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Electric current control of spiral wave dynamics

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The control of spiral wave parameters by electric current was investigated in the Belousov–Zhabotinsky (BZ) reaction. It was found that the wavelength and the period of spiral waves increase by a factor of up to 3 with electric current (both dc and ac). Using this procedure spiral waves with a period higher than the period of medium bulk oscillations were observed. It was also found that hysteresis phenomena occur in the system considered.

1. Introduction

Rotating spiral waves (vortices) have long elicited the attention of researchers in a host of different fields, including biology [1], cardiology [2], chemistry [3–5], and mathematics [6–8]. Along with the simple observation of such vortices the problem of controlling their parameters is of great interest. In its application to well investigated chemical media, it is known that temperature [9], UV [10], visible light [11, 12] and ultrasonic irradiation [13] significantly influence wave and vortex behaviour.

It is also known that electric current affects the wave front dynamics in the BZ reaction. The early papers from Schmidt and Ortoleva [14] consider the effects of electric field on wave propagation in the FKN system [15]. They derive differential equations to describe the possibility of stopping and annihilating the waves, reversal of the direction of the wave movement, increases of the wave velocity and hysteresis phenomena. Their predictions were confirmed by qualitative experiments. In a series of papers Sevčiková and Marek [16] experimentally studied in the one-dimensional BZ reaction the dependence of the wave velocity on concentrations of reaction components, and on the intensity of the applied electric field.

It is the purpose of this paper to investigate the effects of an electric field on spiral waves in a 2D medium. In the current paper we propose a new control method which enables us to drastically change spiral wave parameters. By applying a dc or ac current we have increased the period and wave length of a spiral wave by a factor of 3. By using this procedure it is even possible to obtain vortices that have a higher oscillation period than the bulk oscillations of the medium. When the voltage is decreased hysteresis phenomena and restoration to the initial conditions are found.

2. Experimental method

The experiments were performed in the BZ reaction where the catalyst (ferroin, 0.008 M) was immobilized in silica gel [17]. After preparing the gel layer (0.9 mm thick), the Petri dish (9 cm in diameter) was filled with the following solution: 0.15 M $NaBrO_3$, 0.15 M $CH_2(COOH)_2$ and 0.30 M H_2SO_4. The depth of the liquid layer was higher than 5 mm, to prevent the oxygen in the ambient air from interfering with the BZ reaction (fig. 1). All the experiments were carried out at room temperature (20° C).

Spiral waves were produced by the following procedure: first, a circular wave was induced by touching the gel layer with a silver wire and then the resulting wave front was broken with an iron wire to produce a pair of spiral waves spaced at 4 to 6 cm.

As shown in fig. 1, the experimental cell included two electrodes which were immersed in the liquid layer. One of the electrodes was circular and located at the border of the Petri dish, and the other one was needle-shaped, 0.6 mm in diameter, and placed over the spiral tip (3 mm into the liquid layer). Four different types of electrodes were used in our experiments: stainless steel, platinum, tungsten and silverbromide (AgBr).

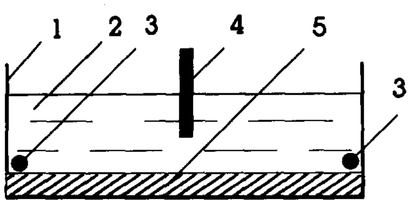

Fig. 1. Scheme of the experimental cell. A silica gel layer with immobilized ferroin (5) was prepared in a Petri dish (1). All BZ reaction ingredients, except for ferroin, formed the liquid layer (2). The circular (3) and needle shaped (4) electrodes were immersed into the solution.

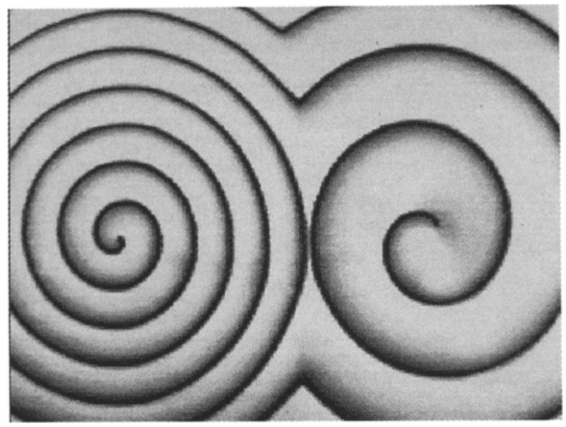

Fig. 2. Spiral waves in the BZ reaction. The right one, being under electric current stimulation, has extremely large wave length and rotation period ($\lambda = 0.62$ cm, $T = 253$ s) in comparison with the nonstimulated spiral in the left part of the figure ($\lambda = 0.32$ cm., $T = 160$ s).

