Removing Barriers to Commercialization of PEF Systems and Processes

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Abstract: Pulsed Electric Field(PEF) Processing has been known as a means of non-thermal pasteurization since the mid-1960s, and has been extensively researched for nearly 30 years in the US and Europe. Despite this activity, commercialization of PEF has proceeded slowly. This paper examines some of the possible reasons for this pace of commercial adoption, and highlights the impact of the disparate results being published for similar processes, primarily due to differences in PEF systems and the reporting of PEF parameters.

INTRODUCTION

The initial patent for Pulsed Electric Field (PEF) processing technology was granted nearly 30 years ago, and the first commercial-scale PEF system delivered over 15 years ago. During this period, several large consortiums have worked in the US and Europe to transition PEF into industry, and thousands of papers on PEF processing have been published at universities and research institutions around the world. After all this time and research, however, PEF systems have established only limited commercial use in food processing.

The only explanation is that there are barriers to the commercialization process which hinder the adoption of PEF technology. These barriers can be classified into several major groups, which include cost, performance, publicity/knowledge, predictability, access to PEF systems for trials and validation, legal/regulatory issues, and integration of PEF into existing processing plants.

Some of these barriers are clearly capital/investment driven, and will disappear as PEF commercialization occurs, making it viable for industry to justify even larger investments. A significant barrier may be publicity. The identification/dissemination of PEF applications where significant and quantifiable improvements in food safety, quality, and/or cost are possible does not typically reach the broader food processing community – in part, because there are no highly visible success stories, and in part because the companies who are adopting PEF processing are not publicizing.

The most critical barrier, however, may be the predictability of results using PEF. Unlike thermal processes, or even High Pressure Processing (HPP), there is no consistent formula or 'cookbook' to predict the PEF processing conditions needed to achieve a specific result for a specific product. In fact, published studies can vary significantly in terms of the results achieved for the same product and the same reported treatment conditions. As a result, each company interested in PEF processing must develop their treatment protocol, on their own equipment, at considerable cost and risk. Widespread adoption of PEF cannot occur until this barrier is removed.

RESULTS & DISCUSSION

PEF History and Status

The first reports of PEF can be traced to the mid-1960s, but the most extensive work begins in the mid 1990s with PEF research at Washington State University and Ohio State University in the US, and the Technical University of Berlin in Germany leading the early group of researchers. By the end of the decade, two significant consortia were underway in the US (DUST) and Europe (EFFoST), which brought together major food processing companies, universities, and equipment manufacturers to explore PEF's commercial potential. Both of these consortia were primarily focused on non-thermal pasteurization of fruit juices and other acidic, liquid foods (tomato sauces, yogurts, etc.), and developed commercial scale PEF Systems to extend throughput beyond the liters/hour of the (primarily) home-grown PEF systems in use at the time.

The first major commercial PEF introduction was made by Genesis Juice in the US, in 2005 (Figure 1). Genesis had been selling unpasteurized juices prior to the change in US laws, and was adamantly opposed to thermal pasteurization. During a one year shutdown due to the new laws, they installed a PEF System, received regulatory approval, and began selling PEF processed juices in a variety of flavors. The extended shelf-life of the PEF processed juice also extended their market reach significantly. Unfortunately, the costs of the shutdown year and market expansion squeezed their capital, and drove them to cease operations and sell their name in 2007. The new owner already possessed juice processing facilities, and did not continue PEF processing.

The press surrounding Genesis' introduction of PEF-processed juice, while initially highly positive, ultimately worked against PEF Technology. Genesis was the focus of a number of articles, and received an IFT Technological Achievement Award (with Diversified Technologies, Inc.) in 2007. Their demise was interpreted as a failure of PEF by many in the industry who weren't familiar with the details.

Genesis' failure might not have proved as detrimental to PEF adoption if not for the financial crisis in 2008. Several other companies in the U.S. and Europe were on the verge of adopting PEF in 2007/2008, but shelved these plans after the crisis, as attention rapidly turned from premium products to low-cost, value products.

The renaissance of PEF processing began after the crisis had passed, with the introduction of PEF processed juices by several companies in Europe around 2012. In most of these products, PEF processing was not used to achieve pasteurization (>5-log kill), but applied at lower doses to increase the shelf-life of fresh juices. This application appears

Figure 1. *Genesis Juice on sale in 2007*

to be growing in Europe, but is not available in the US, where 5-log pasteurization is required.

