EUROPEAN ROADMAP OF PROCESS INTENSIFICATION

- TECHNOLOGY REPORT -

TECHNOLOGY: INDUCTION AND OHMIC HEATING

TECHNOLOGY CODE:

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1. Technology

1.1 Description of technology / working principle

(Feel free to modify/extend the short technology description below)

Inductive Heating is a process wherein electric currents are induced within the food or other material due to the presence of oscillating electromagnetic fields generated by electric coils in the vicinity of this material; with the primary purpose of heating the said material. Such fields may be generated in various ways, including the use of the flowing food material as the secondary coil of a transformer. Inductive heating may be distinguished from microwave heating by the frequency (specifically assigned in the case of microwaves), and the nature of the source (the need for coils and magnets for generation of the field, in the case of inductive heating, and a magnetron for microwave heating).

Information on inductive heating is extremely limited. A project was conducted in the mid-1990's at the Technical University of Munich, under sponsorship from the Electrical Power Research Institute. However, to the best of our knowledge, no data were published relative to microbial death kinetics under inductive heating. Thus the succeeding discussion will principally focus on ohmic heating.

Ohmic heating, also known as Joule heating, electroconductive heating, or direct electrical resistance heating, involves the passage of electric current through a material for the purpose of heating it. James Prescott Joule, in 1840, recognized that an electric current passing through a material generated heat within it. The heat generation is more uniform than with microwave and induction heating. Ohmic heating necessarily involves electrodes that contact the product to create a continuous electrical circuit.

The rate of heat generation within the material is proportional to the square of the electric field strength (calculated approximately as the applied voltage divided by the distance between electrodes) times the electrical conductivity of the material. Most foods and biomaterials; indeed most aqueous-based media, will allow the passage of some current, and consequently may be considered conductors. Even low-electrical conductivity materials may be heated rapidly, provided the electric field strength is high enough; indeed most municipal water supplies may be readily heated with this technology. The only materials for which ohmic heating will not work are pure insulators, as for example pure fats and oils, or deionized water.

Since heat is generated throughout the material, materials that have a uniform spatial distribution of electrical conductivity tend to heat uniformly throughout their volume. This approach offers many advantages over conventional heating methods, where heat transfer limitations and material thermal conductivity plays a significant role. Since ohmic heating does not rely on equilibration with a heat source, there is theoretically no upper temperature limit to which a material may be heated ohmically. In practice, however, practical limits are imposed by heat losses to the surroundings, and phase transitions within materials.

In the later part of the nineteenth century, a number of patents were filed on ohmic heating of flowable materials. In the late 1920s and early 1930s, electric pasteurization of milk was practiced in six states in the United States.

1.2 Types and “versions”

(Describe the most important forms/versions of technology under consideration, including their characteristic features, differences and similarities)

Ohmic heating is an emerging technology, and its commercial exploitation is at a relatively early stage. Currently, most versions of the technology involve simply the heating of materials, either flowable or stationary, for purposes of processing. For example, ohmic heating is currently used in thermal pasteurization of sliced fruit within syrup, destined for storage in aseptic packages; other applications include the treatment of hospital water supplies, and for materials processing and as manufacturing processes.

Perhaps the most promising, yet challenging application for ohmic heating is the continuous sterilization of low-acid foods containing particulates (e.g. soups with vegetable pieces, or stews). For a number of years, industry has been interested in processing foods in continuous flow, due to the potential benefits to be gained by aseptically packaging the product (lower cost than conventional canned food). If successfully implemented, products could be treated in continuous flow by high-temperature-short-time processing, yielding quality improvement. However, in realty, such quality improvement has been difficult to achieve using conventional heat exchangers, due to slow heat transfer through interfaces and solid objects. Ohmic heating may potentially bypass these limitations, and has been shown in pilot scale trials to produce a superior quality product.

Ohmic heating also has a variety of other effects that are only now being understood, and have not been sufficiently exploited. In particular, ohmic heating has been shown to enhance mass transfer effects in cellular materials. In particular, the pretreatment of food and biomaterials by ohmic treatment has been shown to accelerate the subsequent drying and extraction rates from the material. Fermentation processes may be accelerated by the application of appropriate electric fields. These processes principally exploit the effects of the electric field, and only occasionally the heating effect; consequently, they are termed as Moderate Electric Field (MEF) processes. The advantage of MEF processes is the use of a relatively mild voltage, as compared to the better-known but extremely high-voltage Pulsed Electric Field (PEF) or High Electric Field Pulses (HELP) processes. PEF/HELP processes also permeabilize tissue, but require investment in high voltage systems, with major operator safety questions. By contrast, MEF processes do not typically require high voltages of the range involved with PEF/HELP.

