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Extraction of valuable biocompounds assisted by high voltage electrical discharges: A review

Nadia Boussetta *, Eugène Vorobiev

EA 4297/ESCOM, unité « Transformations intégrées de la matière renouvelable », université de technologie de Compiègne, centre de recherches de Royallieu, BP 20529, 60205 Compiègne cedex, France

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ABSTRACT

The application of strong electric fields in gases, water and organic liquids has been studied for several years, because of its importance in electrical transmission processes and its practical applications in biology, chemistry, and electrochemistry. More recently, electrical discharges have been investigated and are being developed in water for enhancing the extraction of biocompounds from different raw materials. This paper reviews the current status of research on the application of high voltage electrical discharges for promoting cell disruption in aqueous suspension of biological materials, with particular emphasis on application to biocompounds extraction.

1. Introduction

There is a growing interest in the study of electrical discharges and breakdowns in water. Electrical discharges in liquid can be used in very different applications like water cleaning from organic chemical impurities, inactivation of microorganisms, electrohydraulic crushing of solids, and oil-well drilling [1,2]. In particular, the technology of electrical discharges has been recently developed for enhancing extraction of biocompounds from different raw materials [3–5]. The technology of high voltage electrical discharges is a green extraction technique as it allows enhancing the rate of extracted biocompounds per initial vegetable material at low treatment energy input [3,4]. It has also been shown that this technology can reduce the required diffusion temperature, the diffusion time [6] and the ethanol content in the diffusion solvent [7] as compared to a control extraction. When compared to other physical treatments (such as pulsed electric fields, microwave and ultrasounds), the application of high voltage electrical discharges results in a higher extraction rate than that obtained with pulsed electric fields and ultrasounds [3]. Another advantage of this technique is the low temperature increase due to the treatment [3] as compared to ultrasounds and microwave. However, the use of HVED can produce very small particles with respect to the applied treatment energy and that can lead to a subsequent solid to liquid separation step more difficult [8].

High voltage electrical discharges produced directly in water (electrohydraulic discharge) initiate both chemical reactions and physical processes. It injects energy directly into an aqueous solution through a plasma channel formed by a high-current/high voltage electrical discharge between two submersed electrodes [1]. Contrarily to the electrical discharges generated in gases, the mechanisms of formation of the electrical discharge in water are insufficiently delighted. Two types of processes may lead to the establishment of a conductive channel in water [9]. The first hypothesis assumes development of a gaseous phase first, in which electronic avalanches take place. The second hypothesis posits that a gaseous phase is not required. It assumes that breakdown is governed by multiplication of the charge carriers caused by ionization

* Corresponding author.
E-mail address: nadia.boussetta@utc.fr (N. Boussetta).

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of the liquid. The confrontation between the so-called bubble theory and direct impact ionization model is ongoing. The electrical discharge leads to the generation of hot, localized plasmas that strongly emit high-intensity UV light, produces shock waves, and generate hydroxyl radicals during water photodissociation.

The general issues and questions regarding the role of electrical discharge processes in extraction of biocompounds include the following: What are the mechanisms occurring during an electrical discharge in water? How are electrical discharges initiated and how do they propagate from one electrode to another? What are the main physical effects induced by electrical discharges that influence cell disruption? How can electrical discharges be applied for the extraction intensification of biocompounds from different biological materials?

Answers to the aforementioned questions are subjects of the current study. The present review seeks for placing these questions and issues within the framework of what is known about electrical discharge processes in extraction of biocompounds.

2. Principles and mechanisms

2.1. Formation and propagation of streamer and arc

With the point-plane electrode system and high pulsed voltage, the breakdown process in water is composed of two distinct phases [10,11]: a pre-breakdown phase (streamer) and a breakdown phase (electrical arc). During the pre-breakdown phase, a "streamer" is initiated at the point tip due to the very high local electric field. In liquids, streamers are composed of thin ionized vapor channels, which propagate toward the opposite electrode. Their typical propagation velocity in water is about 30 km/s (positive high voltage applied to the point electrode) [12]. The ionized gas channels created by the streamer constitute conducting path. When the streamer reaches the grounded plane electrode, an electrical arc takes place within a streamer channel (breakdown phase). Since the arc resistance decreases in a very short time (a few ns), the current rises and the voltage drops very quickly (the gap is almost short circuited). Then, the current becomes mainly limited by the external electrical circuit. A typical recording of current and voltage during one electrical discharge is shown on Fig. 1. The typical value of the total electrical energy per pulse is the sum of the energy first released when the streamer propagates plus the energy later dissipated in the arc.

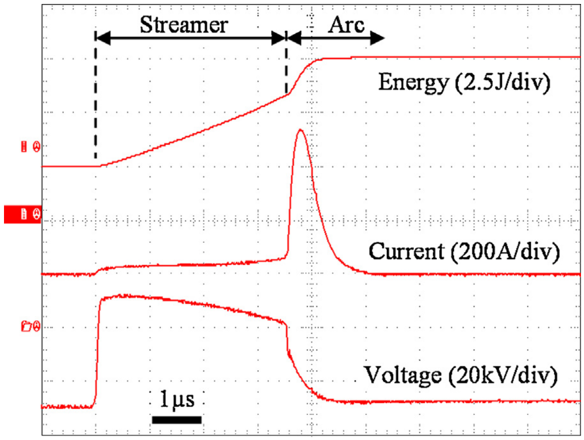

Fig. 1. Typical voltage (lower trace), current (middle trace) and energy (upper trace) (inter-electrode space = 2 cm, electrical conductivity of water = 360 µs/cm) [9].

2.2. Formation of the vapor cavities

For both streamer and arc formation processes, a gaseous bubble appears and propagates in the inter-electrode space (Fig. 2) [12]. Four stages are observed: creation, expansion, implosion and collapse of the gaseous bubble. The maximum bubble diameters or filament diameters are about 12 mm and 2 mm respectively during arc and streamer formation. The lifetime of the bubble is longer during arc (2000 µs) than streamer processes (400 µs). The expansion of these bubbles causes the very fast displacement of a large mass of fluid surrounding the plasma channel and thus alters the solid material.

When an arc occurs as the streamer reaches the plane electrode, the energy dissipated within the filament suddenly increases (Fig. 1). This contributes to further increase the vapor volume. A shock wave is emitted at this moment, and propagates in the surrounding liquid. Its effect is clearly seen on the photograph taken at 100 µs (Fig. 2). A large number of small cavitation bubbles (100 µm in diameter), distributed in the whole liquid volume are observed. Their lifetime is short due to their small size, and most of them already disappeared at 400 µs [12].

2.3. Formation of the shock wave

Depending on the type of the discharge the generated physical and chemical processes also include overpressure shock waves and, formation of various reactive chemical species and molecular species. In the particular case of the arc formation, the electrohydraulic effects are stronger [1]. Arcs are associated with the emission of a powerful shock wave propagating radially into the water. The pressure shock wave is followed by a rarefaction wave that produces cavitations. The collapsing cavitations create strong secondary shocks with very short duration (≈ 60 ns that sometimes result in sonolumeniscence [excitation of light spikes]), and these shocks can interact with structures on the size of cells [13]. Typical pressure profile of a shock wave generated during an electrical discharge in water is shown in Fig. 3. Pressure values of about 100 bar were recorded on the wall of treatment chamber [14]. By means of this pressure profile it is then possible to determine the acoustic energy of the shock wave. The acoustic energy of the shock wave E_A (J) is given by the following equation [15]:

$$E_A = \frac{4\pi d_S^2}{\rho_0 \nu_0} \int p^2 dt \quad (1)$$