PULSED POWER SYSTEMS FOR FOOD AND WASTEWATER PROCESSING

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ABSTRACT

A high voltage process in food and wastewater processing, called Pulsed Electric Field processing (PEF), destroys plant and animal cells in a liquid media through electroporation. In PEF, a series of short, high voltage pulses breaks the cell wall, by expanding existing pores in the cell until they burst. This bursting of the cell wall has three main effects. It kills living cells, such as bacteria, making it an alternative to pasteurization for liquid foods, such as fruit juices and beer. It releases the contents of the burst cell to the surrounding liquid, which can aid in the extraction of sugars and starches from plant cells, such as sugar beets. Finally, the burst cells are much more susceptible to other biological and chemical processes, such as anaerobic digestion, which can significantly reduce the solid content (sludge) in wastewater treatment facilities. PEF processing is currently being demonstrated for all three of these applications, and is beginning to emerge as a viable commercial process.

In liquid foods, PEF maintains the fresh taste lost in heat pasteurization, because it is non-thermal. PEF utilizes less than 10% of the delivered energy required for pasteurization, so the temperature rise during PEF is only a few degrees Celsius for equivalent bacterial kill (versus 80 – 100 Cº for pasteurization). Because PEF only applies a voltage gradient to the treated liquid, without arcing, there are essentially no chemical effects. In taste tests conducted on PEF treated juices, they are essentially indistinguishable from fresh (untreated) juices.

In 2000, Diversified Technologies, Inc. (DTI) of Bedford, MA designed, built, and installed the first commercial scale Pulsed Electric Field (PEF) system at Ohio State University's Department of Food Technology (FIGURE 1). This PEF system is part of a new food treatment system assembled by a DoD sponsored, university-directed industry consortium. The purpose of the program was to research the use of high voltage pulsed power to kill microorganisms, including pathogens, in liquid foods such as juices. This system has been successfully utilized over the last two years to prove that PEF processing is scalable to high volume, commercial applications.

In this paper we will describe the architecture of the pulsed power system and the application and benefits of solid-state high voltage systems to food sterilization. Operational results and status will also be presented.

BACKGROUND

Traditionally, pasteurization or heat processing is used to reduce the level of bacteria, spores, and other agents that

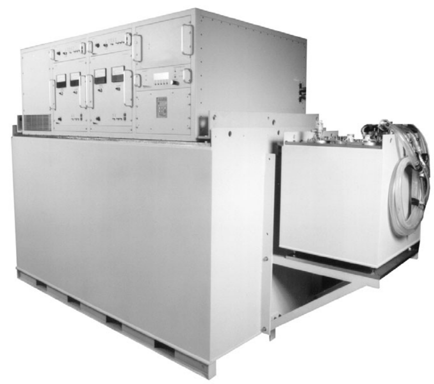

FIGURE 1. OSU 60 kV bipolar pulser

cause spoilage of fruit juices, beer, milk, and other liquid foods. Heat processing, however, also reduces the flavor of these foods. Orange juice, for example, is susceptible to undesirable reactions during heat processing, resulting in off-flavors and dark color. To avoid degradation of food quality during heat processing, researchers at Ohio State University (OSU), Washington State University, and many other institutions have conducted considerable research into non-thermal processing of foods. A highly effective non-thermal process is Pulsed Electric Field (PEF) Processing.

In PEF processing, an electric field, rather than heat, chemicals, or irradiation, is used to kill microorganisms, spores, etc. Kill rates comparable to pasteurization have been demonstrated by multiple researchers across a wide range of liquid foods, including juices, milk, liquid eggs, and sauces. **The key to PEF processing is that the food stays cool because heat is not required for bacterial kill. Because there is little heating, the taste and nutritional value of PEF treated foods are essentially indistinguishable from fresh (untreated) products.**

In PEF processing, a liquid food, such as a juice, sauce, or other pumpable product, is passed through a small treatment chamber, where it is subjected to a short (10 ns – 20 µs) pulse of **very** high voltage. The high voltage field created across the liquid (approximately 35-50 kV/cm) kills microorganisms and spores by disrupting 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 have been achieved, similar to pasteurization. Multiple experiments have demonstrated that the shelf life of PEF processed food is comparable to that yielded by pasteurization. No adverse impact on the taste or nutritional value of the food was found.