The spiral wave dynamics was followed with a video-tape recording system. Digital image processing was carried out before printing the pictures shown in this paper.

3. Results

We have investigated the changes in spiral wave behavior under dc and ac current. When positive constant voltage is applied[#1] to the central electrode, period, wavelength, as well as core size, of the spiral waves increase by a factor of up to three. On the other hand, negative voltage did not influence the spiral wave parameters. ac current affects the spiral wave like dc current does. No dependence on frequency (from 0.03 to 90 Hz) was found. Qualitatively, these results do not depend on the electrodes used. All the results shown below were obtained with dc current and stainless steel electrodes.

A typical picture observed during the experiments is presented in fig. 2. It can be seen that

[#1] For AgBr electrodes we used reversed polarity.

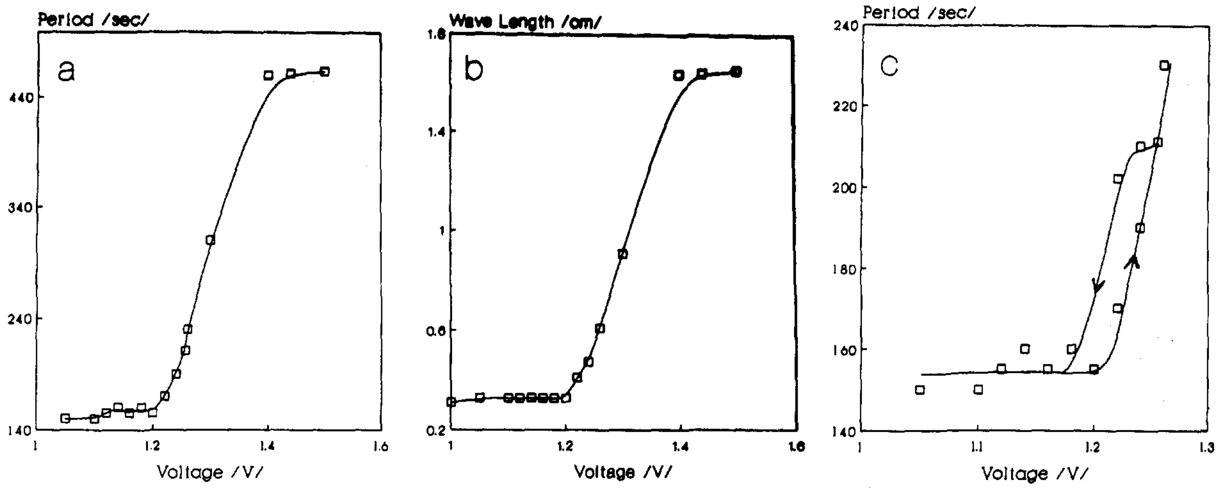

Fig. 3. Dependence of the period (a) and wave length (b) of the spiral wave on applied voltage. The hysteresis loop is presented in picture (c).

the wavelength, as well as the period of the tested spiral (at the right of the figure) is about two times greater than that of the spiral at the left, which has not been controlled by electric current.

The dependence of the spiral wave parameters (rotation period and wave length) on applied voltage is shown in fig. 3. At voltage values less than 1.2 V the spiral wave behavior does not change, but for higher values, the period, wavelength and wave velocity sharply increase with voltage. When voltage is brought back to lower values, experimental points do not lie on the same curve (see hysteresis loop on fig. 3c).

At high voltage (more than 1.4 V) the period of spiral wave rotation becomes larger than the bulk oscillation period (fig. 4). In this case an ordinary technique for period determination (the measurement of time period when waves pass through the test point) yields the values of the bulk oscillation period, but not the real period of the spiral waves. This is the reason for the horizontal line observed at the top of figs. 3a and 3b.

To verify that the vortex does return to its initial parameters, a series of experiments were performed by switching on and off the current successively. Fig. 5 presents the results of such tests. It can be seen that as the electric field is switched off, the initial parameters of the spiral waves are restored (compare wavelengths near the needle electrode on figs. 5a, 5c and 5e with those of 5b and 5d), to change, again, drastically when the electric current is switched on. The time necessary to restore the medium to its initial conditions (three wave lengths) in fig. 5c was about 9 minutes.

