. To characterize the degree of tissue damage he introduced the disintegration index (electroplasmolysis index) based on the specific resistivity ρ measurements:

$$Z = (\rho_o - \rho)(\rho_o - \rho_\infty) \quad (1)$$

Here, index "o" and "∞" refer to the resistivity of fresh and completely plasmolyzed tissues, respectively.

Moreover, he had performed investigation of Z versus the time of treatment t dependences at different values of electric field strength E. He noted also that

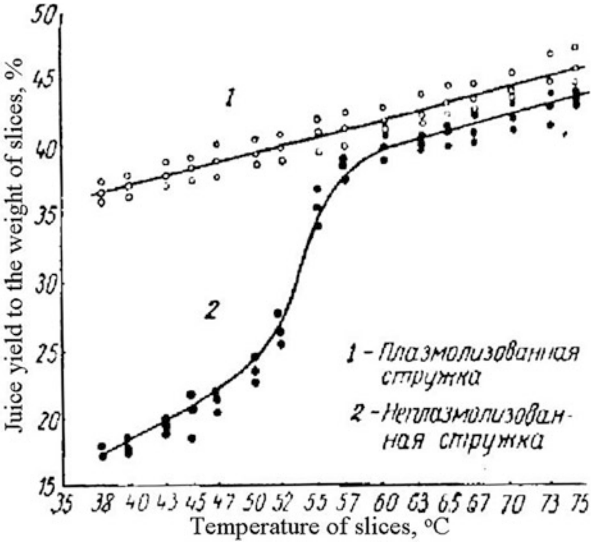

Fig. 8 Juice yield versus the temperature of sugar beet slices for pressing of plasmolyzed (*1*) and untreated (*2*) slices (Kartashev and Koval' 1956)

better efficiency of electroplasmolysis can be obtained by treatment of pressed samples, which was explained by improvement of contacts between sugar beet and electrodes.

The other Ukrainian food engineer Boris Flaumenbaum (Fig. 9) patented his electric machine with rotating electrodes in 1949 (Flaumenbaum and Yablochnik 1949). He graduated from the Odessa Food Institute in 1931 and his doctor science habilitat thesis "Problems of intensification of technological processes of preservation of food products" included materials on electroplasmolysis fruits and vegetables (Flaumenbaum 1969). His main scientific activity was related with Odessa National Academy of Food Technologies, Ukraine.

In 1949–1950, Flaumenbaum in cooperation with engineer Yablochnik constructed the industrial scale setup for AC electroplasmolysis (Flaumenbaum 1953). The raw material was delivered by elevator through a receiving hopper on rotating electrodes and was forced through the gap between them into the bottom hopper. From the bottom hopper the treated raw material was forwarded directly into the press basket or into an intermediate tank. This setup was manufactured, installed, and tested at Tiraspol fruit factory, Chisinau winery, and some other Moldavian wineries. During the 1950s, the various types of electroplasmolyzators with rotating blades and linear electrodes were proposed (see, monographs for a review (Kogan 1968; Rogov and Gorbatov 1974)).

On the other hand, Flaumenbaum performed the fundamental analysis of electrically assisted pressing extraction of juice, issued many interesting works on electrostability of different fruits and berries, and gave theoretical foundations of electroplasmolysis (Flaumenbaum 1969). The inverse quadratic relation between the time of electroplasmolysis τ and electric field strength E was empirically established:

Fig. 9 Boris Flaumenbaum (1910–1996)

$$\tau = K/E^2, \tag{2}$$

where K is parameter of electrostability.

It was demonstrated that the value of K depends upon the current (DC or AC), frequency, type of material, and degree of tissue grinding. The apples demonstrated the highest electrostability and the strawberry the lowest ones. DC treatment caused more efficient electrical damage than AC treatment (Flaumenbaum 1969).