More recently, other applications of PEF processing have been developed and introduced commercially. These include wastewater sludge processing (to enhance anaerobic digestion) and potato processing (to reduce breakage and cutting costs). Applications for extraction, drying, and related plant tissue modification have been explored and proven in research trials, but are not known to be in commercial use at this time.

In late 2015, there appeared to be just over 100 PEF Systems operating around the world, according to the PEF System manufacturers polled by the author, not including a smaller number of 'home-brew' systems in Universities. Of these commercially built systems, approximately 1/3 are R&D systems at Universities and corporate R&D centers, 1/2 are used for industrial applications, and < 20 systems appear to be used for microbial kill. Details of sales, applications, and users can be difficult to gather, given the reticence of many companies to divulge their use of (or even interest in) new technologies. It is possible that other industrial systems and applications exist which are not accounted for in this manufacturer survey, but it provides the best assessment of the state of the industry known at this time.

COMMERCIALIZATION BARRIERS

Given the 30 years of development, and millions of dollars (and Euros) spent on PEF R&D, having only 100 installed systems in the world seems like a massive failure to launch. In searching for an explanation for the slow pace of adoption, five elements were examined to assess their possible impact:

- Performance
- Cost
- R&D Maturity/Data Availability
- Equipment Availability
- Regulation
- Process Development

Each of these factors is discussed below.

Performance

Thousands of PEF studies have been published over the last three decades, examining the impact of PEF on microbial kill, taste, enzymes, proteins, and a host of other factors. The overwhelming consensus from these studies is that PEF is an effective approach to non-thermal pasteurization, which has extremely limited impact on the product's taste and quality. This is only true within a limited range of products, however. The primary limitation is that PEF only effects vegetative organisms (which have cell membranes that can be electroporated), and not spores. This limits PEF to primarily acidic foods, where spore outgrowth is not a major concern. Other limitations have been reported for high protein foods (e.g., liquid eggs), where denaturation can occur at high field strengths.

For a large population of liquid foods, PEF performance is not a limiting issue for commercialization.

Cost

Several studies have looked specifically at the cost of PEF alone, or in comparison to traditional thermal pasteurization and HPP. Most of these studies place the cost of PEF at $0.02 - $0.05 per liter, depending on the specific product, treatment conditions, and assumptions about energy labor costs. These costs include capital costs (PEF equipment), electricity, labor, and maintenance. This puts PEF in the middle of these three processes – at 2-3X the cost of thermal pasteurization, but only ~20–30% of the cost of HPP (not counting the cost of transport of product to and from a tolling processor).

Figure 2. *World's First Commercial-scale PEF System, built by DTI for the DUST Consortium in 2000.*

Given the widespread use of HPP for juices and similar foods, cost does not appear to be a limiting factor for PEF adoption.

R&D Maturity/Data Availability

PEF processing has been studied at several dozen universities around the word in the past three decades. There have been over 1,000 peer reviewed papers on PEF since 1985, and several thousand publications overall – including over a dozen books on PEF alone, or on PEF and other non-thermal processes. A Google search for "Pulsed Electric Field, juice" results in over 70,000 results, with nearly 30,000 related to orange juice alone.

Lack of R&D / data does not appear to be a limiting factor to PEF adoption.

Equipment Availability

When the DUST and EFFoST consortia were initiated in the late 1990s, there were no commercial PEF systems available. Most of the R&D systems in use were built by the PEF researchers themselves, and were limited to low volume applications. Diversified Technologies, Inc. (DTI) delivered the first commercial scale PEF system to Ohio State University under the DUST consortium in 2000, based on its development of solid-state pulse modulators for radar transmitters and particle accelerators in the 1990s (Figure 2).

In the past 15 years, at least six manufacturers have introduced PEF systems, rated from 3 – 600 kW of average power (capable of achieving pasteurization at capacities from approximately 3 liters / hour to 10,000 liters per hour). Several of these companies, including Scandinova in Sweden and DTI in the US, sell PEF systems as an off-shoot of their main pulsed power business, while others (such as Elea in Germany) focus exclusively on PEF systems. Between them, Elea and DTI have sold over 2/3 of the PEF systems in operation today.

Access to commercial-scale PEF systems is not a limitation to PEF commercialization.

Regulation

In the US, PEF is subject to the Juice HACCP laws, which require demonstration and maintenance of >5-log reductions in pathogens of concern (typically *salmonella*, *listeria*, and *E. coli*). The FDA issued a 'letter of no objection' to PEF in 1996. Genesis Juice was able to certify that its PEF process met the FDA requirements, in the face of intense scrutiny as the first PEF processor in the US.