MEF processes have not been hitherto exploited, and represent a significant opportunity for process improvement.

1.3 Potency for Process Intensification: possible benefits

(In Table 1 describe the most important documented and expected benefits offered by the technology under consideration, focusing primarily on energy; CO_2 emission and costs, providing quantitative data, wherever possible. Add other benefits, if needed).

Table 1: Documented and expected benefits resulting from technology application

Benefit	Magnitude	Remarks
Energy use	No specific data available. If hydroelectric or wind power is available, the savings are major.	Fossil-fuel based electricity is more expensive than the fuels themselves; however, much is gained because electricity is much more efficiently transmitted over long distances. Further, at the point of consumption, the efficiency of ohmic heating is in the range of 96%; far greater than other competing electrothermal technologies such as microwave heating (which has about 50-60% efficiency). Conventional heating systems require steam, which typically must be produced on site, with major heat losses from boilers, so a satisfactory comparison has yet to be conducted.
CO_2 emission	Depends on electricity generation source. Local on-site CO_2 emissions are lower than conventional processes	If electricity is produced from hydroelectric or wind energy sources, CO2 emissions are negligible. Even when fossil fuels are used for electricity generation, the CO2 generation site is more localized than with conventional process industries, where steam is used. Steam boilers powered by fossil fuels produce CO2 at the boiler site. CO2 production for electric power generation occurs at the site of processing. It is not known how this type of CO2 generation compares with a more distributed pollution from smaller boilers at many processing plants
Cost	Costs of ohmic heaters are rapidly decreasing as more manufacturers enter the market and commercial installations increase.	Cost of equipment per kW of rated power: 1993: US$ 133,600 2002: US$ 12,500 2007 (estimated): US$ 4,200 (Sources: industry contacts and personal communication)
Better product quality	No data available	Rapid and uniform heating results in improved product quality, as shown by industry and pilot plant trials. While no specific objective data are available, this is information available by personal communication. Ohmic heating can result in more uniform heating than microwave heating.
Fouling prevention	Ph.D. Thesis of Ayadi. (Henri Poincaré University, Nancy, France)	Data of Ayadi indicates that protein fouling can be slowed during milk processing. One commercial installation was used in New Jersey (USA) to process liquid egg. This facility was based on a design that was claimed to prevent fouling. It is unclear however, it very high protein products; e.g. concentrated milk, can be processed without fouling.
Safety	No data available	It is possible to detect in advance, any solid pieces that may not heat satisfactorily under ohmic heating; thus it may be possible to take pre-emptive action by diverting such components prior to processing.

1.4 Stage of development

Ohmic heating is in an early stage of development. Several heater designs are currently available in the marketplace, but the processes of design and optimization are in their infancy. Currently, there are four or five manufacturers of commercial ohmic processing equipment worldwide two in Italy, one in France, one in the UK and one in the United States.

Despite the relatively early development stage, there are over 70 processing lines in operation in Europe, mostly for processing sliced fruit products.

2. Applications

2.1 Existing technology (currently used)

(Describe technology (-ies) that are conventionally used to perform the same or similar operations as the PI-technology under consideration)

Most commercial processing operations use heat exchangers to materials.   This consists of a medium that exchanges heat (via a contact wall) with the product. Such systems have heat transfer limitations because heat must flow from the medium through the system walls to the product. If the product is a solid-liquid mixture, heat must flow from the fluid to the solid phase, and then through the solids. Since this takes time, such devices need to be made large enough to ensure that heat transfer occurs. Further, the highest temperature that can be achieved in such systems is the medium temperature.

Also in use for selected applications is microwave heating (and also radiofrequency heating). However, widespread application of microwaves for sterilization or pasteurization have been limited due to low thermal efficiency and nonuniformity of heating.

