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L 2 OHMIC COOKING OF PROCESSED MEATS - STATE OF THE ART AND PROSPECTS

Gabriel Piette [1], Michel Dostie [2], and Hosahalli Ramaswamy [3]

[1] Agriculture and Agri-Food Canada, Food Research and Development Centre, 3600 Boulevard Casavant West, Saint-Hyacinthe, QC, J2S 8E3 Canada; [2] Laboratoire des technologies électrochimiques et des électrotechnologies d'Hydro-Québec, 600 avenue de la Montagne, Shawinigan, QC, G9N 7N5 Canada; [3] McGill university, Macdonald campus, 21111 Lakeshore Road, Ste-Anne de Bellevue, QC, H9X 1C0 Canada.

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Introduction

Ohmic heating , also called direct resistance heating, is one of the most innovative and promising technologies that have been developed for food processing in the last few decades. It consists in generating heat Q (J) within a food product using the Joule effect, observed when an electrical current of intensity I (A) flows through a product of electrical resistance R (Ω), in an amount defined by the relation $Q = R \cdot I^2$ [eq. 1]. In reality, the first potential applications of ohmic heating for the preservation of foods had been proposed at the end of the 19th century (see review by de Alwis and Fryer, 1990) but it took almost a hundred years before progresses in the control of electrical processes and electrode manufacturing (Simpson, 1980) enabled one to design safe and efficient equipment to process food through direct resistance heating. Commercial implementation of the technology was initiated by APV Systems with the introduction of its ohmic electroheating equipment. As of 1999, four 75 kW units and three 300 kW units were in operation worldwide (Marcotte, 1999), processing a variety of value-added pumpable particulate foods, including prepared meals containing meat, such as beef stew. There is no doubt that ohmic heating is going to grow larger in the future and there is virtually no limitation to its use in heat processing of fluid or particulate meat products.

The situation is quite different with solid meat pieces or processed meats. Even though the forced flow of electrical current through solid meat products has been proposed as a cooking method as early as1882 (Fowler A, 1882), the concept has not led to commercial applications in the meat sector, yet. Earlier attempts to develop an industrial equipment for the continuous ohmic cooking of meat emulsions were abandoned (Vanhatalo *et al.*, 1978; Mälkki and Jussila, 1979), due to the difficulty of maintaining steady state cooking during long periods of times. However, the success obtained with liquid and particulate foods has triggered a new interest in ohmic cooking of solid foods, including processed meats (Peyron, 1996; Piette *et al.*, 2000a, b), and the results obtained were promising enough to encourage the private sector to investigate again the continuous cooking of meat pastes by ohmic heating (Anonymous, 2000). The present article reviews our current knowledge on the application of ohmic heating for processed meat cooking and evaluates the prospects for commercial application of the technology in the near future.

Recent investigations on ohmic cooking of meat emulsions

At least 14 US patents have been filed and accepted between 1937 and 1975 concerning the application of ohmic heating to meat products (de Alwis and Fryer, 1990). Most of them described processes to rapidly heat frankfurter sausages at home or in vending machines and only a few explored the use of ohmic heating as a processing tool to cook raw products (Neumann, 1961; Luijerink, 1962). A Russian study is also worth mentioning in which skinless frankfurter sausages were cooked by a combination of ohmic and traditional smokehouse heating (Ruchkovski *et al.*, 1972, cited by de Alwis and Fryer, 1990). All these earlier reports undoubtedly contributed useful knowledge to the field of processed meat cooking by ohmic heating, but only results of the most recent studies will now be presented in some details because they best illustrate the questions addressed in the present article.

In the mid-seventies, a study was undertaken at the Technical Research Centre of Finland, aiming at developing a continuous ohmic cooking process for meat and fish preparations, with the intention of producing skinless frankfurter style sausages, hence eliminating the need for post-cooking peeling (Y Mälkki, personal communication). A finely comminuted commercial sausage emulsion (ca. 66% water, 14% fat, 9 % protein, and 2% salt), prepared with beef, pork, emulsified pork skin, potato starch, milk powder, water and additives, was continuously pushed through a 3 m long 21 mm internal diameter PTFE (Teflon) tube, at a speed of 1.0-1.5 cm·s^{-1} (Mälkki and Jussila, 1979). The tube was divided into three separate and consecutive ohmic heating sections, connected to separate power generators (alternative current, 50 Hz) which delivered electrical current (100-200 V, 0.4-1.5 A) to the flowing product through cylindrical graphite electrodes (Vanhatalo *et al.*, 1978). A water-jacketed heat exchanger, located between the two first ohmic heating sections, was added to compensate for heat losses through the tube walls, which were not insulated.

