Arabian Journal of Chemistry (2015) 8, 100–104

King Saud University

Arabian Journal of Chemistry

www.ksu.edu.sa
www.sciencedirect.com

ORIGINAL ARTICLE

# Microwave chemistry: Effect of ions on dielectric heating in microwave ovens

Jamil Anwar [a], Umer Shafique [b,*], Waheed-uz-Zaman[a], Rabia Rehman [a], Muhammad Salman [a], Amara Dar [b], Jesus M. Anzano [c], Uzma Ashraf [a], Saira Ashraf [a]

[a] *Institute of Chemistry, University of the Punjab, Lahore, Pakistan*
[b] *Center for Undergraduate Studies, University of the Punjab, Lahore, Pakistan*
[c] *Laser Laboratory & Environment, Analytical Chemistry Department, Faculty of Sciences, University of Zaragoza, Pedro Cerbuna 12, 50009 Zaragoza, Spain*

Received 28 May 2010; accepted 14 January 2011
Available online 20 January 2011

**KEYWORDS**

Concentration of ions;
Dielectric heating;
Dipolar polarization;
Ionic conduction;
Microwaves

**Abstract** To understand the interactions of microwaves with dielectric materials and their conversion to thermal energy in aqueous systems, the effect of ionic concentration has been studied. Aqueous solutions of inorganic ions were exposed to microwaves (2.45 GHz) in a modified oven under identical conditions. Difference in solution temperatures with reference to pure (deionized) water was monitored in each case. A significant decrease in the temperature was observed with an increase in the quantity of ions. Experiments were repeated with several inorganic ions varying in size and charge. The information can be helpful in understanding the role of ions during dielectric heating.


## 1. Introduction

In the electromagnetic spectrum, microwaves having a frequency in the range of 0.3–300 GHz lay between infrared and radio waves (Menéndez et al., 2009; Meredith, 1998; Zlotorzynski, 1995). Microwaves are widely used in communication, remote sensing, navigation, food processing, and electron paramagnetic resonance spectroscopy, but in everyday life, their well-established use is for commercial and domestic heating. Besides, in the last couple of decades, conventional laboratory heating is being gradually replaced by microwave heating. The advantages that attracted the attention of chemists to microwave heating are; higher heating rates in less times, no direct contact between the reactants and energy source, and clean, selective and remote heating of the reactants in the desired atmosphere. In addition, non-thermal applications of microwaves include measuring the dielectric properties of a large variety of substances such as rubber, wood, paper, glass,

* Corresponding author. Tel.: +92 321 4990904; fax: +92 429 9232057.
E-mail addresses: umer0101@hotmail.com, umer@hons.pu.edu.pk (U. Shafique).

Peer review under responsibility of King Saud University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.arabjc.2011.01.014

synthetic polymers, and agricultural materials (Menéndez et al., 2009). Fundamental theories, database of dielectric properties of the substances and applications of microwaves have been adequately summarized in several books (Adam, 1969; Baden, 1990; Reich, 1953) and reviews (Caddick and Fitzmaurice, 2009; Horikoshi and Serpone, 2009; MacKenzie et al., 2009). Widespread use of microwaves gave birth to the continuing public and scientific discussions about the possible health hazards because of the interaction of electromagnetic radiations and tissues, which have also appeared in the literature in the near past (Jauchem, 2008).

Microwave energy can be transformed into heat when a dielectric substance, having permanent or induced dipoles, is exposed to microwave radiation of a certain band of frequency. The literature reveals that microwave heating occurs by two mechanisms, which are dipolar polarization, and ionic conduction whereas another called interfacial polarization is a combination of the two (Kingston and Jassie, 1998; Mingos and Baghurst, 1991; Taylor et al., 2005). Dipolar polarization is by which heat is produced in polar molecules like water. Dipoles align themselves by rotating with the electric field associated with waves. To achieve the thermal effect the frequency of microwave is so adjusted that in an alternating electric field, the phase difference between rotating the dipoles and orienting the field causes molecular friction and collisions that give rise to dielectric heating (Gabriel et al., 1998; Kappe, 2005). In conduction, dissolved charged particles (ions) in a sample oscillate back and forth under the influencing electric force of microwaves creating an electric current. This current faces internal resistance because of collisions of charged species with neighboring molecules or atoms, which cause materials to heat up (Metaxas, 1996; Ponne, 1996). The conduction principal has much stronger effect in comparison to dipolar polarization for heat producing capacity (Keiko, 2003). The interfacial polarization is a combination of conduction and dipolar polarization. It is important for such a heating system that includes a conducting material scattered in a non-conducting medium like dispersion of metal particles in sulfur.

