Scaleup of PEF Systems for Food and Waste Streams

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Abstract

Pulsed Electric Field (PEF) processing works through a process of electroporation in cells – destroying the cell membranes through 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 sugars and starches from plants, because the ruptured cells release their intracellular liquids more easily into their surroundings.

Modern PEF systems are based on conventional pulsed power technology, applied in a very different manner. In a conventional pulsed power system, the load determines the required voltage, current, and average power, and the system can be optimized to these specific parameters. PEF systems, in contrast, typically start with a desired field strength, and ranges of flow rate (processing volume), and fluid conductivities. Furthermore, both the flow rate and the conductivity can change significantly during the system operation. Designing a PEF system capable of adapting to these changes represents a significant challenge to the pulsed power system design and construction.

In this paper, DTI will discuss the interrelationships between pulsed power and PEF processing, and present examples of system designs and configurations.

Figure 1. Commercial PEF System for wastewater treatment. This system is rated at 35 kV, 350 A peak pulses. 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.

I. BACKGROUND

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 ns – 20 microsecond) pulse of very high voltage. The high voltage field created across the liquid (approximately 35-50 kV/cm) kills microorganisms by disrupting their cell membranes. 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.

II. HIGH VOLTAGE SOLID-STATE SYSTEMS

In parallel with the development of PEF processing, Diversified Technologies, Inc. (DTI) has developed solid-state high voltage pulsed power systems capable of orders of magnitude higher performance than conventional technologies. Solid-state, high voltage systems provide the reliability and the process consistency required for commercial PEF systems. These benefits enable the transition of PEF processing from the laboratory into commercial food processing 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 (***Figure 2***) transitions the AC power available from the utility into high voltage, DC power. The second major element of the PEF system is the pulse modulator, which transforms this average power into short, high peak power pulses. The requirements for this modulator are, at a general level, similar to the requirements of a radar modulator - high voltage and peak power, with the ability to provide consistent, short pulses at high frequency.

There are two critical differences between PEF and a radar transmitter modulator, however. First, a PEF system can be designed as either bi-polar (+ and – voltage pulses) or mono-polar (all + or all – pulses). R&D systems for PEF typically must provide both bi-polar and mono-polar capabilities. Radar transmitters are all mono-polar. A bi-polar system requires four times the switch capability of a mono-polar system of the same voltage and current. Second, the RF tubes in a radar present a consistent and predictable load impedance to the modulator. The electrical design of a radar modulator can be tailored to this specific impedance. In PEF systems, and especially in those designed for R&D applications, however, this impedance can vary considerably. The liquid being processed is the load, and is therefore an integral part of the circuit. Its conductivity can vary by over an order of magnitude across different foods, and even a single food type, such as orange juice, can vary in conductivity by 50 – 100% due to changes in the raw materials. This variability eliminates impedance matched modulator designs, using pulse transformers and pulse forming networks from consistent performance in 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 the range of peak currents required as the food conductivity varies. Solid-state switches are ideally suited to both of these requirements.

Figure 2. 150 kW DC Power Supply for the PEF system shown in Figure 1.

The third major element of a PEF system is the treatment chamber (***Figure 3***) where the high voltage pulses are applied to the food. The key attribute of the treatment chamber is its ability to minimally impact the fluid flow, while ensuring a consistent electric field is applied to all elements of the flow. 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. This design, therefore, is best utilized at 5 cm pipe diameters and below, which translates to ~ 200 kV pulses (at 40 kV/cm) – the nominal limit for solid-state, hard switched modulators. For larger pipe diameters, alternative modulator or treatment chamber designs will be required.

A. Key PEF Process Parameters

Any discussion of 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 minimum of 50 µs to achieve a given bacterial reduction. Wastewater processing, on the other hand, may require only half of this field and treatment time to lyse vegetative cells. In designing a PEF system, this protocol (or at least its boundaries) must be known for the particular application(s).

The two major factors affecting PEF system design are the liquid conductivity and flow rate. These two factors form the basis for all other design tradeoffs. Conductivity

Figure 3. Commercial co-field flow treatment chamber, shown inside the 'sidecar', with four treatment cells. Pipe diameter is approximately 1.5 cm.

determines the impedance of the food in the treatment chamber, as well as the power (V^2/R) 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.

Adapting to high flow rate is the key to scale-up of PEF systems. A laboratory system typically processes liters per hour (or less), and a pilot plant typically operates at tens to hundreds of liters per hour. Commercial systems, however, must be capable of processing thousands to tens of thousands of liters per hour – representing 2 to 3 orders of magnitude higher throughput than a pilot system. Fortunately, research at Ohio State University and other organizations has demonstrated that the PEF process itself operates independent of flow rate – so long as the field strength and dose are maintained. This allows treatment protocols to be developed in laboratory and pilot scale systems, and readily transitioned to commercial scale PEF operations.