2.2 Known commercial applications

(Is the technology broadly applied on commercial scale? In which process industry sectors is the technology most often applied: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? What is the estimated number of existing applications? In Table 2 provide the most prominent examples of realized applications and provide their short characteristics)

Table 2. Industrial-scale applications of the Technology (existing and under realization)

Sector	Company - Process/Product name/type	Short characteristic of application	Production capacity/ Plant size	Year of application	Reported effects
Materials processing	Confidential	Heating of activated carbon filters	Unknown	Unknown	No data available
Water disinfection	Confidential	Inactivation of legionella in water supply	Unknown	~2005?	No data available, reported effective
Food processing	Emmepiemme	Pasteurization of sliced fruit in syrup	Unknown	Unknown	No data available
Food processing	Simaco	Pasteurization of solid-liquid food mixtures	Unknown	Unknown	No data available
Food processing	Raztek	Pasteurization of liquid egg products	Unknown	1993-96(?)	No data available, facility no longer operational
Food processing	Capenhurst	Fruit product processing	Unknown	Unknown	

2.3 Known demonstration projects

(Are there any demonstration projects known related to the technology under consideration? In which process industry sectors are those projects carried out: large volume chemicals – specialty chemicals & pharma – consumer products – ingredients based on agro feedstocks? In Table 3 provide the short characteristics of those projects.)

Table 3. Demonstration projects related to the technology (existing and under realization)

Sector	Who is carrying out the project	Short characteristic of application investigated, including product name/type	Aimed year of application	Reported effects
Food processing	The Ohio State University (Sudhir Sastry)	Safety of a military ration (chicken chow mein) processed using ohmic heating, being investigated with funding from the USDA National Integrated Food Safety Initiative	2008	
Food processing and packaging, reheating	The Ohio State University (Sudhir Sastry	Development of a reusable package with built-in electrodes to allow food warming and subsequent containment and sterilization of waste. This is being developed with funding from NASA for their long-duration Mars mission.	2008	Package and heater enclosure have been developed and are under test.

2.4 Potential applications discussed in literature

(Provide a short review, including, wherever possible, the types/examples of products that can be manufactured with this technology)

Meat products

Ohmic heating has shown much promise for meat products. Research on this topic was conducted in Finland in the 1970s. In the 1990s, the French Meat Institute Development Association (ADIV) and Électricité de France (EDF) conducted research on cooking of liver pâté and hams. Recently Piette and Brodeur (2001) found positive results for cooking of sausages and ham in batch operations. Farid and co-workers at the University of Auckland, New Zealand, have developed an ohmic cooking process for hamburger patties which reduced the time by one half. Ozkan et al. (2004) reported that ohmic cooking did not affect the quality of hamburger. Meat thawing has been explored by Wang et al . (2002).

Fruit and vegetable products

Fruit products comprise a major market segment for ohmic processing, and have achieved commercial application in Europe. Some recent work has been published by Castro et al (2003), which showed that the technology was effective in achieving rapid heating for strawberry products. A number of other studies have shown that the technology has potential as a pretreatment resulting in accelerated drying (Wang and Sastry, 2000), improved juice expression (Wang and Sastry, 2002), accelerated extraction (Sensoy and Sastry, 2004a), and blanching (Sensoy and Sastry, 2004b). Other studies have shown that ohmic precooking can improve the texture of processed vegetables (Eliot et al., 1999, Eliot and Gouilleux, 2000).

Seafood products

Ohmic heating has been found useful for processing restructured fish (surimi) products. An improvement in surimi gel quality was achieved with ohmic heating (Yongsawatdigul et al., 1995; Yongsawatdigul and Park, 1996). It was found that ohmic heating was an effective means of inactivating proteases (which could otherwise cause texture degradation) without overheating. Thawing of frozen seafood blocks has also been attempted (Roberts et al., 1998).

Vending and dispensing applications

Applications exist for vending and dispensing, since ohmic heaters may be made in small sizes (Herrick et al., 2000,2003).

3. What are the development and application issues?

3.1 Technology development issues

(In Table 4 list and characterize the essential development issues, both technical and non-technical, of the technology under consideration. Pay also attention to "boundary" issues, such as instrumentation and control equipment, models, etc.) Also, provide your opinion on how and by whom these issues should be addressed)

Table 4. Technology development issues

Issue	Description	How and by whom should be addressed?
Design of novel process equipment and systems	Ohmic heating has the capability of revolutionizing a number of process operations. A large variety of different types of equipment are needed for a variety of applications. Current equipment manufacturers have taken a conservative stance, and are unwilling to invest in development of new technologies as long as current equipment can be sold.	Governments and/or venture capitalists. Availability of venture capital to enable entrepreneurs to enter this arena
Research on further applications of this technology	Although its potential has been demonstrated, ohmic heating technology does not have the high research profile of technologies such as microwave, radiofrequenty, high pressure and pulsed electric field processing, both of which are potentially far more expensive	More governmental and industry funding for ohmic and moderate electric field processing