In Europe, the regulatory picture is less clear. Today, PEF is not typically used for pasteurization, but rather for shelf-life extension. It does not appear to be subject to specific regulation. PEF is not considered a 'Novel Food' in Europe.

Almost no information is available on the regulation of PEF in other parts of the world, although Australia is considered similar to the US regarding food regulations.

Regulation is not a specific obstacle to PEF commercialization, but the use of PEF as a food safety practice is not widespread. Fear of the costs and effort required for regulatory approval may be a larger impediment.

Process Development

Despite the thousands of papers published on PEF, there is no established method of determining the process conditions required to achieve specific microbial kill levels on a product without significant process development and validation. A survey of multiple papers specifically focused on orange juice, for example, showed a wide range (factor of four) in field strength, and over an order of magnitude variation in reported treatment times, to achieve 5-log reductions of common pathogens (Figure 3).

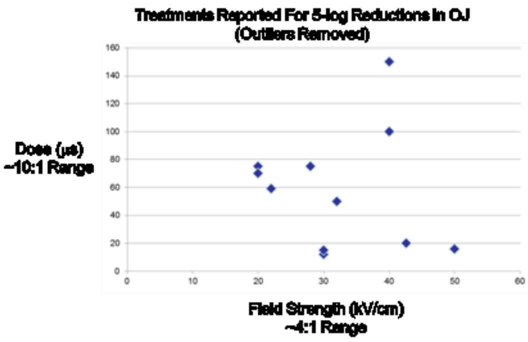

Figure 3. Reported Field Strength and treatment times for 5-log microbial reduction in OJ.

In large part, this variability is due to the range of PEF systems used at different R&D facilities. Depending on their construction, they can have very different pulse shapes and treatment chamber designs. There is also a surprising lack of standardization over reporting the most basic PEF process conditions, such as field strength and treatment time. The variability shown in Figure 3 would be significantly reduced if these measurements were made and reported consistently. A secondary contributor to this wide range is that other process conditions (inlet temperature, pH, conductivity, etc.) can impact the results achieved, even when controlling for field strength and treatment time. It has been reported that there are ~25 different parameters that can affect PEF results (although many of these are directly related to each other).

This lack of standardization and accepted methods forces companies interested in using PEF processing to engage in their own process development efforts, in order to determine the process conditions which work for each product, on their own equipment. Once developed, this process data must then be submitted to regulators, and introduced into their HACCP plans.

There are less than a dozen facilities in the world for a food processor to investigate PEF treatment – and nearly all of them are dedicated to research, not process development for industry. Even where trial facilities currently exist, they often operate on academic schedules, which are typically not consistent with commercial requirements. Finally, ensuring that a process validated in the lab will scale to commercial volumes is not trivial. If commercial processors must commit to buying PEF equipment, before they know if PEF will achieve both the food safety and product attributes they desire, the cost and risk are too high to justify - unless their competitors do it first.

There is substantive evidence that PEF treatments directly scale from the laboratory to commercial operations, if the treatment chambers and high voltage pulse shapes are consistent between these machines. Commercial PEF systems which maintain these critical parameters across a range of throughput (average power) are available, but not widespread.

The need for (and cost of) Process Development by commercial food processors, and the perceived risk of scaling from the laboratory to commercial operations, represent the major impediment to commercial PEF adoption today.

CONCLUSION

The substantive level of research on PEF for non-thermal processing has failed to drive commercial adoption. As discussed above, the primary barrier to adoption are not cost, performance, equipment availability, or even regulation. It is the fact that all of this research has not provided a well-defined roadmap for a company that is interested in adopting PEF processing. In fact, reviewing the literature, even for a specific product, can show whether PEF is applicable, but will provide only limited indicators of the required process parameters needed for commercial implementation.

Figure 4. *DTI Laboratory PEF System.*

Addressing this barrier will require three major steps:

1. **Adoption of standards for measuring and reporting the critical PEF parameters** (primarily field strength and processing time). At minimum, and until standards are in place, researchers should show their high voltage pulse and treatment chamber design, and indicate how they measured these parameters. This would allow translation between studies which use different equipment, and hopefully narrowing the spread of resulted conditions.
2. **Focusing on products for PEF processing that can directly benefit from PEF's unique capabilities:** in-line, continuous processing of heat sensitive foods. Until commercial PEF processing is widespread, the cost of process development will remain high, and can only be justified for foods which are damaged by other processes. Most of the liquid products currently processed with HPP probably fall into this category.
3. **Establishment of trial facilities.** This will allow interested processors to validate PEF processes on their products, and assess the product benefits, rapidly, and at low cost.