Most of the general literature indicates that water containing ions is more efficiently heated by microwaves in comparison to pure (deionized) water (Gabriel et al., 1998) but one report (Metaxas, 1996) points out that microwaves of different frequency regions are needed to create oscillation in ions and rotation in polar molecules. Thus, microwaves of certain frequency band cannot produce heat simultaneously by both mechanisms. There are some reports that indicate less heating in the case of the presence of ions in water. Ponne (1996) developed microwave penetration profiles, calculated by Quasi-optical method, in pure water and 4% NaCl solution and found that microwave penetration depth significantly decreased in NaCl solution. Keiko (2003) studied the effect of concentration of sodium chloride on the heating efficiency of microwave and found that the solution was not efficiently heated in the microwave oven. Hasted (1973) found that at higher salt concentrations, the ions orient the water molecules around them, which lessen the ability of water molecules to adjust in the applied electric field, reducing the dielectric constant and thus, less heat is produced.

The present work has been carried out for in-depth study of the role of ions in dielectric heating. Aqueous solutions with ions having different charge, size, and nature were heated in a modified oven producing microwaves of 2.45 GHz at 900 W. For comparison, urea and sugar solutions were also subjected to investigation under similar conditions. The results can be helpful in better understanding the role of ions and their concentrations in microwave heating in domestic ovens.

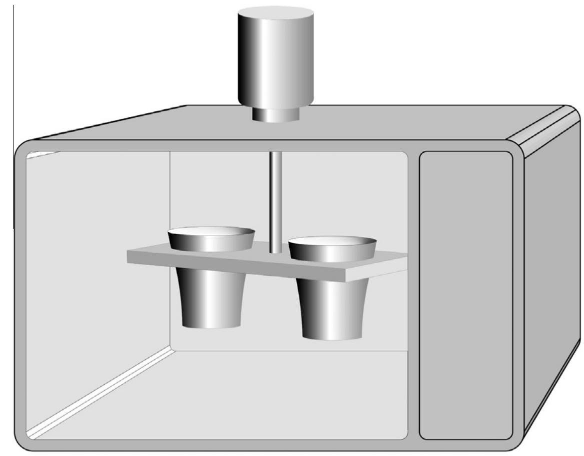

**Figure 1** Personalized domestic microwave oven having rotating turntable with two identical arms to contain polystyrene cups; frequency 2.45 GHz; power full; time of exposure 40 s; volume of each solution 100 ml.

## 2. Materials and methods

### 2.1. Standard solutions

All the chemicals (anhydrous chlorides of lithium, sodium, potassium, cesium, magnesium, calcium, strontium, barium, nickel, copper and cobalt, urea, and sugar) were of AnalaR grade purity and were used without further purification. Deionized water was used throughout the work, while well washed Pyrex glassware was used for preparation of the solutions. Solutions having concentrations 0.01, 0.025, 0.05, 0.1, 0.25, 0.5, 1 mol/dm$^3$ of all the aforementioned compounds were prepared and stoppered.

### 2.2. Procedure

In order to overcome problems like zone heating and hot spots, the oven was fitted with a rotating turntable having two arms fitted with identical sample container holders, rotating at much higher speed (than the original turntable) to create a pseudo uniform exposure environment for both containers (Fig. 1). Rotation of 60 rpm also introduces turbulence in the sample containers thus stirring their contents evenly to rule out the formation of hot pockets. Reference container provides the facility to nullify the effect of magnetron power fluctuation.

One hundred millilitres of the sample solution taken in a polystyrene (PS) cup was placed in one arm of the turntable whereas 100 ml of deionized water in PS cup was placed on the opposing arm of the turntable. After the slow start of the turntable, the magnetron was turned on for full power for 40 s. After the aforementioned duration, both the cups were taken out and their temperatures were simultaneously measured with two separate identical digital thermometers. In each case, three solutions of the same concentration were exposed to microwaves under identical conditions and their average temperatures were calculated for plotting graphs between the concentrations and their respective temperatures.