The intensive activity in food application of electroplasmolysis was continued in the 1960s–1970s decades in Moldova under the guidance of Boris Lazarenko from the Institute of Applied Physics (Chisinau) (Fig. 10). In this period the different methods of electroplasmolysis were tested and patented. Impact of electric fields on microorganisms and sterilization of foods was also investigated in details. The pilot scale electroplasmolysis experiments were started in Moldova in 1964 (Lazarenko et al. 1977). Commonly, the AC and DC electroplasmolyzators with different electric gradients were used. The electroplasmolyzator with productivity of 3000 kg/h was tested at Bendery canning factory in 1966 (Kogan 1968). The noticeable increase in juice yield was observed, for example, electrical treatment of apples allowed increasing of juice yield up to ≈11–20%. The electroplasmolyzator of tubular type was tested for the treatment of whole apples at Bardar experimental winery (Moldova) in 1974. The treatment was applied to the mixture of whole apple with water (1:2–5) at the electric field strength of E = 150–500 V/cm, time of treatment t = 1–50 ms, and energy consumption of 3.6–18 kJ/kg. Electrical treatments allowed increasing the juice yield by 1.2–1.3 times. The industrial scale experiments were also performed at Odessa juice plant using carrots, plums, apricots, grapes, and

Fig. 10 Boris Lazarenko (1910–1979)

apples (Lazarenko et al. 1977). The low gradient type electroplasmolyzator with electric field strength in the interval 10–125 V/cm was tested and such type of electrical treatment was called as electrothermal plasmolysis. The efficiency of PEF-assisted electroplasmolysis was also tested on different vegetable raw materials. The constructed PEF generator produced monopolar pulsed with amplitude 10–40 kV and energy of pulse of 100 J. Experiments on PEF application during the pressing were done. Application of PEF increased juice yield by 10–15%, and extracted juice after PEF treatment was more transparent. The more detailed information on the research and industrial developments for the period 1960s–1970s in Moldova can be found in the monograph of Lazarenko with coworkers (Lazarenko et al. 1977).

The interest to the problem was renewed in Ukraine in 1980s and mid-1990s. The aqueous extraction at 60 °C assisted by DC treatment of sugar beat slices was investigated (Bazhal et al. 1984). The data had showed that application of electrical treatment results in noticeable improvement of sugar yield and juice purity. Extraction of juice from sugar beet slices assisted by DC electric field ($E = 0$–20 V/cm) at constant temperature ($T = 50$ °C) during the time $t = 0$–60 min was studied (Kupchik et al. 1982). The data evidenced the positive effect of electric field on the intensification of the extraction of sugar and improvement of the quality of extracted juice. Impacts of AC and DC electric fields ($E = 30$–100 V/cm) on electroplasmolysis of sugar beet slices were investigated. The electrically assisted processes allowed obtaining the juice with a high purity (Shulika 1988). Empirical relations between the degree of sugar beet tissue denaturation, electric field strength, and treatment time were proposed. It was stated that external electric field can cause plasmolysis of cell cytoplasm and polarization of cell tissue and colloidal substances and their coagulation and retention inside the cells and intercellular space owing to the dipole-dipole interactions. The obtained data evidenced that AC electric fields allowed efficient electroplasmolysis of tissue whereas DC led to electrocoagulation of colloidal substances. The combined method of electrical treatment was proposed that includes the sequential treatments by AC and DC (Shulika 1988). Application of combined AC/DC treatment allowed noticeable increasing (by 1.5–2 times) of the diffusion coefficient of sugar and enhancement of the removing of coloring substances from extract. The potential possibility of low temperature extraction using the combined AC/DC method was also predicted. The pilot scale setup based on the proposed combined AC/DC method was constructed and tested on Yagotin sugar factory (Ukraine) during the 1986–1987 seasons. The impact of thermal ($T = 60$–$80\ ^{\circ}$C) and electrical (DC and AC, $E = 115$ V/cm, $t = 1$–10 s) plasmolysis on the elastic characteristics of sugar beet tissue in dependence of the processing method, temperature, residence time, and particle size was investigated (Dankevich 1995). It was demonstrated that thermal treatment resulted in more prominent softening of tissue as compared with electrical treatment. For example, the coefficient of compressibility after thermal treatment was in average 30% higher compared with that obtained after electrical treatment. It reflected the different mechanisms of thermal and electrical treatment. It was speculated that thermal treatment can affect the structure of cell walls and membranes whereas electrical treatment can selectively damage the membrane without important influence on the cell walls. The mechanisms of electric field assisted intensification of sucrose mass transfer in sugar beet were discussed, and diffusion coefficients of sucrose in dependence of the parameters of the electric field were determined (Matvienko 1996). It was demonstrated that electrical treatment facilitates the transition of 3–4% water from the bound state into the bulk state.

