OHMIC HEATING

Sastry S.K.
Ohio State University, USA

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Contents

Summary

Ohmic heating technology was revived in the 1980s because it showed promise in particulate sterilization. Although that dream has not yet been fully realized, a number of advances have been made regarding the fundamental understanding of this process. This has involved research into fundamental fluid mechanics and heat transfer phenomena, microbial death kinetics, and the monitoring of temperatures and of microbiological and chemical changes within solids.

Ohmic heating can be extended to a wide array of processes and shows great promise for future applications, including the detection of starch gelatinization in solutions and pastes, and as a pretreatment for drying and extraction.

1. Introduction

Georg Ohm, in 1827, was first to outline what is now known as Ohm’s Law, but recognition of the thermal effects of electricity within a conductor was first elucidated by James Prescott Joule in 1840. This resulted in a number of patents on the heating of flowable materials in the latter part of the nineteenth century. The technology has since been revived periodically, having seen industrial application for milk pasteurization in the 1930s, before falling out of favor. In the 1980s, the technology was once again revived, and some industrial applications have resulted, including pasteurization of liquid eggs and processing of fruit products, among others.

The basic principle of ohmic heating is the well-known dissipation of electrical energy into heat, which results in internal energy generation proportional to the square of the electric field strength and the electrical conductivity:

$$\dot{u} = |\nabla V|^2 \sigma \qquad (1)$$

where the electrical conductivity σ is a function of temperature (see *Electrical Properties*). The type of function depends on the material and the method of heating. It has been found that for cellular materials, the electrical conductivity undergoes a significant increase at 70 C and above, with the denaturation of cell-wall constituents. However, when an electric field is applied, cell-wall breakdown occurs at lower temperatures; thus, the increase occurs over a wider range of temperatures (Figure 1).

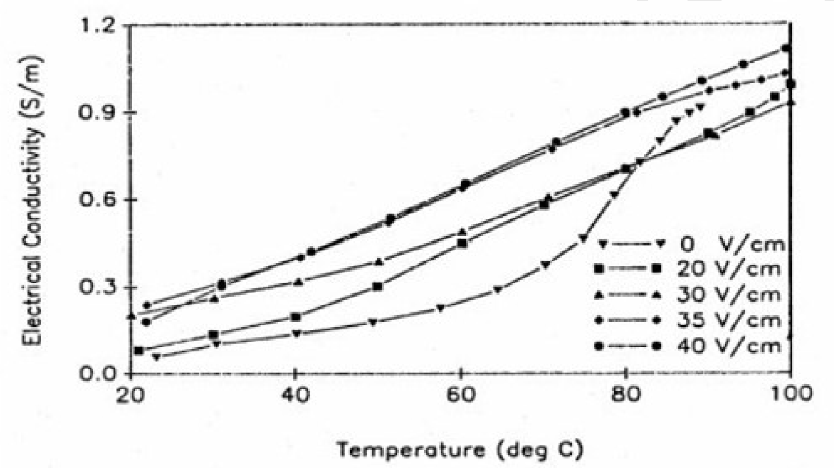

Figure 1. Electrical conductivity of carrot (parallel to stem axis) subjected to various electric field strengths.
Source: Palaniappan and Sastry (1991a)

Above a certain electric field strength, or if the material has been thermally pretreated, the electrical conductivity-temperature curve often becomes linear. Thus,

$$\sigma = \sigma_0 (1 + mT) \qquad (2)$$

Since the electrical conductivity increases with temperature, ohmic heating becomes more effective at higher temperatures.

The electrical conductivity of liquid foods tends to follow a linear trend, regardless of mode of heating. Since no cellular structure exists, the properties remain essentially the same in all liquid foods (Figure 2).

Since the rate of heating is affected by varying either the electric field strength or product electrical conductivity, the technology offers many attractive avenues to the process engineer or product developer. It is even possible to design heaters for materials of relatively low electrical conductivity if the electric field strength is made sufficiently large.

