Experimental evidence of a microwave non-thermal effect in electrolyte aqueous solutions

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Received (in Montpellier, France) 9th December 2008, Accepted 20th February 2009
First published as an Advance Article on the web 1st April 2009
DOI: 10.1039/b821970b

Microwave non-thermal effects have aroused extensive attention. Some studies have affirmed that microwave non-thermal effects can never be observed below electric field intensities of 10^7 V m^{-1}. In this paper, a precisely designed experiment was used to corroborate the existence of a microwave non-thermal effect in electrolyte aqueous solutions. The measurements were carried out at 2.45 GHz and the electric field magnitude was in the order of 10^4 V m^{-1}. The electrical conductivity (EC) of sodium chloride aqueous solutions can be changed using microwaves. The measured effect is related to the concentration and temperature of the solution, and we used techniques to exclude the temperature effect in our experiments. The results validate the existence of a non-thermal microwave effect.

Introduction

Microwave non-thermal effects have been postulated to result from a direct stabilizing interaction of the electric field with specific molecules in the reaction medium that is not related to a macroscopic temperature effect. Microwave non-thermal effects have received much attention in recent years and are the subject of intense debate within the scientific community.[1–3] Some recent studies have demonstrated that microwaves are capable of causing non-thermal effects.[4–11] Loupy and others believe that microwave non-thermal effects do indeed exist, even if they cannot yet be adequately explained.[12] Oppositely, some studies have concluded there is no evidence to support the existence of microwave non-thermal effects.[13] Stuerga and others have denied the existence of microwave non-thermal effects because the energy of single photons in the microwave range (0.1–3 GHz, 10^{-3}–10^{-4} eV) is too low to break hydrogen bonds.[10,11] Besides, they affirmed that in microwaves used to heat chemical reactions, the electric field intensity is usually well below that of the saturation of the induced polarization and cannot induce any shifting of chemical equilibria in many situations. They predicted that an electric field intensity up to 10^7 V m^{-1} is required to produce a measurable microwave non-thermal effect.[14,15] Because the electric field intensity is usually in the order of 10^4 V m^{-1} in a microwave chemistry reactor, refined from domestic microwave oven, microwave non-thermal effects should not be observable in these situations.

In this paper, we have designed an experiment for corroborating the existence of a microwave non-thermal effect on electrolyte aqueous solutions in low-level intensity electric fields. A specially designed ridged waveguide was used to produce a uniform electric field, and the electric field intensity in solution was about 10^4 V m^{-1}. Next, we employed a circuit to measure the slight electrical conductivity (EC) variations of a solution flowing through the ridge gap under microwave irradiation. Some special techniques, such as precise temperature measurements and multi-physics calculations including the electromagnetic field, fluid dynamics and heat transfer, were used to exclude the temperature effect. By measurement, slight EC variations with microwave power at 2.45 GHz were observed and explored. The results reveal the existence of a non-thermal microwave effect.

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Experiment and methods

The precisely designed experiments included some special techniques: (1) A specially designed ridged waveguide with a hole in the side wall was used to produce a uniform distribution electric field in the solution; the solution was pumped to flow through the ridge gap in a quartz glass pipeline with a diameter of 5 mm. The space between a pair of ridges was 10 mm, the electric field intensity in the solution was in the order of 10^4 V m^{-1} and the input power was 400 W. (2) The temperature of the solution under test was precisely controlled by using a KXS-A trough (±0.5 °C) and pump (5 m s^{-1}). (3) The temperature at the output port of the pipeline was precisely measured by using a UMI-8 optical fiber thermometer with a 1 mm diameter optical fiber. (4) A Wheatstone bridge circuit was used to accurately measure the voltage variations resulted from the slight EC changes of the solution. (5) To observe the concomitant EC change with microwave power, the microwave power was on–off-modulated irregularly during the experiments.