In the period 1980s and mid-1990s the various types of special purpose electroplasmolyzators were also developed by members of the Moldavian group (Bologa, Botoshan, Grishko, Koval', Papchenko, Scheglov, et al.) (for a review see Bologa (2004)). The noticeable acceleration of drying of apple pomace after AC treatment at $E = 100$ V/cm during the time of 30 s was observed. The combination of electroplasmolysis with various mechanical actions (grinding, pressing, mixing, etc.) allowed more effective for processing of pulps. Moreover, it was demonstrated that preliminary electroplasmolysis of fish was useful for the decreasing of oil and moisture content in the product, preserving the yield of vitamin A and intensification of drying.

The described advances of Ukrainian and Moldavian food engineers in the period between 1949 and mid-1990s were scientifically proven and were very important for the development of the field. However, due to a number of technical difficulties (electrical arcing between electrodes, inhomogeneous treatment, limitations of delivered power by electrical generators), and absence of sufficient financial support, successful testing of AC/DC electrical machines and PEF generators in the food industry never led to their industrial implementation.

Table 1 Producers of commercial scale Pulsed Electric Fields generators

Company, country, and Web site	Short description of equipments and technologies
Arc Aroma Pure AB, Sweden: arcaromapure.se	Closed environmental PEF treatment (CEPT) for cold pasteurization, juice extraction, extraction of olive oil, ballast water treatment, and purification of water. CEPT® pretreatment unit (10,000 l/h) for biogas production is available for purchase. This pretreatment improves the methane production by 15–50%. OptiFreeze AB approach based on the application of vacuum technology along with PEF treatment was used to maintain the food flavor, texture, and quality throughout the freezing and thawing process
Basis EP (electronique de puissance), France: basis-ep.com	PEF generators (with pulse voltage 5–18 kV, pulse current up to 1600A and power up to 250 kW) for different applications in sugar and other industries (sugar beet cossettes, apple mash, juices) High voltage electrical discharge (HVED) generators (50–100 kV, 100 kA, 10 Hz) for the treatment of different types of biomass suspensions (microalgae, yeast, seeds, etc.)
CoolWave Processing, Netherlands: purepulse.eu	The different PurePulse systems for PEF-assisted processing of fluid foods (fresh juices, sauces, or milk) are produced. A nonthermal preservation technology PurePulse systems allow extending the shelf life of fresh juices (just "freshly squeezed") with preserving their entire flavor, colors, aroma, vitamins, and other goodness. PurePulse is available for large-scale (600–2.000 l/h) and small-scale (350 l/h) production
DIL/ELEA, Germany: elea-technology.com	A large-scale Elea PEF machineries and generators suitable for treatment of a wide range of food types (e.g., microalgae, nutrient media, enzyme solutions, foods, dairy products, protein concentrates, seafood and fish marinades, sauces and dressings)
Diversified Technologies (DTI), Inc., USA: divtecs.com	The different commercial PEF systems operating at 30–35 kV with co-field flow treatment chambers capable of up to 200 l/h throughput are developed. PEF treatment permits extract the algal oil (28–44%) into a water solution without the use of other solvents or preliminary drying. PEF-assisted processing can reduce the overall biomass drying cost by nearly 50%
Energy Pulse Systems, Portugal: energypulsesystems.pt	High performance pulse generators, based on semiconductor transformerless Marx generator topologies EPULSUS®-PM1-10 and EPULSUS®-PM1-25 systems deliver up 10 kV/240 A and 25 kV/250 A square wave bipolar pulses, with 500 ns rise time, flexible frequency, and variation of pulse width, respectively. The PEF equipment can be used for bacterial inactivation, juice, olive and grapes processing, enzyme inactivation, and assistance of drying of foods
KEA–TEC GmbH, Germany: kea-tec.de	Different industrial scale electroporation equipment, including a mobile experimental plant (trailer) with

