Enhancing Industrial Processes by Pulsed Electric Fields

Michael Kempkes, Ian Roth, Nicholas Reinhardt
Diversified Technologies, Inc.
Bedford, MA, USA

***Abstract*— Pulsed Electric Field (PEF) processing works through the process of electroporation in cells – destroying the cell membranes through the application of short, very high voltage pulses across a liquid. PEF processing can also improve the performance of industrial processes such as the removal of water from sludge, or the extraction of oils, sugars, or starches from plants, because the ruptured cells release their intracellular liquids more easily into their surroundings.**

Over the last decade, the equipment and processes required for PEF treatment have undergone extensive development, and commercial scale PEF systems are now available at very high throughput. These PEF systems and processes have been adopted for both commercial operation and research applications in a range of applications unrelated to non-thermal pasteurization. The largest of these is wastewater treatment, and related anaerobic digester applications. PEF processing is now in use at municipal treatment plants in the US, and additional plants are scheduled for operation. PEF processing has also found applicability to biofuel processes, for dewatering of biomass, and for enhancement of the ability to extract lipids from algae to create biofuels. Other emerging applications, including extraction processes, and pre-treatment for mechanical processing are also being introduced around the world.

Keywords: PEF, extraction, algae, wastewater, non-thermal

I. INTRODUCTION

Pulsed Electric Field processing was developed over 20 years ago as a non-thermal alternative to pasteurization. In PEF processing, a liquid food or other pumpable product, is passed through a small treatment chamber, where it is subjected to a short (10 nanosecond – 20 microsecond) pulse of very high voltage. The high voltage field created across the liquid (approximately 20-50 kV/cm) disrupts the cell membranes of bacteria, yeasts, and molds. The pulses are so short and frequent that all of the liquid in a pipe can be treated as it flows through the treatment chamber. By using multiple treatment chambers to apply pulses to a stream of fluid, kill ratios of 5-9 log, similar to those resulting from pasteurization, have been achieved. Multiple experiments have demonstrated that the shelf life of PEF processed food is comparable to that yielded by pasteurization, with no adverse impact on the taste or nutritional value of the food.

Extensive research on the applications and limitations of PEF processing to a wide range of foods and pathogens has been conducted by researchers in academia as well as industry. A large set of experimental data now exists to guide food processing applications. Despite this history, however, commercial PEF food processing is only now entering commercial use around the world in a meaningful way.

This same membrane disruption impacts larger cells to open cellular materials to the surrounding environment. These cells require lower fields (such as 1 – 10 kV/cm) for electroporation. The utility of this process is now being explored in a number of potential industrial applications, including wastewater processing, biofuels, and extraction processes. All share the same objective of accessing the intracellular material in either plants or micro-organisms, as an initial step to the desired process results. In wastewater processing, for example, PEF can be applied prior to anaerobic digestion, resulting in higher methane production and lower residual solids at the end of the wastewater treatment process.

The following sections will describe PEF equipment being delivered by Diversified Technologies, Inc. and results of several projects focused on non-pasteurization applications.

II. HIGH VOLTAGE SOLID-STATE SYSTEMS

Solid-state, high voltage systems provide the reliability and the process consistency required for commercial PEF systems, thereby enabling the transition of PEF processing from the laboratory into commercial applications. DTI has delivered PEF systems capable of handling low volume, laboratory scale flow rates to large, production scale installations (Figure 1).

There are three basic elements to the PEF system. First, a DC power supply transitions the AC power available from the utility into high voltage, DC power. Second, a pulse modulator transforms this average power into short, consistent, high peak power pulses at high frequency. In PEF systems, the liquid being processed is the load, and is therefore, an integral part of the circuit. Conductivity can vary by over an order of magnitude across different foods, and even within a single food type, such as orange juice, which can vary in conductivity by 50 – 100%. This variability eliminates impedance matched modulator designs, such as pulse transformers from consideration as part of a PEF system. The optimal approach is to use a 'hard switch', capable of switching the full voltage. This switch must be low impedance to provide consistent output voltage over a range of peak currents. Solid-state switches are ideally suited to both of these requirements.