The primary **limitation** to commercialization of PEF processing has been the inability to generate the high voltage pulses having sufficient peak power (typically megawatts) needed to process large quantities of fluid economically. Typical laboratory systems have used vacuum tubes or spark gaps to create the high voltage pulses. These systems are expensive, inefficient, and limited in either peak or average power. Without the ability to provide high peak power levels efficiently, the throughput and cost of these systems is not economical for commercial operations.

The emergence of solid-state pulsed power systems, which can be arbitrarily sized by combining switch modules in series and parallel, removes this limitation. The solid-state pulsed power system delivered to OSU provides bipolar 60 kV, 600 A pulses at 75 kW average power into four PEF treatment chambers. It consists of two fully independent switching power supplies and solid-state switches – one at positive voltage, and the other at negative voltage. This provides a very high level of pulse flexibility to the OSU researchers as they optimize PEF treatment parameters across a wide range of liquid foods.

HIGH VOLTAGE SOLID-STATE SYSTEMS

In parallel with the development of PEF processing, DTI has developed solid-state high voltage pulsed power systems capable of orders of magnitude higher performance than conventional technologies. This new technology has been funded and developed through a number of SBIRs from the Departments of Energy and Defense, commercial contracts, and DTI investment over the last decade. Solid-state, high voltage systems are significantly more efficient and reliable than the tube-based approaches which have been the conventional approach since the 1920's. This solid-state technology enables the transition of PEF processing from the laboratory into commercial food processing applications. DTI has several patents and patents pending on this technology. The major features and benefits of PEF processing using solid-state modulator technology are summarized in Table 1.

PEF processing is now, for the first time, being demonstrated in a commercial scale system by a university and industry consortium under an Army-funded Dual Use Science & Technology (DUST) Program. Consortium members include the Army's Natick Laboratory, OSU, DTI, TetraPak, and several major food processing companies, including Kraft and General Mills.

Under this effort, DTI built and delivered the world's first commercial scale solid-state PEF pulser system, which has been integrated with treatment chambers developed at OSU, and an aseptic packaging system from TetraPak. This system was built in approximately eight months, and delivered to OSU late in 2000. Full-scale operation began in May, 2001, and the initial testing will be complete at the end of 2002.

The primary objectives of this project included the development of PEF process parameters, and verification of the scalability of PEF processes to commercial volumes. The program has been highly successful in proving that PEF performance scales directly from low

TABLE 1. OSU/DTI PEF processing system highlights

Feature	Advantages	Benefits
>5-log Pathogen reduction / Inactivation	• Meets FDA standards for commercial sale • Extended Shelf Life	• Commercially usable – meets FDA regulations • Lower costs of spoilage in transport and sale
Low Heat Process	• Retained flavor and nutrients • Applicable to heat sensitive foods	• Enhances safety of foods • "Fresh" taste and quality
High Speed Continuous Process	• Scalable to both low volume and high volume facilities • No process waiting time	• Allows upgrade of existing process lines with minimal impact • High processing throughput / unit
Solid-state	• High reliability • Long operating life	• High up-time and throughput • Low cost of maintenance
Energy Utilization	• High Efficiency • Low energy required (for some foods)	• Lower Utility costs for pasteurization (for some classes of foods)
Integrated / Automated System	• Installation in existing processing lines • Simple operation	• Retrofit to existing plants • Little training / low costs