## 3. Results and discussion

Domestic microwave ovens do not deliver the radiations uniformly inside the cavity. Instead, there are certain ‘hot spots’ where flux density is higher in comparison to other regions. It was very difficult that the sample placed on the turntable would get the same exposure during each run. Another problem encountered during the microwave heating is ‘zone heating’ where certain pockets in the solution get heated more than the others and cease to absorb more energy thus affecting the bulk heating phenomena. The last challenge faced in this study was the relative decrease in microwave throughput during the experiment conduction period probably due to heating of HV transformer and magnetron itself. The provision of a reference container provides the facility to simultaneously examine the effect of exposure on reference (water) in order to eliminate the microwave power output fluctuation. Thus, assembly shown in Fig. 1 ensures accurate results. Furthermore, same concentration solutions were exposed to microwaves three times under identical conditions and average temperatures were used for plotting graphs.

Fig. 2 represents the change in the temperatures when chlorides of alkali metals (lithium, sodium, potassium, and cesium) were exposed to microwaves for 40 s. As shown in figure, solutions with more ions have less temperature in comparison to dilute solutions. Water dipoles in the absence of ions were supposed to be free to rotate in the oscillating electromagnetic field of microwaves. Their movement increased the overall kinetic energy of the system resulting in a rise in the temperature of water. In other words, when water molecules rotated, they had collided with each other and had produced heat via friction. However, when the ions were introduced in water, ions probably bound water molecules around them, and no rotation had taken place, consequently, solution was heated to a lesser extent. Water molecules with their oxygen atoms bound to metal ions and hydrogen atoms to chloride ions failed to align themselves in the field of microwaves and as a result, alternative to all dipoles of water, only free or loosely bound molecules caused water to heat.

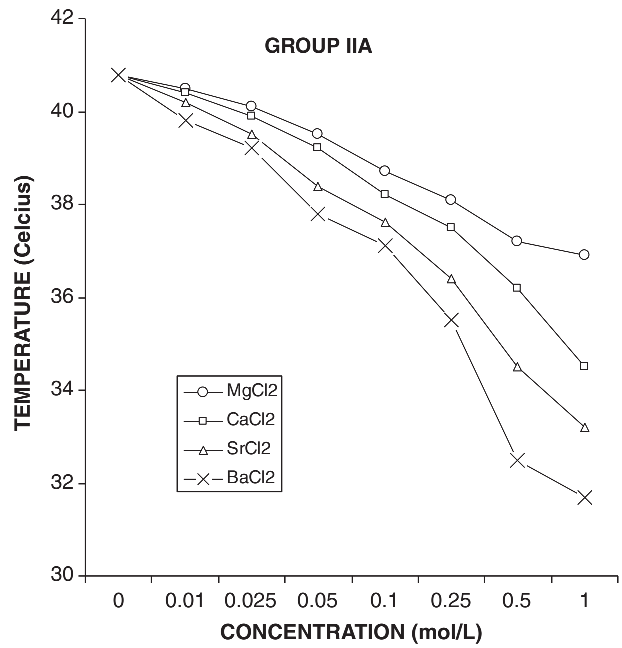


**Figure 3** Temperatures of different concentration solutions of chlorides of magnesium, calcium, strontium, and barium after exposure to microwaves (2.45 GHz) for 40 s, volume of each solution = 100 ml.

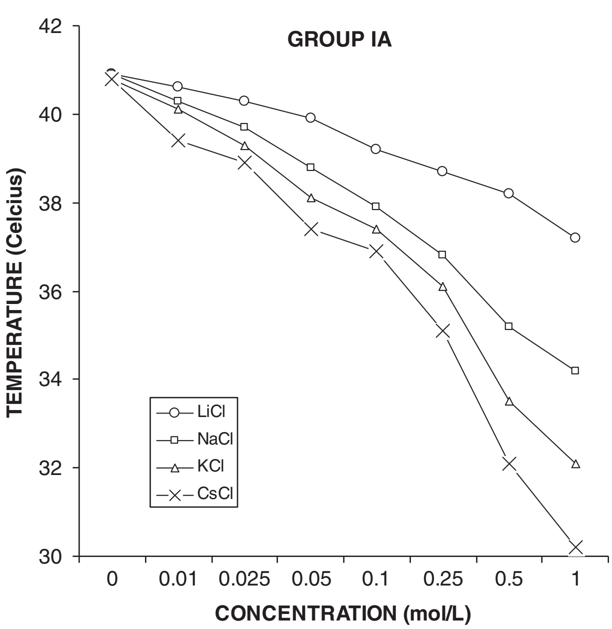


**Figure 2** Temperatures of different concentration solutions of chlorides of lithium, sodium, potassium, and cesium after exposure to microwaves (2.45 GHz) for 40 s, volume of each solution = 100 ml.