There is of course, the view that this is the path new technologies take. This path can be long, and filled with obstacles. For perspective, it is helpful to look at another NTP technology. There were ~50 HPP systems installed in the world in the first fifteen years of research, but the growth rate of HPP has been exponential since the first guacamole product hit the market in 1997. It may be that PEF just needs to "find its guacamole" – that first highly successful product.

REFERENCES

[1]Barbosa-Canovas, G., Gongora-Nieto, M., Pothakamury, U., and Swanson, B. 1999. Preservation of Foods with Pulsed Electric Fields. Academic Press.

[2]Barbosa-Canovas, G., Tapia, M., and Cano, M. 2004. Novel Food Processing Technologies. C.H.I.P.S.

[3]Buckow, R., Ng, S., and Toepfl, S., 2013. *Pulsed Electric Field Processing of Orange Juice: A Review on Microbial, Enzymatic, Nutritional, and Sensory Quality and Stability.* Comprehensive Reviews in Food Science and Food Safety, Vol 12.

[4]Clark J. 2006. *Pulsed Electric Field Processing.* Food Technology. 60: 66-67.

[5]Ganeva, V, Galutzov, B. 2015. *Pasturization of apple juice by pulsed electric fields and effects on quality properties,* presented at the 1st World Congress on Electroporation, Portoroz, Slovenia

[6]Gaudreau, M., Hawkey, T., Kempkes, M., and Petry, J. 2008. *PEF Systems for Food and Waste Streams.* Proceedings of the 2008 Power Modulator Conference.

[7]Grimi, N., Turk, M., Vorobiev, E. 2015. *Pulsed Electric Field in Juice Processing: Quantitative, Qualitative, and Economical Aspects,* presented at the 1st World Congress on Electroporation, Portoroz, Slovenia

[8]Kempkes, M., Reinhardt, N., and Roth, I. 2012. *Enhancing Industrial Processes by Pulsed Electric Fields. Proceedings* of the 2012 Bio & Food Electrotechnologies Conference.

[9]Mathys, A. 2012. *Alternative Processing Technologies for Natural and Fresh Food Products*, European Symposium on Food Safety

[10] Min S., Jin T., and Zhang Q. 2003. *Commercial Scale Pulsed Electric Field Processing of Tomato Juice. Journal of Agricultural and Food Chemistry.* 51: 3338-44.

[11] Raso J. and Heinz V. 2007. Pulsed Electric Fields Technology for the Food Industry. Technical University of Berlin.

[12] Redondo, L. and Pereira, M. 2015. *Application of pulsed electric fields for the apple juice industry*, presented at the 1st World Congress on Electroporation, Portoroz, Slovenia

[13] Sampedro, F., McAloon, A., Yee, W., Fan, X., Zhang, Q.H., and Geveke, D.J. 2013. *Cost Analysis of Commercial Pasteurization of Orange Juice by Pulsed Electric Fields.* Innovative Food Science and Emerging Technologies. 17 : 72-78.

[14] Sperber, B. *Making Pasteurization'Cool'.* Plant Operations Magazine, May 2011.

[15] Toepfl, S. 2006. *Pulsed Electric Field (PEF) for Permeabilization of Cell Membranes in Food and Bioprocessing - Applications, Process and Equipment Design and Cost Analysis.* PhD Thesis. Technical University of Berlin.

[16] Toepfl, S. 2015. *Industrial Applications of PEF Processing*, presented at the 1st World Congress on Electroporation, Portoroz, Slovenia.

[17] USDA, Center for Food Safety and Applied Nutrition, 2000. *Kinetics of Microbial Inactivation for Alternative Food Processing Technologies: Pulsed Electric Fields*, 2000.

[18] Yeom, H.W., Streaker, C., Zhang, Q.H., and Min, D., 2000. *Effects of Pulsed Electric Fields on the Activities of Microorganisms and Pectin Methyl Esterase in Orange Juice. Journal of Agricultural and Food Chemistry.*

[19] Zhang, Q.H., 2008. *A Pulsed Electric Field Case Study.* Presented at the Non-Thermal Processing Symposium, Madrid, Spain.

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Mr. Kempkes has seven patents, and is the author of numerous papers on radar transmitters, high voltage electronics, and PEF systems and applications.