In the early nineties, exploratory work was carried out at ADIV (Clermont-Ferrand, France), in collaboration with the French power corporation EDF-GDF, with the general objective of evaluating the potential of ohmic heating to cook and/or sterilize various meat preparations. Cooking cells similar to those described by Zuber (1999) were used, consisting of open plastic moulds (ca. 20 cm long, 12 cm wide, 10 cm high), at both extremities of which were inserted flat stainless steel electrodes (ca. 10 cm wide, 10 cm high) connected to a 5 kW, 50 Hz AC generator. The moulds could hold ca. 2 kg of raw product and were used, in particular, to investigate static ohmic cooking of liver paste, country-style pâté (traditional French meat loaf), and low-injection cooked ham, prepared according to standard commercial formulations (Peyron, 1996).

In the late nineties, scientists at the Food Research and Development Centre (Saint-Hyacinthe, Canada) initiated an industry-government-academia collaborative study aiming at gathering all the scientific data pertaining to processed meat cooking by direct resistance heating, whether kinetic, qualitative, energetic, or microbiological in nature, that would be required to subsequent successful development of processing equipment. Static prototypes were used, consisting of 30 cm long Nylon or Teflon tubes (7.5 cm ID, 0.64 cm wall thickness) in which a basic raw bologna emulsion or ham paste, containing only meat, water, and curing ingredients (NaCl, $NaNO_2$, sodium erythorbate; no fillers, binders or spices) was pushed with a vacuum stuffer, and at both ends of which were inserted 7.5 cm diameter flat circular Titanium electrodes, connected to a 60 Hz AC power

Finally, following the work done at ADIV and at the EDF-GDF Research Centre in Les Renardières (C Aussudre, personal communication), an automated industrial prototype for heating/cooking viscous food has been designed and is presently tested by the French company Tecnal, in collaboration with EDF-GDF (Anonymous, 2000). It consists of a large diameter plastic tube (ca. 1.5 m long), through which meat emulsions can be pushed, equipped with what appears to be circular electrodes. Claims are made that the equipment can heat meat emulsions or pastes to 50-60°C at a processing rate of 400 kg·h^{-1} or cook them to 90-95°C at a rate of 200 kg·h^{-1}.

Suitability of commercial meat formulations for ohmic cooking

The amount of energy Q (J) required to heat a mass m (kg) of product is directly related to the product specific heat c_p (J·kg^{-1}·°C) and the extent of temperature increase ΔT(°C), according to the equation $Q = m{\cdot}c_p{\cdot}\Delta T$ [eq. 2]. The current intensity I (A) and voltage (V) needed to deliver this energy can be derived from the basic electrical equations $Q = |J|^2{\cdot}\sigma^{-1}$ [eq. 3] and $Q = E^2{\cdot}\sigma$ [eq. 4], in which J is the current density (A·m^{-2}), σ is the electrical conductivity (S·m^{-1}), and E is the potential gradient (V·m^{-1}). Irrespective of the electrical conductivity value, it is always possible, theoretically, to provide a food with enough electrical power to generate the targeted temperature increase ΔT, but this will require using increasingly large current densities or increasingly large potential gradient when electrical conductivity values become very large or very small, respectively (see eq. 3 and eq. 4). In reality, various considerations related to safety, cost, and product quality limit the extents of potential gradient and current density that can be used in practice. As a result, ohmic heating is only possible between a certain range of electrical conductivity values (ca. 0.01 S·m^{-1} to 10 S·m^{-1}), and it works optimally in the range of 0.1 to 5 S·m^{-1}.

As observed with other foods (Yongsawatdigul *et al.*, 1995), the electrical conductivity values of processed meats have been shown to increase with increasing temperature and increasing salt content, and to decrease with increasing fat levels (Curt and Eynard, 1995; Piette *et al.*, 2000b). More important is the fact that, given salt and fat contents typical of commercial formulations (5-30% fat, 1-2.5 % salt), the σ values for processed meats always remain between ca. 1 and 7 S·m^{-1} within the range of temperatures normally encountered during cooking (Figure 1). In this respect, processed meats in general are therefore well suited for ohmic cooking.

