SOLID-STATE POWER SYSTEMS FOR PULSED ELECTRIC FIELD (PEF) PROCESSING.

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Abstract

Pulsed Electric Field (PEF) processing disinfects liquid foods and water. The process kills pathogenic cells by rupturing their cell membranes with short, high voltage pulses. 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.

Though PEF systems are based on conventional pulsed power technology, they present a very different set of challenges in meeting the requirements of specific biological applications. For example, while most pulsed power specifications are based on voltage, current, and power requirements, PEF systems typically start with a desired field strength, flow rate, and range of fluid conductivities. Translating these parameters into a pulsed power system design can be a challenging process.

Figure 1. PEF pilot plant. Capacity up to 400 l/hr. Power electronics in cabinet on left; four-chamber processing unit on right.

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

I. BACKGROUND

Traditionally, pasteurization or heat processing is used to reduce the level of bacteria, spores, and other agents that cause spoilage of fruit juices, beer, milk, and other liquid foods. Heat processing, however, also reduces the flavor of these foods. 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.

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 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, 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.

Translating these parameters into affordable and effective PEF systems is a complex problem. The major food parameters, such as conductivity, interact directly with the electrical system design. When the demands of the overall process, such as flow rate, cleaning, and plant operation are included, the overall design becomes a multi-dimensional problem with numerous potential solutions. The challenge is to optimize the overall PEF system design in light of all of these parameters.

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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 2).

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. The major element of the PEF system is the pulse modulator. The requirements for this modulator are, at a general level, similar to the requirements of a radar modulator - high voltage and peak power, short pulse, and high frequency.

There are two critical differences between PEF and these RF applications, however. First, a PEF system can be designed as either bi-polar (+ and – voltage pulses) or mono-polar (all + or all – pulses), and R&D systems typically must provide both bi-polar and mono-polar capabilities. Radar transmitters are all mono-polar. A critical factor in the modulator cost is that a bi-polar system requires four times the switch capability of a mono-polar system of the same voltage and current. Only two switches are required, but each switch must stand off the full difference between the positive and negative voltages when it is open. Second, RF tubes present a consistent and predictable load impedance to the modulator – at a given voltage, the current required is constant and predictable. The electrical design of the modulator can be tailored to this specific impedance. In PEF systems, however, the liquid being processed is the load, and is therefore an integral part of the circuit. The conductivity of different foods can vary by over 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 conductivity of a single food type, such as orange juice, can vary by 50 – 100% due to changes in the raw materials. The PEF modulator, therefore, must be able to accommodate these changes in load impedance. This variability in the load eliminates most transformer coupled modulator designs 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 also be low impedance, to provide consistent output voltage over the wide range of peak currents which may be required as the food conductivity varies. Solid-state switches are ideally suited to both of these requirements.

Figure 2. OSU 60kV, 750 A bipolar PEF system.

The third major element of a PEF system is the treatment chamber where the high voltage pulses are applied to the food. The key attribute of the treatment chamber is its ability to provide minimal impact on the food 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. 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 directly proportional to the pipe diameter. Therefore, as larger pipe diameters (to 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 current limit for solid-state, hard switched modulators. For larger pipe diameters, alternative modulator or treatment chamber designs may be required.

A. *Key PEF Process Parameters*

Any discussion of PEF system design must be based upon an effective PEF treatment protocol. Development of a new protocol requires a significant number of trials at different field strengths and durations, and microbiological assessment of the resulting product. The literature contains a great deal of information to guide protocol development, which can vastly reduce the range of potential trials required. A typical treatment protocol might require application of a 35 kV/cm field for a minimum of 50 μs to achieve a given bacterial reduction. For the purposes of this paper, we are assuming that this protocol is known, and provides the microbiological efficacy required for the particular application.

The discussion of PEF system elements has already raised the two major factors affecting PEF system design – food characteristics and flow rate. These two factors form the basis for all other design tradeoffs. The major food characteristic of interest is resistivity. This parameter determines the impedance of the food in the treatment

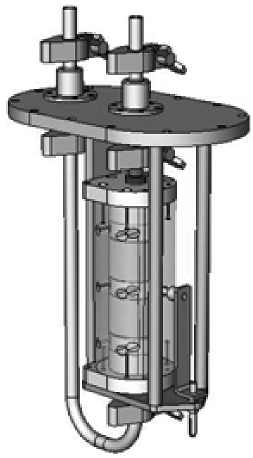

Figure 3. Cutaway drawing of 20 kV, 150 l/hr PEF treatment chamber.

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 resistivity.

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 the gap distance is a function of chamber diameter, and larger gaps require higher voltages to maintain a given field strength, balancing pressure and voltage is a critical optimization that must be made.

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.

As one example, 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.

III. DESIGN EXAMPLE

DTI recently delivered an R&D PEF system to a European University. Since the university budget was constrained, there was considerable effort on both sides to optimize the performance and cost of this unit, while retaining the desired flexibility in treatment protocols the system could support. The basic requirements for provided by the university included:

- Up to 60 kV/cm field strength
- 1 to 10 µs pulsewidths
- Bi-polar and mono-polar operation
- Fluid Conductivity of 1 to 6 ms/cm
- Up to 150 l/hr capability at all conductivities
- Four treatment chambers
- 20 kW average power

The design process started with the flow rate. DTI determined that 150 l/hr could be supported with a 0.3 cm diameter in the treatment chambers at reasonable pressure (Figure 3). This chamber was approximately 1/3 the size of the OSU treatment chambers used in the 2,000 l/hr system. This, in turn, determined the peak voltage required to be 20 kV, with a peak current of approximately 150 A at the highest conductivity. To provide these electrical parameters, DTI investigated the use of a pulse transformer, with a 3 kV, 1000 A primary (which could use an existing, commercial DTI switch). Unfortunately, in modeling this design, we found that the combination of transformer inductance with the conductivity range made it very difficult to achieve consistent risetimes and pulse shapes. This design would also require a reset power supply to support mono-polar operation. At that point, we decided to use four hard switches, at 40 kV each, in an H-bridge configuration, to provide the pulses.