It is also possible to heat materials at extremely rapid rates. Furthermore, for materials of uniform electrical conductivity, energy generation is far more uniform than in microwave heating. The basic principles have been addressed in a number of publications (see *Electrical Properties*).

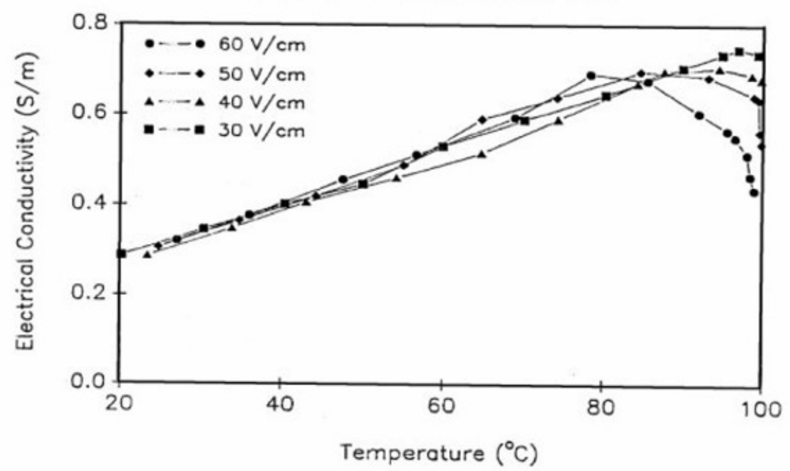

Figure 2. Electrical conductivity of orange juice subjected to various electric field strengths
Source: Palaniappan and Sastry (1991b)

2. Microbial Death Kinetics

A number of studies in the literature have considered whether ohmic heating results in a nonthermal contribution to microbial lethality.

Early literature on this topic has been inconclusive, since most studies either did not specify sample temperatures, or failed to eliminate this as a variable. It is critically important that studies comparing conventional and ohmic heating be conducted under temperature histories that are as near-identical as possible. In 1992, researchers attempted to compare ohmic and conventional heat treatments on the death kinetics of yeast cells (*zygo Saccharomyces* bacilli) with identical histories, and found no difference. However, a mild electrical pretreatment of *Escherichia coli* decreased the subsequent inactivation requirement in certain cases.

More up to date studies suggest that a mild electroporation-type mechanism may operate during ohmic heating. The presence of pore-forming mechanisms on cellular tissue has been confirmed by recent work. Another recent study, conducted under near-identical temperature conditions, indicated that the kinetics of inactivation of *Bacillus subtilis* spores can be accelerated with ohmic treatment. A two-stage ohmic treatment (ohmic treatment, followed by a holding time prior to a second heat treatment) was found to accelerate death rates further. Study has also indicated that leakage of intracellular constituents of *Saccharomyces cerevisiae* was found to be enhanced under ohmic heating, compared with conventional heating in boiling water.

The principal reason for the additional effect of ohmic treatment may be the low frequency (50–60 Hz) of ohmic heating, which allows cell walls to build up charges and form pores. This is in contrast to high-frequency methods, such as radio frequency or microwave heating, where the electric field is essentially reversed before a sufficient charge build-up (Figure 3). Some contrary evidence has also been noted; in particular, the work of Lee and Yoon has indicated that a greater leakage of *Saccharomyces cerevisiae* constituents occurs under high frequencies. However, the details of temperature control within this study are not available at the time of writing; thus, it is not clear whether or not these researchers have adequately eliminated temperature effects.