The third major element of a PEF system is the treatment chamber (Fig. 2) where the high voltage pulses are applied to the liquid. While there are many chamber designs, DTI's experience is primarily with the co-field flow chamber design, developed and patented by OSU, and licensed by DTI for manufacture and sale as part of our PEF systems. This design has been shown to provide an optimal balance between the flow and field requirements. One attribute of this design, however, is that to maintain consistent field strengths, the gap over which the field is applied must be proportional to the pipe diameter. Therefore, larger pipe diameters, which support higher flow rates, require proportionally higher pulse voltages to maintain the same field strength.

III. KEY PEF PROCESS PARAMETERS

PEF system design must be based upon an effective PEF treatment protocol. A typical treatment protocol for food disinfection might require application of a 35 kV/cm field for a ~50 µs to achieve a given level of bacterial reduction – typically described as a 3 – 5 log reduction, meaning that only one out of 1,000 to 100,000 of the original bacteria survive the PEF treatment. Wastewater processing, on the other hand, may require only half of this field and treatment time to lyse vegetative cells. Figure 3 shows a typical treatment pulse.

The liquid's conductivity and desired flow rate form the basis for all other design tradeoffs. Conductivity determines the impedance of the food in the treatment chamber, as well as the energy required to treat each liter of fluid. The electric field is set by the treatment protocol, so the energy required to deliver this field to a liter of food is a direct function of the fluid conductivity.

Flow rate determines several major PEF system characteristics. The diameter of the treatment chamber must be sized to pass the desired flow at reasonable pressure. The presence of particulates and 'chunks' in the flow can also impact the sizing of the chamber, since a larger diameter pipe is required to prevent clogging. Flow rate also determines the average power required for a given fluid and protocol. The conductivity and field strength required determine the energy per liter required – multiplying this by the flow rate gives energy/time, which is power. The power required increases linearly with flow rate for a given protocol.

Figure 1. Commercial PEF System for wastewater treatment. This system is rated at 35 kV, 350 A peak pulses, and delivers 150 kW of average power. The modulator is on the left, with the treatment chamber in the 'sidecar' box shown in front. The rack on the right contains the controls and data logging system.

Figure 2. Commercial co-field flow treatment chamber, shown inside the 'sidecar', with four treatment cells. Pipe diameter is approximately 1.5 cm.

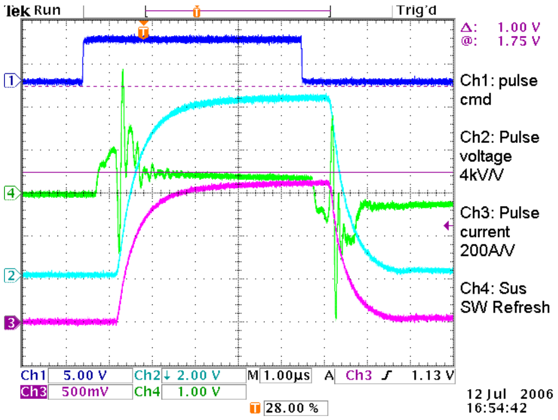

Figure 3. Sample pulse from the PEF system shown in Figure 1, at 34 kV, 320 A, 4 µs flattop.

IV. ALGAE TREATMENT FOR OIL EXTRACTION

Algal oil represents a potentially plentiful, renewable source of fuel. It has not been commercially adopted, because of the high cost of growing and converting algae into a usable form, at large scale, compared to petroleum. There are many steps required to produce fuel from algae, and the most expensive is growing the algae itself; this is a current issue of research, being pursued by many organizations. The next largest cost is extracting oil from the algae.

In our preliminary research, DTI successfully lysed multiple algal species through PEF, in collaboration with the Laboratory for Algae Research and Biology (LARB) at Arizona State University (ASU).

Our first success was Isochrysis algae. These cells were visibly damaged (Fig. 4), and we analytically confirmed that oil had been released from within the cells. In testing other species, however, we found that the membrane rupturing cannot typically be seen by optical microscopy. Instead, we developed a fast, semi-quantitative test of oil release after PEF treatment; the algae are centrifuged, and the color of the remaining supernatant fluid is measured (Fig. 5). The darker the supernatant fluid, the more intracellular pigment has been released, and therefore, the greater the amount of oil released as well. This test can be done in only 20 minutes, which is much faster than the 17 hours or more needed for quantitative oil extraction.