Until recently, simply housing four 40 kV, 150 A switches would have required a very large modulator. A key element in this design was DTI's recent efforts to develop IGBTs specifically for pulsed power applications. Figure 4 shows one such device, developed in collaboration between DTI and Powerex, under a U.S. Department of Energy SBIR. This device allowed us to build a compact 20 kV, 150+ A switch module, shown in Figure 5. Eight of these modules (2 per switch) were fully capable of supporting the 20 kV, 150 A bi-polar pulses required, and could be assembled in a very compact configuration (in oil). These modules are fully capable of supporting operation across the 1 – 10 µs pulsewidths required, at frequencies up to several kHz.

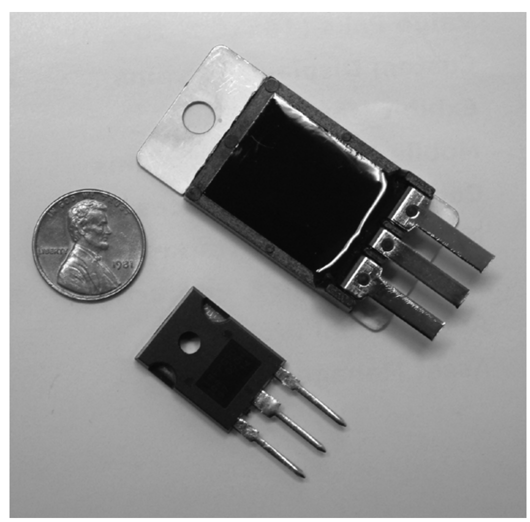

Figure 4. Pulse power transistor (PPT) top; conventional T0-247 bottom.

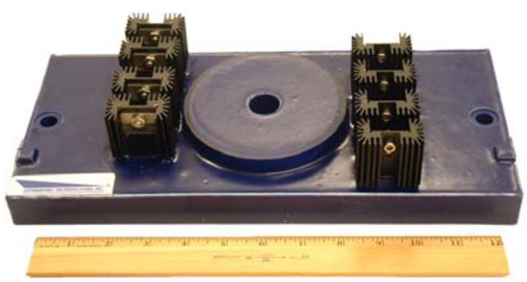

Figure 5. 20 kV, 100+ A, PPT switch module.

The average power was determined by the university, and significantly exceeds the power required at 150 l/hr. It is, in fact, enough power to boil the fluids at high conductivities. This power rating offers the ability to increase the flow rate of this system to 300 – 400 l/hr, at 40 kV/cm peak field strength, simply by replacing the treatment chambers.

Figure 6 is a sample pulse from the configuration shown in Figure 1. The overall system includes the power supply, 20 kV, 150 A H-bridge modulator, and a Pulse Control Unit in a single, 24” rack. The treatment chambers are enclosed in a separate, vegetable oil filled tank containing two assemblies, each with a single high voltage input and two treatment chambers (gaps). This system provides very fast risetimes (~ 200 ns) across the full conductivity range.

The overall system design provides a highly flexible, moderate flow system for a range of PEF R&D and protocol developments. This system can also support commercial, low volume PEF operations.

IV. FUTURE SYSTEMS

The cost of the system shown in Figure 1 is approximately $250,000, including the treatment chambers. While this is consistent with the price of other pulsed power systems, comparable in power and

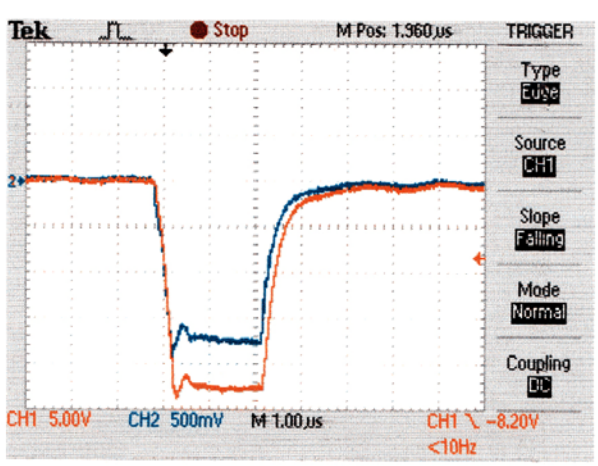

Figure 6. 20 kV, 35 A pulse into orange juice. Risetime ~ 200 ns, 1 kHz frequency

complexity, this is an order of magnitude higher than conventional food processing systems, such as pasteurization systems. The energy costs for PEF processing are typically lower than those of pasteurization systems, however, making the PEF process comparable to pasteurization over a 2 – 5 year period of time. Reducing the capital costs of PEF equipment will be an important factor in the commercial adoption of this process.

To achieve this capital cost reduction, DTI is developing future PEF systems which are designed to meet both the microbiological requirements of the PEF process and lower the equipment costs of PEF systems. To achieve these objectives, DTI has identified the following design objectives for future PEF systems:

- •Monopolar operation, to reduce the number of switches required,
- •Hard switching (no pulse transformer), to accommodate changing product conductivity,
- •Simplified power supplies, such as buck regulators,
- •Smallest treatment chamber gaps possible, to reduce peak voltage requirements,
- •High pulse frequency to accommodate high flow rates

With these design features, we believe that the total size and cost of future PEF systems can be reduced by a factor of two or more, compared to the research systems built to date.

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.

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.