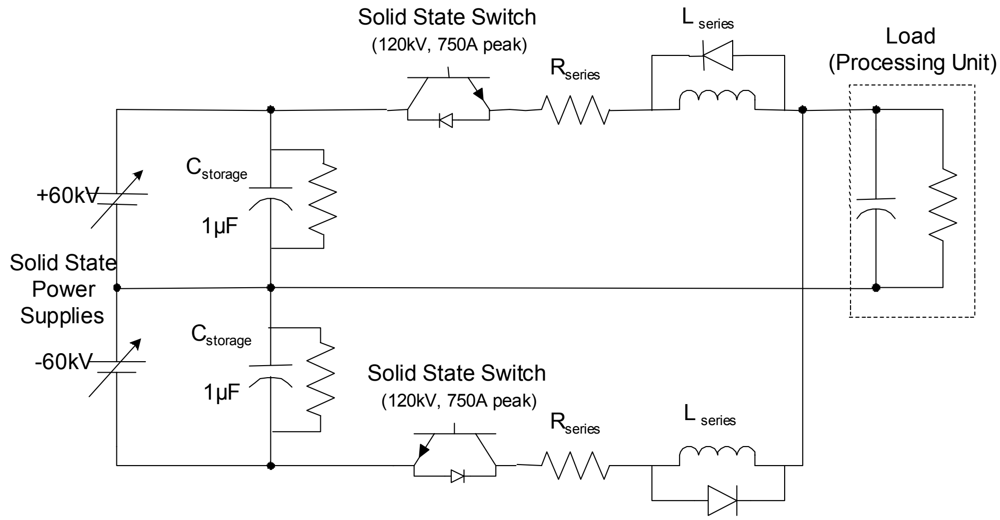

FIGURE 2. Bipolar PEF system block diagram

volume, laboratory scale systems to large, production scale installations.

This commercial-scale prototype opens the door to a revolution in food processing by providing the safety of pasteurization, with higher food quality at lower processing cost.

SYSTEM ARCHITECTURE AND OPERATION

The OSU PEF (FIGURE 1) modulator system built by DTI is fully bi-polar. It provides both positive and negative pulses at up to 60 kV, 750 A peak. Each polarity has fully independent power supplies and solid-state switches, allowing full control over the pulse parameters for PEF research and process optimization efforts. With this architecture, the pulse width, pulse repetition frequency, and positive and negative voltages are independently variable over a wide range, limited only by the 75 kW average power of the system and the need to avoid simultaneous positive and negative pulses at the output. OSU researchers can run in one polarity alone, alternate polarities, or use multiple positive pulses followed by multiple negative pulses.

Each solid-state switch in this unit is composed of multiple IGBTs connected in series. DTI's patented technology ensures that all of these individual IGBTs switch on and off simultaneously, and that the voltage is evenly distributed across these devices. In this way, each switch operates as a single device. The maximum voltage seen across the switch, under both normal operation and during any potential load arcing, determines how many individual devices must be combined in series.

Each treatment chamber is designed to apply a uniform electric field across the food. The repetition rate of the high voltage pulses, and the fluid flow rate, are both controlled to ensure that all of the food is subject to multiple electrical pulses as it flows through the system. Electrically, treatment chambers are connected in parallel, so the same peak voltage (up to ±60 kV) is applied to the food in each treatment chamber.

Each pulse in a treatment chamber can deliver 10 - 100 joules of energy – enough to raise the temperature of the food in the chamber by several degrees centigrade. The OSU system has provisions for cooling the food being processed as it passes between treatment chambers – limiting the maximum temperature of the food being treated to the temperature rise in one treatment chamber alone.

A significant consideration in the design of this system was the required voltage standoff of the solid-state switches. The total potential difference within the unit is 120 kV. Since each switch can independently see this full potential (when the opposing switch is closed, there is 120 kV across the open switch), this design requires two independent 120 kV capable switches. With two switches rated at 120 kV, the OSU PEF system is the largest solid-state switch assembly built to date by DTI, with a total of 240 kV in switch modules. We expect that the research at OSU will show how commercial PEF systems can be optimized for specific process applications, and therefore to become smaller and less expensive.