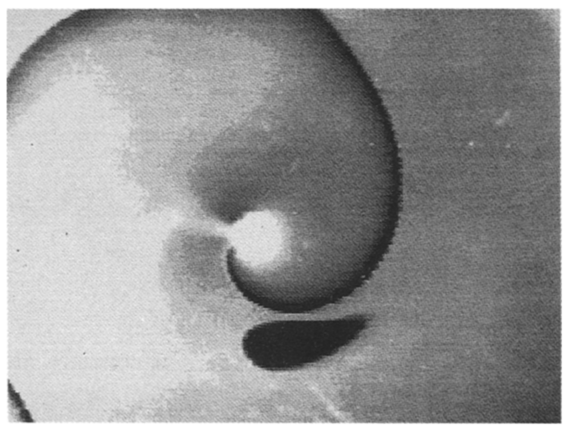

Fig. 4. Spiral wave with a rotation period higher than the period of bulk oscillations. The black spot at the bottom of the figure is the place where spontaneous oscillations were born.

Similar experiments have been carried out with platinum, tungsten and AgBr electrodes. These

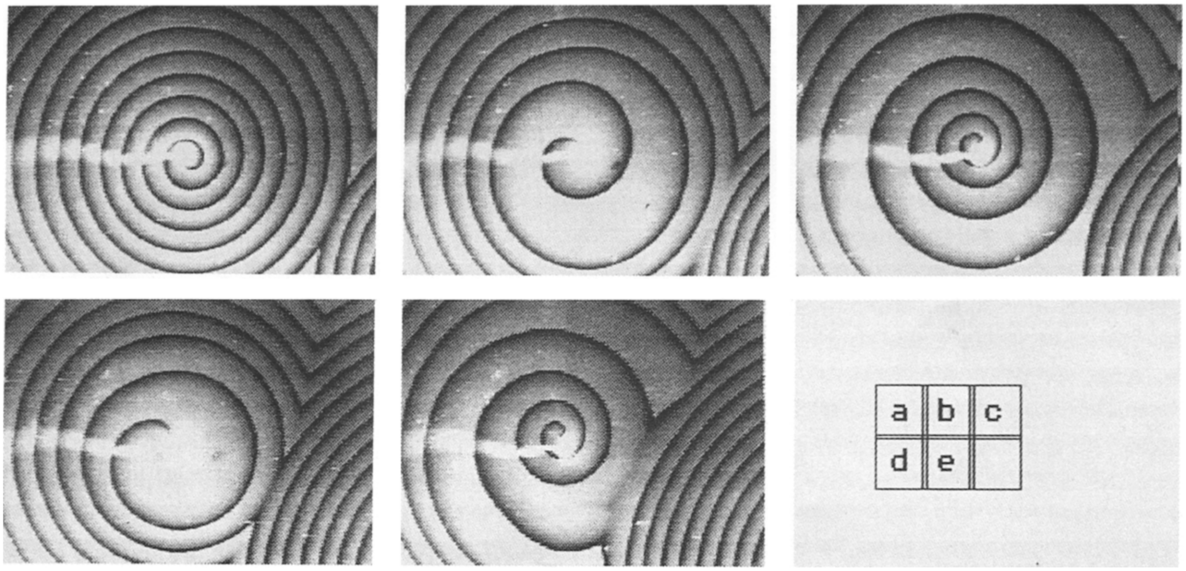

Fig. 5. Control of spiral wave dynamics with electric current. The wavelength as well as the period of the spiral waves grow while the current is switched on (b), (d) and decrease when the current is off (c), (e), returning to their initial values, close to the needle electrode (compare with the spiral before stimulation (a). Nearly three wavelengths were restored to their initial values in picture (c), while the remaining wavelengths can be observed to retain, still, their increased values. In each picture, from the left to the center of the spiral the shadow of the electrode can be observed. The space necessary to develop the tested spiral becomes more and more reduced as another autowave source in the medium increases its size (bottom right of each picture).

investigations have shown that the described phenomena took place when we used platinum and silverbromide electrodes, but were not observed for tungsten electrodes for the range of used values of voltage. When platinum electrodes are used, the wave length and period of the tested spiral waves also increase (by a factor of two for an applied voltage of 2.2 V). The silverbromide electrodes reproduce the same results when negative voltage is applied.

To understand the different effects of these electrodes the current–voltage characteristic of the medium was measured. The four curves (fig. 6), corresponding to the electrodes used, have the same shape, but the range of electric current values is quite different. We observed experimentally that to modify the parameters of the spiral waves dynamics a current higher than 300 μA was needed (fig. 6a, b, d). Note that for tungsten electrodes this value could not be reached for the voltage range used (fig. 6c).