Heating patterns, heating rate, and flow throughput

In ohmic cooking, heating of a meat emulsion does not involve convective/conductive heat transfer phenomena. Instead, heating is related to two important characteristics of the emulsion, i.e.: a.) Its permeability to the free circulation of electrons (electrical conductivity σ), and b.) Its capacity (specific heat c_p) to store the energy generated by the electron flow (eq. 1), resulting in a temperature increase. In practical terms, the rate at which a product heats at any given moment in time t (s), at which temperature is T_t (°C), depends on the rate at which electrical energy is supplied to the cooking unit (power P, expressed in J·s^{-1}) and on the values σ_{Tt} and c_{pTt} of the electrical conductivity and specific heat at that precise moment. This is well illustrated in the following paragraphs, in the particular case of batch cooking.

If the power supplied for cooking was supplied at a constant rate (dP/dt) and assuming that heat losses through the cooking cell walls could be minimized enough to become negligible, the rate of heating $dT/dt = (dQ/dt){\cdot}m^{-1}{\cdot}c_p^{-1}$ (from eq.2) would remain constant throughout cooking since dQ/dt is constant (equal to dP/dt), provided m and c_p remain also constant. In reality, however, the specific heat of meat emulsions does increase slightly with increasing temperature, according to the relation $\sigma = 0.0409\ T + 1.3537$ (Piette *et al.*, 2000b; measured on a 2% salt 20% fat bologna emulsion in the range of 5°C to 75°C). The observed increase is ca. 7% and would cause a slight decrease in heating rate between the beginning and end of cooking. The slowing effect of increasing c_p values on cooking rates also exists under conditions of decreasing or increasing power supply, although it may be masked by the greater effect of electrical conductivity changes.

Depending on the processed meat formulation used, changes in electrical conductivity as temperature rises can be considerable (Figure 1). For example, a 2% salt 30%fat bologna emulsion sees its electrical conductivity value increase by 197% between 5°C and 85°C, according to the relation $\sigma = 0.0409 + 1.3537$ (Piette *et al.*, 2000b). Consequently, ohmic heating under conditions of constant current intensity requires less and less voltage as cooking progresses, resulting in a decreasing rate of power supply and causing heating rate to decrease with increasing time. In contrast, cooking under constant voltage causes the current intensity to increase with time, as electrical conductivity increases, resulting in an accelerating rate of power supply and therefore an increasing heating rate.

Technically, the three operating conditions mentioned above (constant power, constant current intensity, and constant voltage) are suitable for ohmic cooking of processed meats (Mälkki and Jussila, 1979; Peyron, 1996; Piette *et al.*, 2000a,b) and they can all be implemented industrially. Cooking at constant power is attractive because it results in a near constant heating rate, but a sophisticated feedback control is required (since both voltage and current intensity vary with time) which may translate into additional equipment cost. Cooking at constant voltage is also attractive for its simplicity but it results in most of the cooking being done below optimal operating conditions, since the chosen voltage is limited to avoid excessive current density values at the end of cooking (Piette *et al.*, 2000b). This is clearly an area in which more research, testing, and development is needed.

In all studies so far, 1-2 kg of product could be cooked to a core temperature of 70-90°C within 5-20 min in a static unit, when submitted to a power intensity of ca. 500-1000 W, corresponding to heating rates in the 0.05-0.2°C·s^{-1} range (Peyron, 1996; Piette, unpublished data). A similar rate, ca. 2.5°C·s^{-1}, was achieved in a continuous cooking unit, when a 40-300 W power was delivered between adjacent electrodes (Mälkki and Jussila, 1979). All experimental ohmic units mentioned above had low production rates of 7-18 kg·h^{-1} but a much larger prototype (200-400 kg·h^{-1}) is already under trial in France (Anonymous, 2000), and production output is expected to be limited only by unit design.

Effects of ohmic heating on processed meat quality

All experimental results available so far suggest that the use of ohmic heating for processed meat cooking is not detrimental to product quality.