To prepare suitable solutions, 11.69 and 58.44 g of sodium chloride were added to 2 L of de-ionized water, respectively. The power of the generator was 400 W and the frequency was 2.45 GHz. A continuous microwave source was used in our experiments. The output power could be sampled and recorded using a Tektronix DPO7254 oscillograph through a directional coupler. On the other hand, a pair of Pt electrodes connected to the Wheatstone bridge circuit was inserted into the glass pipeline to measure EC variations. EC variations could then be obtained and recorded using a Tektronix DPO7254 oscillograph from the Wheatstone bridge circuit. A UMI-8 optical fiber thermometer was employed to inspect the temperature rise during the experiment. The construction of the ridged waveguide and the distribution of the electric field in cross-section at $X = 0$ are shown in Fig. 1 and Fig. 2, respectively. To avoid disturbing the uniform distribution of the electric field in the ridged gap area and unnecessary microwave energy coupling, the electrodes were kept away from the high-level electric field area. Furthermore, the direction of the applied electric field was vertical to the electrodes, and a filter was employed in the circuit. Therefore, the influence of the coupled microwave energy from the electrodes could be ignored. Please note that the indicative voltage would become very weak and noise would seriously disturb measurements if the electrodes were to be placed outside of the ridged waveguide. A sketch of the experiment is shown in Fig. 3.

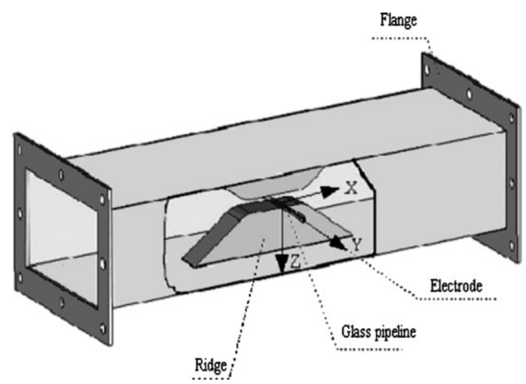

Fig. 1 The construction of the ridged waveguide with a glass pipeline.

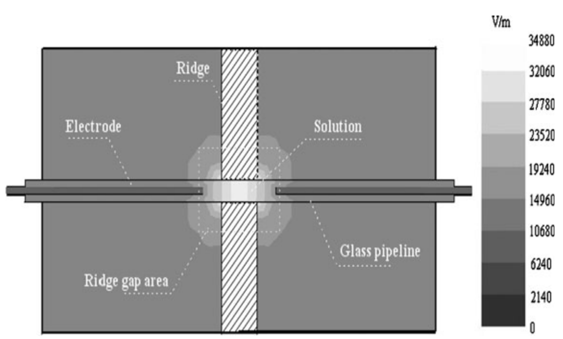

Fig. 2 The distribution of the electric field in cross-section at $X = 0$.

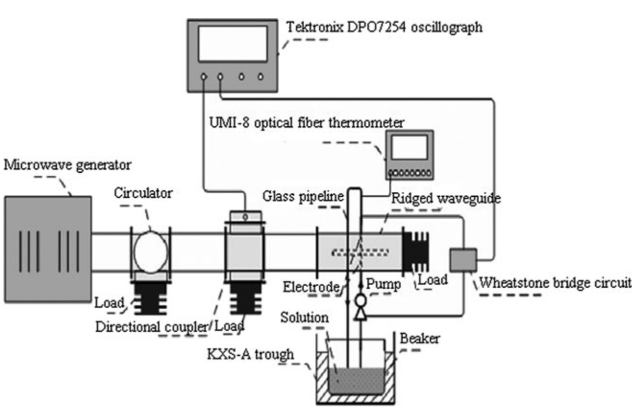

Fig. 3 The experiment system.

Results and discussion

In the experiments, the microwave power was on–off-modulated irregularly. Meanwhile, the maximum electric field intensity in the solution was 3.488×10^4 V m^{-1} when the output power of the generator was 400 W, as obtained by multi-physics calculations. The measured EC variations with microwave power of sodium chloride aqueous solutions at three constant temperatures are shown in Fig. 4.

As can be seen from Fig. 4, it is obvious that the EC of the sodium chloride aqueous solutions depended on the microwave power directly. The higher the concentration of solution, the more obvious the EC change.