3.2 Challenges in developing processes based on the technology

(In Table 5 list and characterize the essential challenges, both technical and non-technical, in developing commercial processes based on the technology under consideration. Also, provide your opinion on how and by whom these challenges should be addressed)

Table 5. Challenges in developing processes based on the technology

Challenge	Description	How and by whom should the challenge be addressed?
Ensuring the safety of ohmically sterilized foods	Most commercial applications of ohmic heating are continuous flow systems. When processing solid-liquid mixtures, the solids temperature cannot be measured; thus modeling is necessary to estimate the coldest location in the product, to ensure that the heat treatment is sufficient to ensure a commercially sterile product (i.e. one that is free of *Clostridium botulinum* spores, which might cause food poisoning if consumed). Further, microbiological testing must be done to verify such models.	Currently, this is being addressed at Ohio State (Sastry lab) with support from USDA (see demonstration projects in Table 3 above.

4. Where can information be found?

4.1 Key publications

(Provide the list of key publications in Table 6)

Table 6. Key publications on the technology

Publication	Publication type (research paper/review/book/ report)	Remarks
Castro, I., Teixeira, J.A., and Vicente, A.A. 2003. The influence of field strength, sugar and solid content on electrical conductivity of strawberry products. J. Food Proc. Engr. 26:17-29	Research paper	Fruit products
Eliot, S.C., Gouilleux, A., and Pain, J-P. 1999. Processing of cauliflower by ohmic heating : influence of precooking on firmness. J. Sci. Food Agriculture. 79:1406-1412	Research paper	Vegetable products
Eliot, S.C. and Gouilleux, A. 2000. Application of the firming effect of low-temperature, long-time pre-cooking to ohmic heating of potatoes. Sciences des Aliments, 20:265-280.	Research paper	Vegetable products
Orangi, S., and Sastry, S.K., and Li, Q. 1998. A numerical investigation of electroconductive heating of solid-liquid mixtures. Int. J. Heat Mass Transfer 41(14):2211-2220.	Research paper	Modeling of continuous sterilization
Ozkan, N., Ho, I., and Farid, M. 2004. Combined ohmic and plate heating of hamburger patties: quality of cooked patties. J. Food Engr.	Research paper	Meat

63(2):141-145.		
Palaniappan, S., and Sastry, S.K. 1991. Electrical conductivity of selected solid foods during ohmic heating. J. Food Proc. Engr. 14:221-236.	Research paper	Addresses the role of electrical conductivity
Palaniappan, S., and Sastry, S.K. 1991. Electrical conductivity of selected juices: influences of temperature, solids content, applied voltage and particle size. J. Food Proc. Engr. 14:247-260.	Research paper	Electrical conductivity of liquid foods
Piette, G., and Brodeur, C. 2001. Ohmic cooking for meat products: the heat is on! Le Monde Alimentaire 5(6):22-24.	Research paper	Meat
Roberts, J.S., Balaban, M.O., Zimmerman, R., and Luzuriaga, D. 1998. Design and testing of a prototype ohmic thawing unit. Computers & Electronics in Agriculture 19(2):211-222.	Research paper	Seafood thawing
Salengke, S., and Sastry, S.K. 2007. Models for ohmic heating of solid-liquid mixtures under worst-case heating scenarios. J. Food Engr. 83:337-355.	Research paper	Addresses safety of ohmically processed food
Salengke, S., and Sastry, S.K. 2007. Experimental investigation of ohmic heating of solid-liquid mixtures under worst-case heating scenarios. J. Food Engr. 83:324-336	Research paper	Addresses safety of ohmically processed food
Sastry, S.K. 1992. A model for heating of liquid-particle mixtures in a continuous flow ohmic heater. J. Food Proc. Engr. 15(4):263-278.	Research paper	Modeling of continuous sterilization
Sensoy, I., and Sastry, S.K. 2004. Extraction using moderate electric fields. J. Food Sci. 69(1):FEP7-13.	Research paper	Fruit/vegetable extraction
Sensoy, I., and Sastry, S.K. 2004. Ohmic blanching of mushrooms. J. Food Proc. Engr. 27(1):1-15.	Research paper	Fruit/vegetable
Wang, W-C., and Sastry, S.K. 2000. Effects of thermal and electrothermal pretreatments on hot air drying rate of vegetable tissue. J. Food Proc. Engr. 23(4):299-319.	Research paper	Fruit/vegetable
Yongsawatdigul, J., and Park, J.W. 1996. Linear heating rate affects gelation of Alaska Pollock and Pacific Whiting surimi. J. Food Science 61(1): 149-153.	Research paper	Seafood processing
Yongsawatdigul, J., Park, J.W. and Kolbe, E. 1995. Electric conductivity of Pacific Whiting surimi paste during ohmic heating. J. Food Science 60(5):922-935.	Research paper	Seafood processing