Even though they did not investigate *per se* the effects of ohmic cooking on the functional and organoleptic characteristics of the sausages, Mälkki and Jussila (1979) reported that typical Finnish finely emulsified pork and beef sausages cooked by ohmic heating were of good quality with regard to colour, taste, and consistency. Similar results were obtained by Peyron (1996). A jury of 12 specially trained panellists was asked to evaluate the appearance of whole or sliced liver paste prepared by ohmic cooking or in a smokehouse, as well as its aroma, taste, and texture, on an intensity scale. Panellists found little difference between the ohmic and traditional products, and the overall evaluation scores were very similar. Also, aroma profile analysis indicated that all principal aromatic compounds found after smokehouse cooking were also present in products cooked by ohmic heating and that ohmic cooking did not induce the formation of new compounds.

A study in which a simplified bologna formulation (no spices, fillers or binders) was used to evaluate the effects of ohmic cooking on product quality yielded different results. Whereas the colour of bologna was not different when sausages were cooked by ohmic heating rather than in a smokehouse (Table 1; Piette, unpublished data), ohmic-cooked sausages were found significantly (P >0.05) softer (hardness, Table 1) and noticeably blander (results not shown) than traditional sausages (smokehouse), without being judged inferior by untrained panellists. These last findings are not surprising since it is known that the establishment of the product texture is affected by the cooking pattern (Mittal *et al.*, 1987) and that the development of a full cooked meat flavour relies on the generation of flavour precursors by heat (Imafidon and Spanier, 1994) and is, therefore, also dependent on heating pattern. In any case, the fact that the softer texture and blander taste of ohmic-cooked fine emulsions observed in Piette's study have not been reported when complete commercial formulations were used (Mälkki and Jussila, 1979; Peyron, 1996) suggests that the flavour and textural differences caused by ohmic cooking, when any, will be easy to mask.

Because the flow of electrons is reversed 50-60 times per second during cooking, no changes in the concentration of charged ionic species in ohmic-cooked products are expected and, indeed, no meaningful differences in pH was observed between bologna cooked in a smokehouse and bologna prepared by ohmic heating, regardless of the heating rate or final temperature (Table 1). In contrast, oxidation reactions, which are triggered by exchanges of electrons, might have been affected by the alternating electrical field used in ohmic heating. This, however, does not seem to be the case. Although the redox potential of ohmic-cooked bologna was found to be significantly higher than that of smokehouse products (Table 1), the difference was small in magnitude, compared with the differences normally observed between different samples of the same product (Rödel and Scheuer, 1998) or caused by changes in formulation (Rödel and Scheuer, 1999). As a result, no acceleration of fat oxidation during storage (TBA after 10 days at 2°C) was observed in ohmic-cooked bologna, compared with traditional smokehouse products (Table 1).

Intuitively, cooking coarse-ground meat emulsions by ohmic heating is a greater challenge than cooking fine emulsions, because the electrical current is expected to flow through fat particles at a much lower rate than through lean meat portions, resulting in uneven cooking throughout the product mass, with possible consequences on product quality. However, coarse ground country style French pâtés were not found to be different when cooked by ohmic heating (batch process) rather than in a smokehouse(Peyron, 1996), indicating that heat transfer by conduction, during or after ohmic cooking, corrects the potential quality problems related to uneven current flow. As good product quality was also reported for batch ohmic heating of whole muscle products (low-injection hams; Peyron, 1996), it is reasonable to assume that ohmic cooking can be applied successfully to most processed meat types, at least in batch.

Food safety considerations

In traditional smokehouse cooking, a product is considered to be safe if its coldest point has reached a regulatory target temperature at the time when cooking is interrupted and cooling initiated. Normally, the coldest point is assumed to be located at the geometrical centre of the product, and the target temperature is generally fixed at ca. 70°C. This is called the "end-point temperature" concept. It is the basis of many processed meat cooking regulations worldwide and has been successful in ensuring that known pathogenic contaminants are inactivated during cooking. However, it does not enable one to quantify the extent of bacterial inactivation actually achieved during cooking.