Experiments were also performed under 10^3 and 10^5 V m^{-1} order of magnitude electric fields. The effect was too weak to be measured under the 10^3 V m^{-1} order of magnitude electric field. On the other hand, an obvious temperature rise of the solution was measured under the 10^5 V m^{-1} order of magnitude electric field. Here, the effect was only measured under the 10^4 V m^{-1} order of magnitude electric field.

The following two reasons exclude the temperature effect in the experiments. (1) From Fig. 4, the lower the temperature is, the more obvious the EC change. Just as illustrated in the literature,[16] the microwave absorption capability of the sodium chloride aqueous solution increases with temperature. This means that a larger temperature rise is observed for solutions at higher temperatures. Therefore, if the EC change results from a temperature rise, more significant EC variations should be observed at higher temperatures. However, the experimental results are inconsistent with this. (2) The measured results show that the maximum temperature rise was less than 0.1 °C. At the same time, by multi-physics calculations, we obtained a temperature rise for the solution. The coupled Maxwell equations, the fluid field equation and the heat transport equation were solved using the finite-element method (FEM). Multi-physics calculations showed the temperature rise during the experiment was less than 0.12 °C. Even if the temperature rise of the whole solution was up to 0.5 °C, the relative EC variation was only 1% by calculation. The measured relative EC variations were calculated from the recorded data and are listed in Table 1. As can be see from Table 1, the maximum measured EC variation is 4.0%. Therefore, the temperature rise of 0.12 °C cannot result in the obvious EC variation.

When we replaced the sodium chloride aqueous solution with de-ionized water, the calculated intensity of the electric field was 3.046×10^4 V m^{-1}. This is the same order of electric field intensity as that seen in the sodium chloride aqueous solution. The sodium chloride aqueous solution was replaced