4. Discussion

The electric current affects the ion mobility and kinetics of BZ reaction. The mechanisms of this effect has not been completely investigated until now. To explain the results of our experiments, it is natural to assume that close to the needle electrode the concentration of inhibitors ions (for example, Br^- for platinum and AgBr electrodes, and Br^- and iron ions for stainless steel electrodes) increases with voltage, an electrostatic screening effect taking place around the needle electrode. This effect could explain the fact that the size of the spiral core increases, as well as wave length and period. Note that for AgBr electrodes, negative voltage was used to increase the concentration of Br^- ions that go from the needle electrode to the liquid layer.

Similar effects can be observed in computer simulation of vortex rotation in an excitable medium with a nonuniform system with radial

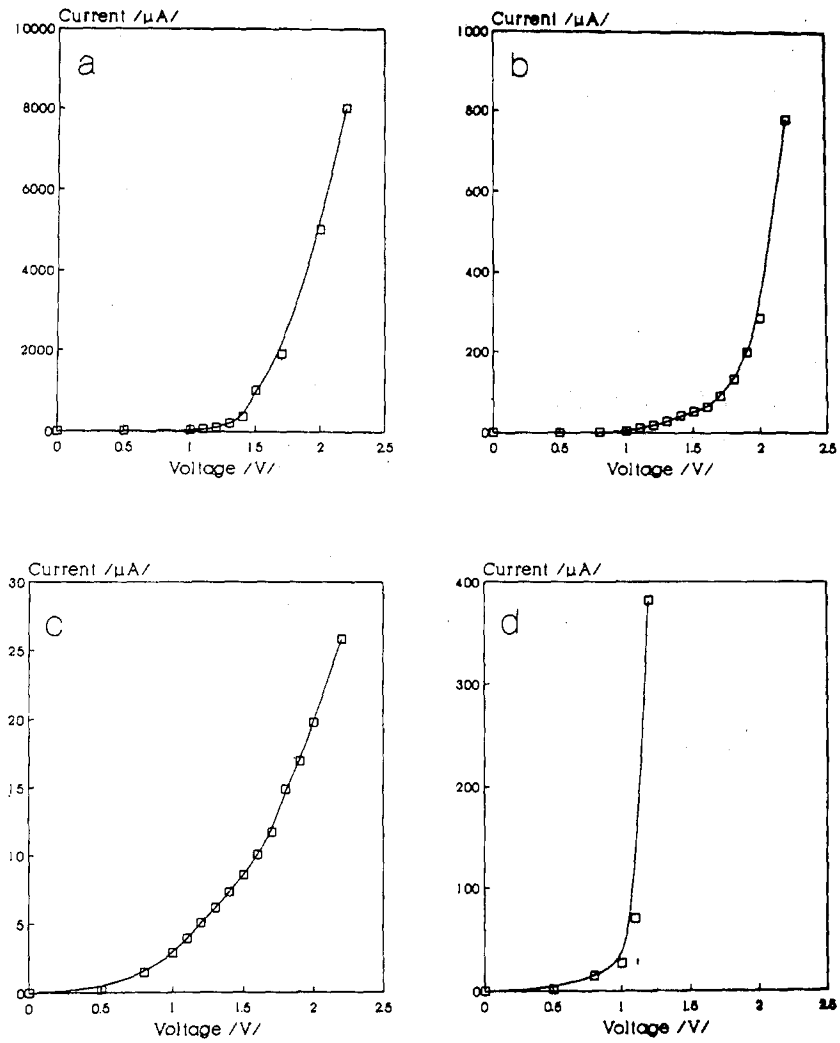

Fig. 6. Voltage–current characteristic of the BZ reaction for the stainless steel (a), platinum (b), tungsten (c) and AgBr (d) electrodes.

symmetry. This is the case for the electric field distribution in the studied system.

The method used to control the spiral wave dynamics presented in this paper points to the possibility of varying the spiral wave parameters in a very wide range. We have obtained spiral waves with a period of rotation comparable and even higher than the period of bulk oscillations. This result contrast with the fact that until recently all the experimentally observed spiral waves were accounted to be the fastest sources in an excitable medium [18].

It should also be mentioned that the hysteresis phenomenon was not investigated at length. We succeeded in the measurement of only a few points of the hysteresis loop. The main reason for this is that the period of the spiral waves under electric current increases and becomes greater than that of other autowave sources in the medium. So, the space necessary to develop the tested spiral waves becomes more and more reduced with time, creating experimental difficulties (see fig. 5). The detailed investigations of the hysteresis phenomenon are a subject for further research.

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