Appreciating the safety status of a cooked product can be further refined by use of pasteurization values. Knowing the changes in temperature occurring at all time during an actual cooking cycle, in a specific portion of the product, it is possible to calculate the heating time at a constant reference temperature (T_{ref}, generally chosen as 70°C for meat cooking) that would yield the same bactericidal effect. This time is called pasteurization value (Pv_{Tref}^{z}, expressed in minutes), it depends on the reference temperature selected, and it is specific to a reference microorganism of known temperature sensitivity (z value, expressed in °C). The actual amount of cells inactivated, expressed in $\log_{10}$ CFU·g^{-1}, can then be obtained by dividing Pv_{Tref}^{z} by the thermal decimal reduction time of the selected reference organism at the reference temperature (D_{Tref}, in min).

Because of its unusual heat resistance in the range of temperatures typical of cooking (z = 10°C; $D_{70°C}$ = 2.95 min), *Enterococcus faecalis* is generally chosen as the organism of reference, and pasteurization values ($Pv_{70°C}^{10°C}$) between 40 and 100 min, measured at the product core, are generally recommended for processed meat cooking (Mekhtiche and Martin, 2001). Pasteurization values are not used for regulatory purposes in North America at the present time, but some European countries enable product manufacturers to demonstrate the safety of cooking processes by use of either a target $Pv_{70°C}^{10°C}$ value or a target end-point temperature. The question of whether cooling should be included or not for calculation of pasteurization values is still debated, but cooling does contribute to the bactericidal effect until the temperature of 55°C is reached, albeit to a smaller extent than cooking.

The situation is quite different in ohmic cooking for three reasons. Firstly, there is no geometrically defined coldest point *per se*. In general, the spatial temperature distribution during batch cooking of bologna sausage is homogeneous, with a variation coefficient of 2.2°C at 70°C (Piette *et al.*, 2000b). Local differences in temperature do exist, however, and some product portions appear to heat faster or slower than the remaining portions (Piette *et al.*, 2000a). This is likely due to local differences in product composition or to the presence or air bubbles in contact with the temperature probes. As a result, differences of up to 7°C have been measured between the hottest and coldest points at the end of cooking (70°C). Even though these differences are expected to be eliminated rapidly by heat conduction, after the flow of current is interrupted, additional research is needed to evaluate if the presence of colder spots during ohmic cooking of processed meats is a real concern and if it has practical implications on the methodology to be used for assessing the process safety.

Secondly, the end-point temperature concept is totally irrelevant in ohmic heating. Because of the short time frame involved, cooking can be completed before any significant bactericidal effect occurs. In effect, pasteurization values $Pv_{70°C}^{10°C}$ are virtually null at the time cooking is interrupted (Figure 2). Therefore cooking to 70°C by ohmic heating does not result in safety and safety must be evaluated by calculating the extent of bacterial inactivation actually achieved, by use of pasteurization values or any other means to be developed. If pasteurization values were to be used, research is needed to collect and measure reliable D and z values (measured in the product itself, with cells of known physiological status) for a large variety of spoilage and pathogenic microorganisms, with a particular care to account for strain variability, with the ultimate objective of finding the most meaningful reference organism. This being said, the safety of ohmic heating *per se* is not in question since increasing the cooking final temperature to 80°C, rather than the usual 70°C, and adding a 5 min holding time prior to cooling are enough to obtain $Pv_{70°C}^{10°C}$ values of 100 min, equivalent to those found in smokehouse cooking (Figure 2; Peyron, 1996). In reality, higher cooking final temperatures can even be used. Non emulsified products such as hams can be cooked to temperatures close to 100°C without loss of quality. As for emulsified products, the absence of a temperature gradient between the outside and inside portions of the product enables one to cook at higher temperatures than in a smokehouse, before emulsion is heat-destabilized.

Thirdly, the relative contribution of cooling to the bactericidal effect is much greater in ohmic cooking than in traditional smokehouse cooking, due to the short duration of cooking. This contribution might be used as a tool to further increase the safety of ohmic-cooked meat products, provided care is taken to ensure rapid cooling between 55°C and 5°C in order to avoid potential pathogen regrowth in this favourable temperature zone.