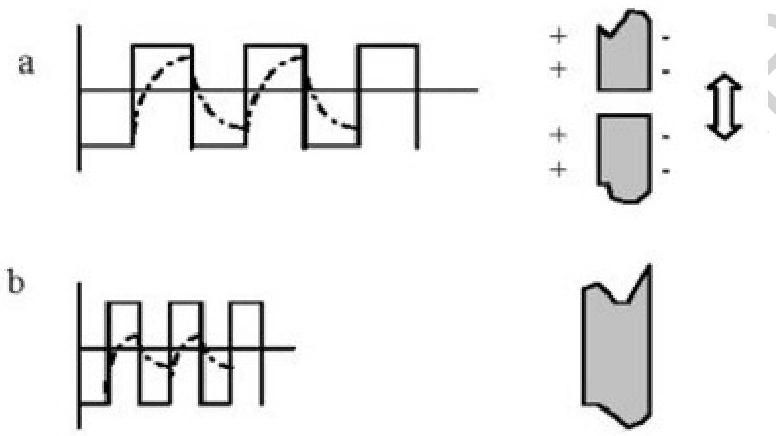

Figure 3. Illustration of square waves showing the effect of frequency on cell-wall pore formation. (a) Low-frequency fields allow membrane potential (dotted line) to build up to sufficient levels to cause pore formation. (b) High frequency fields do not permit time for pore formation to occur.

Temperature (C)	D-values for conventional heating (min^{-1})	k for conventional heating (s^{-1})	D-values for ohmic heating (min^{-1})	k for ohmic heating (s^{-1})
88	32.8	0.00117	30.2	0.001271
92.3	9.87	0.003889	8.55	0.004489
95	5.06	0.007586		
95.5			4.38	0.008763
97	3.05	0.012585		
99.1			1.76	0.021809
Z value (C) or Activation energy (E_a)(kcal/mol)	8.74*	70.0**	9.16*	67.5**

* - Z value; ** - Activation Energy

(Source: Cho, H-Y., Yousef, A.E., and Sastry, S.K. (1999). *Kinetics of inactivation of Bacillus subtilis spores by continuous or intermittent ohmic and conventional heating,* C 8 .

Table 1. D-values and kinetic reaction rate constants (k) for *B. subtilis* spores under conventional and ohmic heating

Stage #	D-values for conventional heating (min^{-1})	k for conventional heating (s^{-1})	D-values for ohmic heating (min^{-1})	k for ohmic heating (s^{-1})
1	17.1	0.002245	14.2	0.002703
2	9.2	0.004172	8.5	0.004516

Table 2. D-values and reaction rate constants for inactivation of *B. subtilis* spores during single- and double-stage conventional and ohmic heating at 90 ºC
Source: Cho H-Y., Yousef A.E., and Sastry S.K. (1999). *Kinetics of inactivation of* Bacillus subtilis *spores by continuous or intermittent ohmic and conventional heating*, c 8.

Temperature (ºC)	D-values for conventional heating (min^{-1})	k for conventional heating (s^{-1})	D-values for ohmic heating (min^{-1})	k for ohmic heating (s^{-1})
49.8	294.6	0.008	274.0	0.009
52.3	149.7	0.016	113.0	0.021
55.8	47.21	0.049	43.11	0.054
58.8	16.88	0.137	17.84	0.130
Z values (C) or Activation energy (E_a) (kcal/mol)	7.19*	29.63**	7.68*	27.77**

* Z value; ** Activation energy

Source: Palaniappan S., Sastry S.K., and Richter E.R. (1992). Effects of electroconductive heat treatment and electrical pretreatment on thermal death kinetics of selected microorganisms. *Biotechnical Bioengineering*, **39**: 225–232.

Table 3. Kinetic reaction rate constants (k) for *zygo Saccharomyces* bacilli under conventional and ohmic heating.

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Biographical Sketch

Sudhir Sastry is a professor at Ohio State University. He obtained his doctoral degree in mechanical engineering at the University of Florida, and he was on the faculty at Penn State University for seven years until joining Ohio State in 1987. He took sabbatical leave to work with Nestlé in 1997–8.

His research interests include ohmic heating, aseptic and PEF processing, and the influence of moderate electric fields on biological materials. He has written over 140 articles, obtained three patents, and written one book. He is also co-director of the Center for Advanced Processing and Packaging Studies (CAPPS).