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Influence of Temperature on a Spiral Wave in Excitable Chemical Media

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Abstract. We present a study on the dynamics of a spiral wave in a thin-layer medium of the Belousov-Zhabotinsky reaction at different temperatures ranging from 10 to 30°C. As the temperature decreases, the wavelength and the wave period increase, however, the wave velocity decreases. The temperature affects the motion of the spiral tip in two ways: The tip trajectory changes from a simple circle to a meandering pattern, when the temperature is lowered and vise versa. Otherwise, the form of the tip trajectory remains unchanged, whereas its size becomes larger at a lower temperature. The results suggest that at low temperature instabilities of spiral waves at low excitability may possibly be observed in three-dimensional media of the Belousov-Zhabotinsky reaction.

Keywords: Belousov-Zhabotinsky reaction, Meander, Tip trajectory

1. Introduction

Spiral waves have been observed in many excitable biological and chemical systems [1–6]. In the heart, such re-entrant forms of electrical excitation and their instabilities concern cardiac tachycardia and life-threatening fibrillations [7–9]. The dynamics of spiral waves have been often studied in the Belousov-Zhabotinsky (BZ) reaction as a convenient laboratory model [10]. Depending on the initial concentrations of reagents, the spiral tip may either rotate simply on a circular path or it may meander, involving a more complicated path of motion [11–16].

In this report, we present a study on the effect of temperature on a spiral wave in the BZ reaction. We investigate two sets of initial concentrations of reagents which result in different behaviour of a spiral wave at room temperature [16]. The trajectory of the spiral tip, the wavelength, the wave period, and the wave velocity are analyzed.

2. Methods

In our study, the BZ reaction was prepared from $NaBrO_3$, H_2SO_4, malonic acid, and ferroin, all purchased from Merck. We used the BZ reaction with two sets of initial concentrations of reagents, as shown in Table 1. To prevent any hydrodynamic perturbation, the reaction was embedded in a 1.0% w/w agarose gel (Sigma). Furthermore, a surfactant, 0.05 mM sodium dodecyl sulfate (SDS, Fluka) was added to the reaction medium to reduce the production of CO_2 bubbles [16-18].

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Experiments were performed with a uniform thin layer of the BZ reaction in a flat reactor constructed from transparent plexiglas plates, as described in detail in [16]. The medium volume was 100×100×1.0 mm^3. An isolated spiral wave was initiated at about the middle of the medium by the following procedure: The reactor was oriented vertically and 5 ml of BZ solution were filled into the reactor forming the first layer of 5 cm height. Then, we waited until the gel was formed. Wave fronts were initiated by immersion of a silver wire of 0.5 mm diameter close to the left edge of the reactor. Next, we waited until one open end of the wave front reached the edge of the reactor and the other open end was located near the middle of the reactor. Another 5 ml of the BZ medium were added to the reactor as the second layer. Shortly after filling the second layer, the open end of the wave front started to curl in and began to form an isolated spiral wave in the BZ system.

Table 1 Initial concentrations of the BZ reaction used in this study. At room temperature the patterns of the spiral tip trajectory in BZ media with recipe I and II are a simple circle and a 4-petal meander [16].

Recipe	$NaBrO_3$ (mM)	H_2SO_4 (mM)	malonic acid (mM)	ferroin (mM)
I	50	200	50	0.5
II	40	130	40	0.5

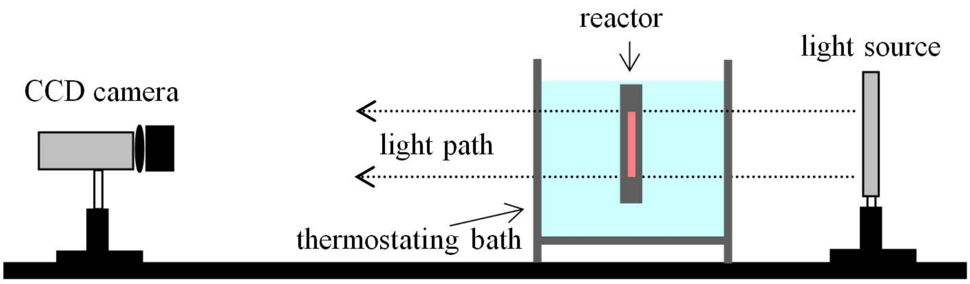

Fig. 1: Experimental setup. A flat reactor containing a thin layer of BZ medium is placed in a thermostating bath to control the temperature. The BZ medium is illuminated by a white light source and observed by a CCD camera.

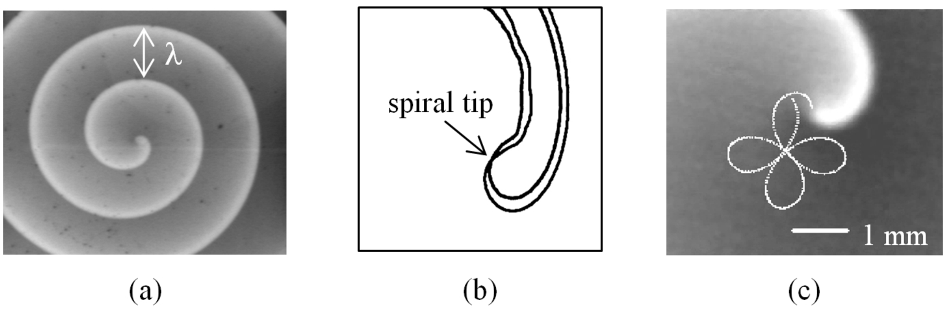

Fig. 2: Analysis of spiral wave dynamics. (a) Image of a spiral wave. Its wavelength λ is the distance between adjacent fronts. (b) The spiral tip is defined as the intersection of contour lines of two consecutive spiral images. (c) The spiral tip trajectory is a temporal set of spiral tip locations. A 4-petal meandering pattern is traced by the spiral tip during 30 min.