The liquid being processed is an integral part of the circuit – the liquid in the treatment chamber during each pulse is the load resistance seen by the modulator. The throughput of the unit is directly related to the resistivity of the liquid being treated. Typical resistivities of liquid foods can range over nearly an order of magnitude, depending on the composition of the liquid and the amount of dissolved minerals (e.g., salt) and solids (e.g., pulp) in the liquid. The modulator is a very low impedance, constant voltage source. This ensures that the desired electric field is

FIGURE 3. 500 kV, 500 A hybrid modulator

present at all times. The current in each pulse will vary as the resistivity of the product changes over time.

At 75 kW average power, the OSU system is nominally sized to operate at 2000 liters per hour. For highly resistive foods, such as apple juice, this unit can process up to 5,000 liters per hour, while highly conductive foods (such as salsa) will have much lower throughput at this power level. For commercial processing, throughput is directly proportional to the average power for a given field strength.

DTI has recently delivered a modulator to SLAC for cathode pulsing of an X-band klystron at 500 kV, 500 A. The core of this system is a solid-state modulator, rated at 80 kV, 3500 A (FIGURE 3) This modulator would support PEF processing at approximately ten times the throughout of the OSU system – a nominal 20,000 liters per hour for orange juice. This solid-state pulsed power technology, therefore, is readily scalable to a wide range of commercial food processing applications and plant configurations.

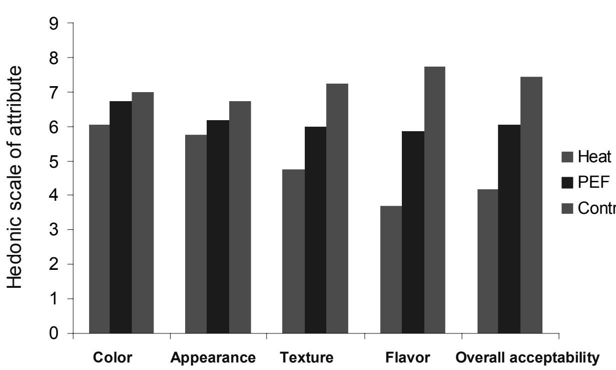

FIGURE 4. PEF results versus pasteurization. Left bar represents heat, middle bar PEF, right bar is control (Source: OSU)

Evaluation of the applicability of PEF to water and wastewater treatment is currently underway in several organizations. DTI is currently under contract with the U.S. Environmental Protection Agency to investigate the ability of PEF to reduce bacterial loadings in stormwater discharges, which can contain high levels of E. Coli from sewage overflows or farmland runoff. The main benefits of this technique are that there are no chemicals, such as chlorine, required, and the energy needed can vary instantaneously as the stormwater flows change. DTI is working with other organizations to develop systems to reduce sludge volume from wastewater treatment plants (through improved anaerobic digestion after PEF treatment), and to improve the ability to reuse water in papermaking (through reduction in bacterial loads).

Researchers at the Technical University of Berlin have demonstrated that the same electroporation effect that kills bacteria in food can be used to break the cell walls of plants, such as potatoes and sugar beets. In their experiments, whole sugar beets, conveyed in a water bath, were pulsed to significantly improve the extraction of sugar from the beets themselves. In this application, the required electric field is much lower than required for bacterial kill (approximately 10 kV/cm, versus 35 kV/cm). The total voltage required, however, is much higher (100's of kV), since the gap distance must be much larger to treat whole beets or potatoes. For this type of process, a Marx Bank or transformer-coupled solid-state modulator appear to be the best architectures.

CONCLUSIONS

PEF processing has been shown by multiple researchers 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 (FIGURE 4). 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.

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. Based on the success of DTI's bipolar system at OSU, PEF processing is poised to transition from the laboratory to commercial utilization.

Acknowledgments: The authors wish to acknowledge Dr. Q. Howard Zhang, OSU; Dr. Patrick Dunne, U.S. Army Natick Laboratory; and the members of the DUST PEF Consortium for their contributions and support to this project. The high *voltage, solid-state switch technology utilized in this effort was developed by DTI with the support of multiple U.S. Department of Energy Small Business Innovative Research grants.*