In subsequent tests, we found that PEF treatment ruptured two species of Chlorella, releasing 28% and 44% of the total lipid content of the algae into a water solution – without the use of drying or any other solvent. The fraction of total lipid released in these experiments represents a much larger fraction of the intracellular oil available, since the total lipid content also includes the lipids from the cell walls and organelle membranes that cannot be released without additional processing. The next steps are to determine the pulse conditions that maximize the oil extracted while using minimum energy input.

V. DRYING OF BIOFUEL FEEDSTOCKS

Biomass for the production of biofuels is typically harvested in a short timeframe, but must be processed in biorefineries operating year-round. In order to spread the processing load over the entire year, the biomass must be dried before storage, to prevent rotting. Propane dryers have traditionally been used to remove water from biomass feedstock. This can be an expensive, energy-intensive process.

In a recent effort for the U.S. Department of Energy, DTI investigated the impact of PEF processing on reducing this drying cost, by electroporation of the biomass cell membranes and releasing intracellular water. PEF processing, combined with mechanical pressing reduced the amount of liquid in the biomass prior to drying, so the energy required is reduced proportionately. The electroporation of the biomass cells is also expected to make subsequent processing of the biomass into cellulosic ethanol cheaper, since it may eliminate some pre-processing required to open the cells chemically.

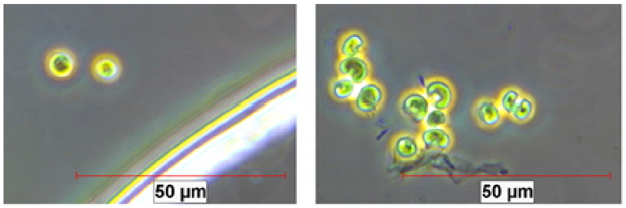

Figure 4. Left: Untreated Isochrysis control cells. These cells are motile and were easier to capture near a bubble (bottom right of photo). Right: PEF-treated Isochrysis cells, all dead (non-motile). Nine of eleven cells are clearly lysed in this view. The treatment released the biofuel compound methyl hexadecanoate.

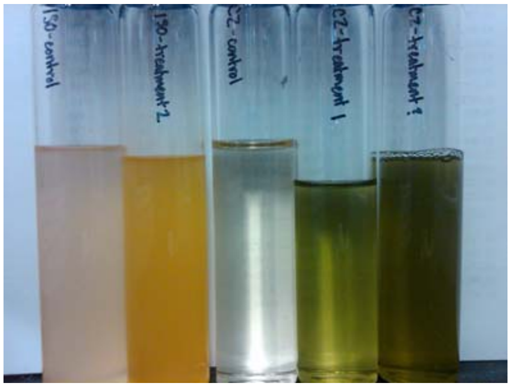

Figure 5. Supernatant liquids from (left two) Isochrysis and (right three) Chlorella zofingiensis (CZ) algae. The dark supernatant from the treated samples shows released pigment.

PEF processing alone significantly changed the appearance and texture of the treated biomass (Figure 6), with moisture clearly evident on the surface of the material, but without a subsequent pressing step, did not appear to have any significant impact on drying time. The combination of pressure and PEF, however, released significant water from the biomass – greatly reducing the energy required for drying. A combination of PEF and pressing removes significant amounts of water in its liquid phase, at very low cost. We have demonstrated that this process can conservatively reduce the overall biomass drying cost by nearly 50%.

Figure 6. PEF treated (left) and untreated (right) wheatgrass samples. Although the raw masses are identical for each sample, the PEF treated sample appears wilted and wetter. More than 30% more liquid was

VI. CONCLUSIONS

Multiple researchers have shown PEF processing to be equivalent to pasteurization in terms of pathogen reduction for a wide range of liquid foods. For foods that are heat sensitive, there are considerable benefits in taste, color, and nutritional value from the non-thermal PEF process. The cost of PEF processing, and the admirably conservative nature of the food industry with regards to food safety, however, have resulted in only minor commercial PEF applications to date.

The application of PEF to other industrial processes builds directly on the research in food processing, and new applications of PEF are emerging at a significant pace. These applications are potentially widespread – wherever it is critical to extract water, chemicals, or oils from within an organic cell. These applications are primarily paced by their economic value alone, in comparison to alternative approaches. The use of solid-state, high voltage pulsed power systems for PEF processing is the key to these commercial applications. Solid-state technology allows PEF systems to scale from small laboratory versions to large-scale processing facilities.