(*continued*)

Table 1 (continued)

Company, country, and Web site	Short description of equipments and technologies
	dimensions 5.5 m × 2 m × 2.4 m and electrical power 21 kW. BLIZZAR technology is suitable for the electroporation of whole or sliced fruiting bodies with a capacity of up to 20,000 kg/h and for the production of French fries
Pulsemaster, Netherlands: pulsemaster.us	Different PEF systems for the food and beverage industry. The typical average power range of PEF systems is up to 80 kW, the systems for cell disintegration allows processing capacities of 1 to 50 t per hour. The capacity of the systems for microbial inactivation of liquids vary from 50 to 5000 l per hour
Scandinova Systems AB, Sweden: scandinovasystems.com	Different PEF generators (with pulse voltage of 16–600 kV, pulse duration up to 3 ms and pulse current 0.1–10 kA) suitable for PEF treatment of different foods (e.g., potatoes, olive oil, and fruit juices)
Steri-Beam Systems GmbH, Germany: steribeam.com	Small-scale generators suitable for disinfection of fluid products (juices, milk, etc.) as well as for sanitation of jell, jams, and extraction of nutrients/colors from plant cells. The generators produce bipolar and monopolar pulses with operational pulse voltage u = 2–20 kV, pulse durations t_i = 2.5–20 μsec, maximum electric current Im = 150A, pulse repetition rate f = 1–100 Hz, and maximum pulse power W = 2 kW

Conclusions

Starting from the mid-1990s there is a continuously growing interest for the applications of PEF technology in food processing. The numerous reviews and the monographic books on the topic were already published (Raso and Heinz 2006; Vorobiev and Lebovka 2008). The efforts of several dozed research groups worldwide were aimed to facilitate the processes of separation, extraction, pressing, freezing, diffusion, drying, and osmotic treatment of food products (Barba et al. 2015). The extensive research studies were carried out regarding microbial inactivation of liquid foods. Nowadays, the PEF-assisted processing became very promising in food industry. Numerous laboratory experiments have been established the optimal PEF protocols minimizing energy consumption and providing high product quality for different liquid and solid foods, fruit and vegetable tissues, meat, fish, and mushrooms. Many interesting receipts for selective extractions of bioactive and value added substances by PEF from food wastes, debris, and residues were already proposed.

During the long history of AC and DC and PEF studies in food processing many serious problems and obstacles were revealed. Different exciting ideas and pilot scale PEF apparatuses were not realized or industrialized owing due to the technical difficulties, insufficiency of PEF generators reliability, the absence of necessary financial support, and the lack of knowledge about basic mechanisms responsible for the impact of PEF. The full potential of PEF technology can be realized just by common efforts of scientists, manufacturers of high power pulse generators, and end uses adapting upstream and downstream processes for optimal PEF processing.

In recent years many commercial scale PEF generators with wide range possibilities and applications were manufactured. The short description of modern equipments and technologies provided by different companies is presented in Table 1.

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Cross-References

- ► Basic Concepts of High-Voltage Pulse Generation
- ► Industrial Pulsed Electric Field Systems
- ► Pulsed Electric Field Treatment for Fruit and Vegetable Processing
- ► Pulsed Electric Fields as Pretreatment for Subsequent Food Process Operations
- ► Selective Extraction of Molecules from Biomaterials by Pulsed Electric Field Treatment
- ► Techniques to Detect Electroporation in Food Tissues

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