4.2 Relevant patents and patent holders

(Provide the list of relevant patents in Table 7. Under "remarks" provide, where applicable, the names/types of products targeted by the given patent.)

Table 7. Relevant patents

Patent	Patent holder	Remarks, including names/types of products targeted by the patent
Berthou, M., and Laurent, M-H. 1999.	Électricité de France	

Processs for determining the electrochemical behavior of an electrode material and for measuring the interfacial potential drop, method and apparatus for ohmic heating and the application of materials for this use. European Patent 0942629.		
Berthou, M., and Aussudre, C. 2001. Improved device for ohmic heating of fluid, fluid-treating apparatus having the device built-in, and method for treating fluid by ohmic heating. Japanese Patent 2001211825.	Électricité de France	
Herrick, J.P., Sastry, S.K., Clyde, G.F., and Wedral, E.R. 2000. On-demand direct electrical resistance heating system and method thereof. United States Patent 6,130,990.	Nestec S.A.	Food Service
Herrick, J.P., Sastry, S.K., Clyde, G.F., and Wedral, E.R. 2003. On-demand direct electrical resistance heating system and method thereof for heating liquid. United States Patent 6,522,834.	Nestec S.A.	Food Service
Reznik, D. 1998. Apparatus and methods for rapid electroheating and cooling. United States Patent 5,768,472	Raztek	Any electrically conducting flowable material
Reznik, D. 1997. Electroheating of food products using low-frequency current. United States Patent 5,609,900.	Raztek	Any electrically conducting flowable material
Wongsa-Ngasri, P., and Sastry, S. K. 2004. Method and apparatus for peeling produce. US Patent Application. (Pending).	The Ohio State University	Peeling process

4.3 Institutes/companies working on the technology

(Provide the list of most important research centers and companies in Table 8)

Table 8. Institutes and companies working on the technology

Institute/Company	**Country**	**Remarks**
The Ohio State University	USA	Dr. Sudhir Sastry
University of Minho, Braga	Portugal	Dr. Antonio Vicente

5. Stakeholders

5.1 Suppliers and developers

(Provide the list of key suppliers/developers in Table 9)

Table 9. Supplier and developers

Institute/Company	Country	Remarks
The Ohio State University	USA	Dr. Sudhir Sastry and group develop custom ohmic technology and devices
Emmepiemme SRL	Italy	Manufacturer: continuous flow ohmic heaters
Simaco	Italy	Manufacturer: continuous flow ohmic heaters
Alfa-Laval Vicarb	France	Manufacturer: continuous flow ohmic heaters
Capenhurst	UK	Manufacturer: continuous flow ohmic heaters
Raztek	USA	Manufacturer: continuous flow ohmic heaters

5.2 End users

(Describe the existing and potential end-users, other than those already listed in Table 2)

Existing and potential end users include the entire food industry segment that produces canned or sterilized food products; buildings where water supplies need decontamination, other process industries where conductive fluids need to be heated, biochemical process industries. Other segments may include cooking appliance manufacturers and by extension, foodservice establishments and eventually, consumers.

6. Expert's brief final judgment on the technology

(maximum 5 sentences)

Ohmic and moderate electric field technology has outstanding potential, but is currently in an early stage of development. In addition to its heating capability, a number of interesting mass transfer effects add to its attractiveness for processing of cellular materials. Past concerns about electrochemical reactions are increasingly being addressed by improved electrode materials and processes. Further, the cost of these devices is decreasing, and likely highly competitive relative to other competing technologies: e.g. high pressure, pulsed electric fields and microwave heating.