The dynamics of the spiral wave was observed in a spectrophotometric setup, as shown in Fig. 1. To control the temperature of the medium, the reactor was placed into a transparent plexiglas bath thermostated with an accuracy of ±0.1 °C. The bath was set between a white light source and a colour CCD camera (Super-HAD, Sony). To trace the spiral tip precisely, the images of the medium were recorded every second with a resolution of 0.033 mm $pixel^{-1}$.

For analysis, the colour images were converted to 8-bit gray scale ones. The contrast of the images was further enhanced by background subtraction and histogram stretching. The background was calculated as the temporal average of all images. The spiral wavelength (λ) was measured as the distance between two adjacent fronts (Fig. 2a). The period was the duration which it took a wave front to travel for a distance of one wavelength. The velocity of the wave front was calculated as the ratio between wavelength and period. The tip of the spiral wave was defined as the intersection of contour lines (at 0.6×amplitude) of two subsequent images with a time interval of 5-15 seconds (Fig. 2b) as proposed in [19]. A set of the tip positions was plotted to show the tip trajectory (Fig. 2c).

3. Results and Discussion

The properties of the spiral wave were affected by temperature in the same way for both recipes I and II, as shown in Table 2. When temperature was decreased, both wavelength and wave period increased. Due to the fact that the increasing rate of the period was larger than that of the wavelength, the velocity decreased while temperature was decreased. It is worth to note that the results of the wave velocity in this study agree with a previous investigation [20], which presented a theoretical work as well as experimental measurements on the temperature dependence of the velocity of curved fronts in the BZ reaction.

Table 2 Influence of temperature on properties of a spiral wave in the BZ medium.

recipe	Temperature (°C)	wavelength (mm)	period (min)	velocity (mm min^{-1})
I	10	6.3	11.2	0.56
I	17	5.3	7.6	0.70
I	23	4.9	4.6	1.1
II	10	12.8	35.4	0.36
II	23	6.0	11.3	0.53
II	30	5.3	5.8	0.91

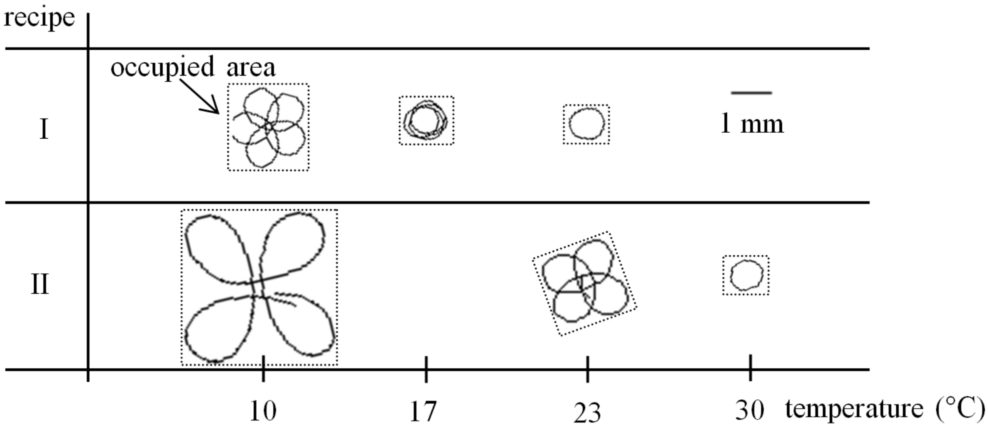

Fig. 3: Influence of temperature on the trajectory of a spiral tip in the BZ medium. At room temperature (23°C), the trajectory for recipe I is a circle. It becomes a 5-petal meandering pattern at lower temperatures of 17°C and 10°C. In the case of recipe II, the trajectory changes from a 4-petal pattern to a circle, when the temperature is increased from 23°C to 30°C. In contrast, the pattern remains in a 4-petal form with a larger size, if the temperature is decreased to 10°C. Dashed rectangles represent the occupied area of the spiral tip. A 1-mm scale bar is inserted at the upper right.

Figure 3 shows the tip trajectory of a spiral wave for the two recipes of the BZ reaction used in this work. At room temperature (23°C), the BZ media with the chemical recipes I and II were found to support a rigidly rotating spiral wave (circular tip trajectory) and a 4-petal meandering spiral wave, respectively. At a lower temperature, a transformation as well as an enlargement of the tip trajectory was observed. For recipe I, the circular trajectory became a meandering pattern with 5 tiny petals at 17°C. This 5-petal form remained; its size, however, was clearly enlarged at 10°C. The area occupied by the spiral tip (dashed rectangles in Fig. 3) increased by about 3 times.

For recipe II, the tip trajectory did not change qualitatively at a lower temperature. We only observed an enlargement of the tip trajectory of 4-petal meandering, when the temperature was decreased from 23°C to 10°C and the occupied area increased by a factor of 3. At a higher temperature of 30°C, the tip trajectory transformed to a simple circle and the occupied area decreased to one fourth in comparison to that at room temperature.

These results on the tip trajectory show that spiral waves meander more strongly at lower temperatures. Simulations [21,22] have demonstrated that the pronounced meandering of a spiral wave in a three-dimensional (3D) system potentially causes a wave filament expansion which leading to a 3D wave turbulence, when the filament hits the system boundaries. When a 3D system is viewed as a stack of two-dimensional slices, the filament is a line connecting all spiral tips in the stack [17,18]. This implies that the 3D wave turbulence, predicted in the simulations, could possibly be observed in the BZ reaction at low temperature, where the reaction supports a strongly meandering spiral wave.

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5. References

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