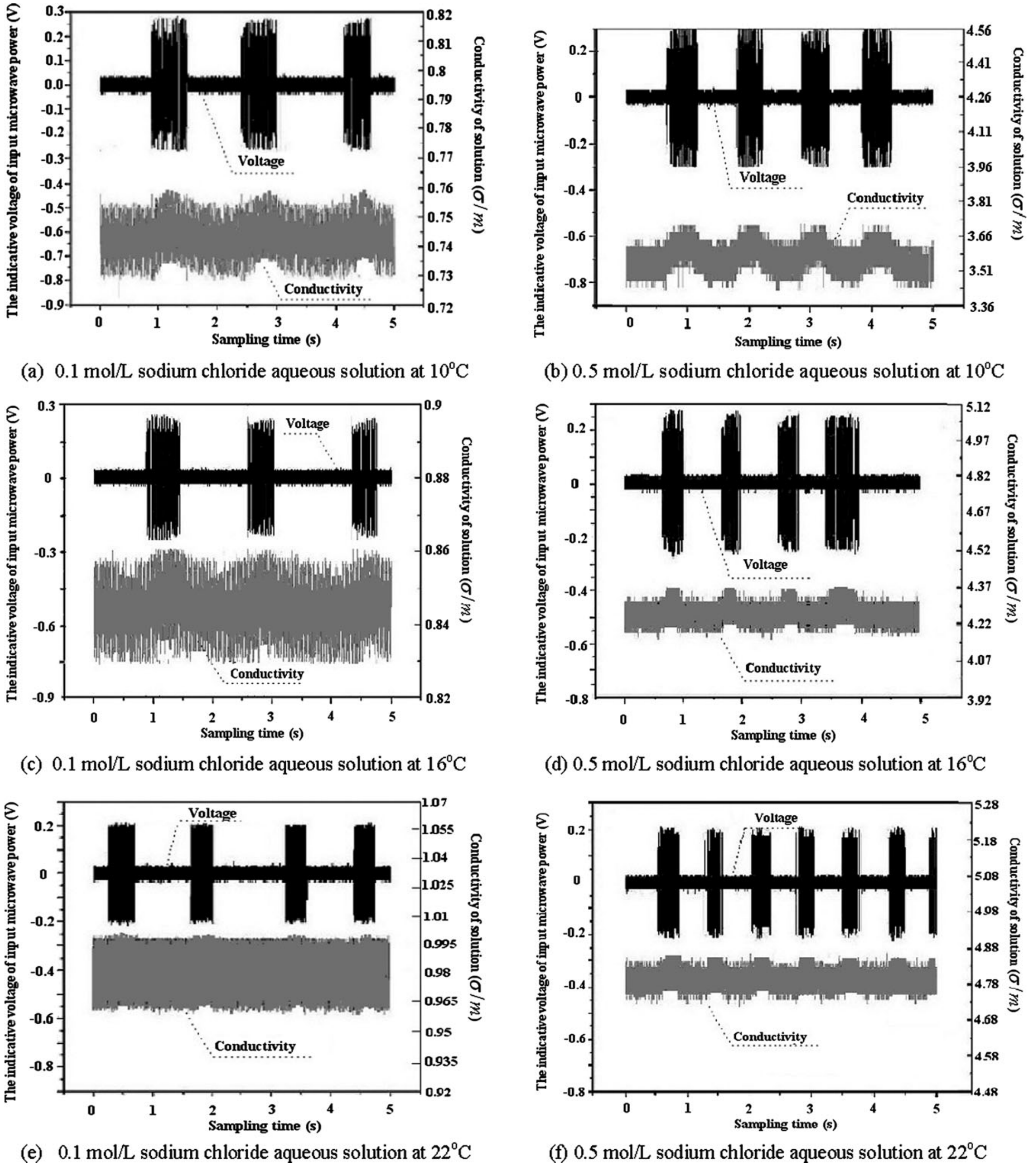

Fig. 4 The EC variations with microwave power of sodium chloride aqueous solutions at three constant temperatures: (a) 0.1 mol L^{-1} sodium chloride aqueous solution at 10 °C, (b) 0.5 mol L^{-1} sodium chloride aqueous solution at 10 °C, (c) 0.1 mol L^{-1} sodium chloride aqueous solution at 16 °C, (d) 0.5 mol L^{-1} sodium chloride aqueous solution at 16 °C, (e) 0.1 mol L^{-1} sodium chloride aqueous solution at 22 °C and (f) 0.5 mol L^{-1} sodium chloride aqueous solution at 22 °C.

by de-ionized water to test the influence of coupling microwaves from the electrodes on the measured results. The result in Fig. 5 shows that the influence of coupling microwave energy from the electrodes on the measurements can be ignored.

By measurement, the slight EC variations of sodium chloride aqueous solutions with microwave power validate the existence of a non-thermal microwave effect in low-level intensity electric fields. However, this effect is too weak to be detected in typical applications of microwaves. More

Table 1 The measured relative EC variations

Temperature→ Concentration↓	10 °C	16 °C	22 °C
0.1 mol L^{-1}	2.1%	1.3%	0.6%
0.5 mol L^{-1}	4.0%	1.7%	0.9%

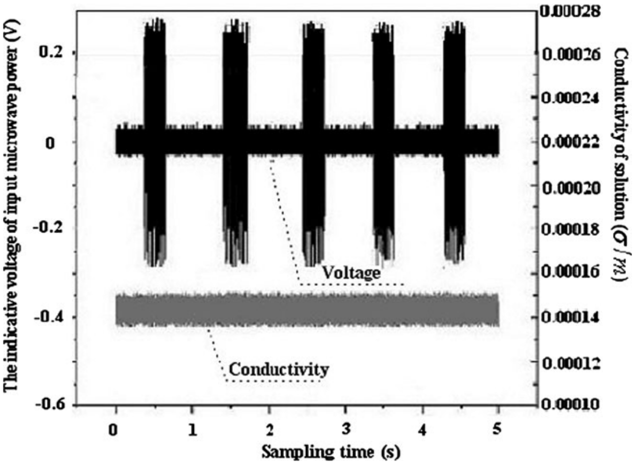

Fig. 5 The EC variations of de-ionized water with microwave power at 10 °C.

experiments under the different conditions, such as different frequencies and electrolytes, are required to verify this effect further. We assume that the effect results from cluster structure changes in electrolyte aqueous solutions under microwave irradiation, but evidence of this requires further study.

Acknowledgements

This project was supported by the National Science Foundation of China under Grant no. 60531010.

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