Energetic benefit of ohmic cooking

In a traditional smokehouse, several operations are successively required to deliver the energy needed for product cooking, with energy losses occurring at each step. A primary source of energy (natural gaz, fossil fuel or electricity) is first used to produce a hot fluid (steam or humid air) that transfers some of its energy to the product surface by convection. Because the transfer is incomplete, aı d to ensure cooking homogeneity, the hot fluid has to be circulated at a fast rate within the smokehouse, and this requires additional energy. Also, it is necessary to maintain a large temperature gradient between the hot fluid temperature and the product core at all times to force heat from the surface to the product core, due to the resistance of the product matrix to heat penetration. This causes the superficial layers of the product being unnecessary overcooked (and thus energy being wasted) when the product core reaches its target temperature for safety. For all the above reasons, the energy efficiency of a modern, well designed and well insulated smokehouse cannot exceed 45% (Freeland Smokehouse, personal communication), and it is often considerably lower in practical industrial conditions.

In contrast, ohmic heating is almost the ideal cooking technology in terms of energy use. Theoretically, all the energy delivered to ohmic cooking units is used to raise product temperature, and energy efficiency values of 90-95% have been reported in the literature (Rice, 1995). Studies involving processed meats, however, have shown considerable heat losses in or through the unit walls (Mälkki and Jussila, 1979; Piette *et al.*, 2000a), or in the air when using open moulds (Peyron, 1996), which lowered energy efficiency to values in the 60-70% range (Piette *et al.*, 2000a). Even under these non optimized conditions, though, the specific energy consumption during ohmic cooking of bologna sausage was found to be only 24-30% (210-258 $kJ \cdot kg^{-1}$) of that typical of smokehouse cooking (859 $kJ \cdot kg^{-1}$; Piette *et al.*, 2000a). Therefore considerable energy savings can be expected when heat losses are controlled, through proper unit design (material selection, wall thickness, efficient insulation).

Potential problems and practical considerations that may limit the application of ohmic heating to processed meat cooking

Mälkki and Jussila (1979) encountered two major problems in their attempts to develop a continuous equipment for ohmic cooking of frankfurter sausages: a.) The small diameter (ca. 2 cm) of the cooking tube resulted in considerable frictions and additional frictions were caused by the surfaces of graphite electrodes becoming fouled with coagulated proteins, possibly due to local overheating (Y Mälkki, personal communication). These frictions resulted in the sausage surface being unusually rough, which was seen as a problem for consumer acceptance. In addition, frictions hindered the establishment of plug flow and caused heterogeneous cooking conditions. Friction problems are expected to become smaller as the tube diameter increases, but no attempt was made to verify if the results obtained under these new conditions would be acceptable; b.) The presence of air bubbles or vacuum space within the emulsion mass was also found to be a problem, which caused local overheating and water separation from the emulsion, leading to increasing heterogeneity in heating, until the product became unacceptable. Preparing and pumping the emulsion under vacuum improved the situation but the research was interrupted before establishing whether a critical air bubble size existed, below which no uneven heating would occur.

Whether the above problems associated with the continuous ohmic cooking of meat emulsions can be solved is not known but unpublished information suggests that the challenge has not been resolved since the continuous ohmic cooker for viscous food designed by EDF-GDF and Tecnal is actually used in a discontinuous mode for meat emulsion cooking (C Aussudre, personal communication).

In contrast, no unsoluble problem has been identified when ohmic heating is used for batch cooking of processed meats. Heat losses through the unit walls (Piette *et al.*, 2000a) or from the product top surface (open mould cooking; Peyron, 1996) have been reported, resulting in the product surface being undercooked, compared to the core. This, however, does not result in substantial quality loss as conduction phenomena cause a temperature equilibration within the product mass, during and after cooking. Moreover, results obtained by Piette *et al.* (2000a; unreported data) suggest that heat losses can be nearly eliminated by design alterations of the cooking unit.

A potentially more serious problem was encountered by Peyron (personal communication). Stainless steel electrodes used in their experiments became corroded in contact with the sodium chloride and contaminated the products with minute amounts of metal. A solution was later found by EDF-GDF scientists by using a new material X of undisclosed composition for the making of the electrodes (C Aussudre, personal communication) and by keeping current density well below 4 000 $A \cdot m^2$.

Conclusions and final thoughts

It is clear from the above review that ohmic heating has some unique characteristics which make it an interesting technology, able to considerably shorten cooking time for processed meats, while yielding quality and safe products, at a fraction of the energy expense typical of traditional smokehouse cooking.