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. To achieve uniform field strength within the treatment chamber, the gap across which the voltage is applied must increase with pipe diameter, and larger gaps require higher voltages to maintain a given field strength. For example, doubling the pipe diameter allows four times the flow at a given pressure, but requires twice the peak voltage to maintain the same field strength.

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. For commercial processing, throughput is directly proportional to the average power for a given field strength – a 100 kW average power system can process five times the volume of product per hour as a 20 kW system, for the same protocol.

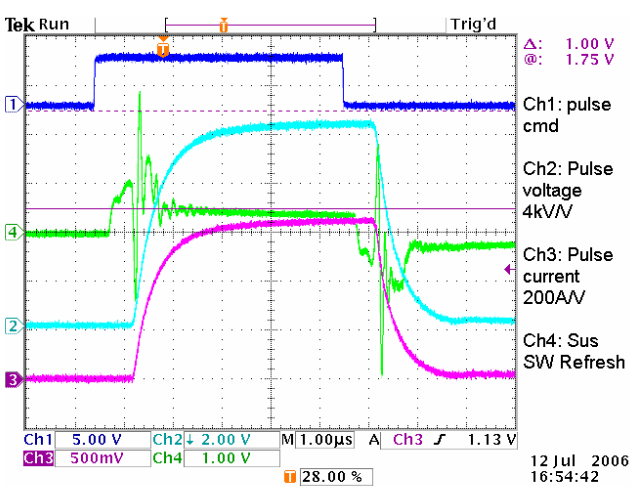

Figure 4. Sample pulse from the PEF system shown in Figure 1, at 34 kV, 320 A, 4 uS flattop.

III. DESIGN EXAMPLE

DTI has recently completed a high volume, commercial scale PEF system for wastewater processing. This system, shown in ***Figure 1***, is designed to process 10,000 liters / hour of wastewater. As with all PEF systems, the basic three elements of this system are the DC power supply, rated at 150 kW average (***Figure 2***); the pulse modulator, rated at 35 kV and 350 A; and the treatment chamber (***Figure 3***), containing 4 treatment gaps at 15 mm diameter.

There are several aspects of this design that make it both applicable to commercial operation, as well as scalable to higher volume processing. First, this system is mono-polar – all of the pulses are negative polarity, rather than the bi-polar systems discussed previously. This means that only a single switch, rated at 35 kV and 350 A (***Figure 4***) is required, rather than four. Additionally, only a single DC power supply is required. Second, the average power of the system, and therefore its processing capacity, can readily be doubled by the addition of a second, 150 kW power supply in parallel with the first.

This system is designed to operate with full PLC control, which coordinates the PEF system operation with the other equipment in the process stream, such as pumps and pre-process operations (e.g., de-aeration). This minimizes the operator inputs required. The system is designed with the modulator and treatment chambers in a NEMA 4 enclosure, allowing their placement in areas where washdown is required. The DC power supply and controls can be located in another area of the plant, typically near the controls for other aspects of the plant operation.

Finally, the treatment chamber design has been significantly revised from the original design which DTI licensed from OSU. The overall design is focused on simple assembly and disassembly for maintenance and cleaning. In this design (***Figure 3***), four treatment cells are directly in-line with the flow (which enters at the bottom of the chamber). In other iterations, where cooling between treatment chambers is required, each pair of cells would be separated by a coupling allowing a heat exchanger between each pair of cells.

IV. FUTURE SYSTEMS

The cost of a bi-polar, 400 liter / hour pilot system, as shown in ***Figure 5***, is approximately $250,000, including the treatment chambers. This system is rated at +/-25 kV, 200 A, at 25 kW average power. The commercial system shown in ***Figure 1*** has four times the average power and is capable of processing over an order of magnitude higher flow (at lower field strengths), and sells for approximately $500,000. This compression in price is typical of many pulsed power systems – the cost of the controls and fault protection is relatively constant, so costs do not increase proportionally only to power. It also points out the large cost differential between commercial, mono-polar systems (designed for a narrow range of treatments and flow characteristics), and bi-polar systems designed for R&D over a wide range of potential conditions.

As PEF technology moves into commercial operation, future systems will move towards the commercial model – with simpler controls, mono-polar pulsing, and higher average power. This will allow the cost of PEF systems to continue to drop in the future.

V. 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 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.

Figure 5. PEF pilot plant. Capacity up to 400 l/hr. Power electronics in cabinet on left; four-chamber processing unit on right.

The use of solid-state, high voltage pulsed power systems for PEF processing is the key to these commercial applications. Solid-state technology allows this PEF to scale from small laboratory systems to large-scale processing facilities. Developing a common language and process for defining PEF requirements and systems will help researchers, system developers, and food processors communicate their needs and constraints, and allow all sides to achieve their objectives more economically. New technologies are allowing PEF systems to become smaller and less expensive. The entire community is gaining experience in specifying, building, and operating PEF systems. As a result, the gulf between research and commercial application in PEF processing is rapidly disappearing.