Whereas the use of ohmic heating for batch cooking of processed meats is already technically possible, the adaptation of the concept to continuous cooking is considerably more challenging and the problems faced may not be easily solved. This leaves us with the question of how best put ohmic heating to use in processed meat cooking in the near future. Is it possible to design batch equipment with a throughput large enough to become economically viable, and simple enough to operate to be accepted by industry? Only the future will tell.

Interestingly, the problems associated with the continuous application of ohmic heating in processed meat cooking, with the exception of electrode corrosion, are not due to the use of electricity. Rather, they are generic problems related to the fact that cooking occurs very rapidly, within the product mass. In this respect, similar difficulties are expected in the development of other continuous fast cooking processes, such as that based on radio-frequence heating.

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Data

Table 1: Qualitative comparison of bologna sausages cooked by ohmic and smokehouse heating

Cooking cycle: rate / end point (°C · min⁻¹ / °C)	L*	a*	b*	Hardness (N)	pH	Eh (mV)	Drip loss (%)	TBA (mg malon-aldehyde · kg⁻¹)
Control [1]	76.4 ± 0.6cd [2]	6.7 ± 0.3a	11.2 ± 0.6b	35.3 ± 6.1a	6.1 ± 0.1bc	154 ± 11d	0.8 ± 0.3ab	0.13 ± 0.04b
3.9 / 70	77.1 ± 1.5a	6.7 ± 0.9a	11.9 ± 0.5ab	29.4 ± 3.6c	6.1 ± 0.0bc	174 ± 19b	0.6 ± 0.2ab	0.14 ± 0.00ab
5.6 / 70	76.8 ± 0.4b	6.7 ± 0.6a	11.6 ± 0.6b	28.5 ± 3.3c	6.1 ± 0.0cd	164 ± 23c	0.5 ± 0.0b	0.18 ± na [3]
5.6 / 75	76.6 ± 0.6bc	6.4 ± 0.2b	11.5 ± 0.2b	31.4 ± 2.9b	6.2 ± 0.0ab	162 ± 3c	0.7 ± 0.2ab	0.14 ± 0.03ab
5.6 / 80	76.3 ± 0.5d	6.8 ± 0.6a	11.8 ± 0.5ab	31.4 ± 4.2b	6.2 ± 0.0a	181 ± 10a	0.8 ± 0.2ab	0.12 ± 0.01b
10.3 / 70	76.3 ± 0.5d	6.7 ± 0.6a	11.9 ±0.3ab	28.3 ±3.5c	6.1 ±0.1cd	166 ± 19c	0.5 ± 0.2ab	0.15 ± 0.04a

[1] Smokehouse cooking; [2] Mean ± SDE, N ≥3. Means sharing common letters in the same column are not significantly different (P >0.05); [3] Not available.

Figure 1 : Electrical conductivity of ham paste and bologna emulsion as a function of temperature (Piette, unpublished data)

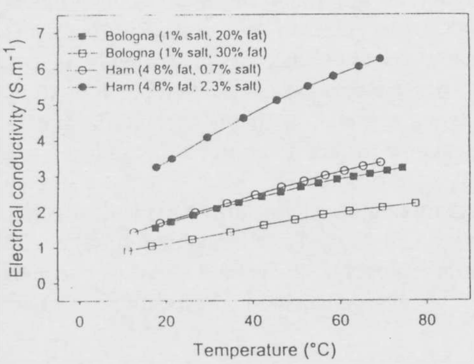
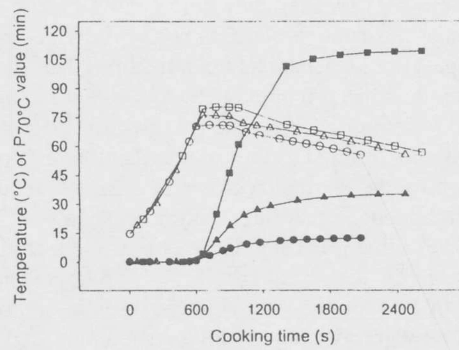


Figure 2: Pasteurization effect of various ohmic cooking cycles



Clear symbols = T°C ; Dark symbols = $P_{70°C}$; Squares = cooking to 85°C
Triangles = cooking to 75°C ; Circles = cooking to 70°C