Since, molar solutions were used; counter ion (chloride) had the same effect in all cases. More decrease in the case of cesium pointed out more capability of the said ion to bound water molecules. Ionic radii of metals used in Fig. 2 are of the order $Cs^+ > K^+ > Na^+ > Li^+$, the temperatures of one molar solution of these ions after exposure to microwaves pointed out that cesium had a temperature of 30.2 °C while the temperature of the same concentration solution of lithium under identical conditions had risen to 37.2 °C. This indicates that the same number of cesium ions may bind more water molecules due to their larger size in comparison to sodium, potassium, and lithium. Furthermore, it was found that as the concentration increased, the temperature difference between the same concentration solutions of different ions also increased.

Fig. 3 shows the temperatures of magnesium, calcium, strontium, and barium chloride solutions that were exposed to 2.45 GHz microwaves for 40 s. A similar effect that is less temperature in the case of larger ion was observed. Under similar conditions, one molar solution of magnesium chloride has the temperature of 36.9 °C while barium chloride has 31.7 °C. Barium being smaller than cesium has the high temperature in comparison to that of the latter. Thus, the size of ion is more prominent to fix water molecules around them in comparison

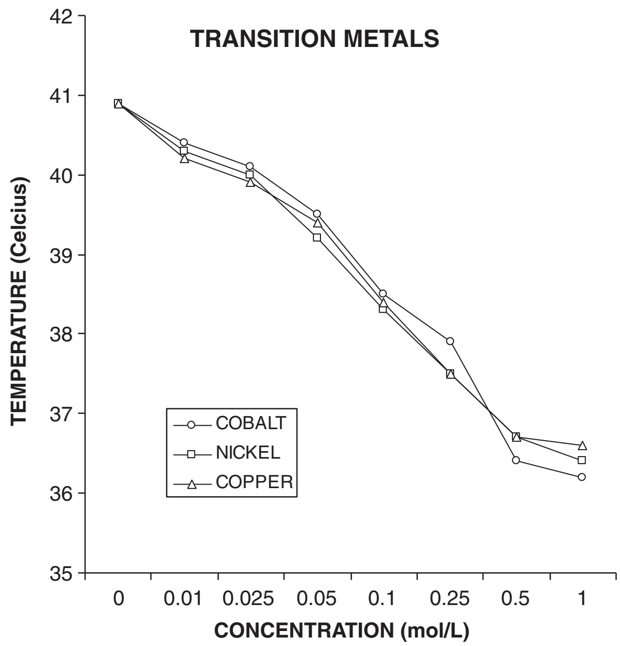


**Figure 4** Temperatures of different concentration solutions of chlorides of cobalt, nickel, copper after exposure to microwaves (2.45 GHz) for 40 s, volume of each solution = 100 ml.

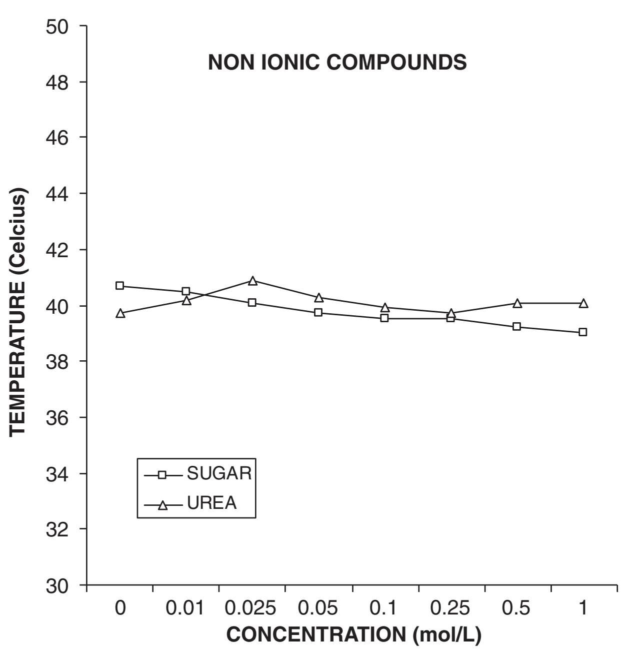


**Figure 5** Temperatures of different concentration solutions of urea and sugar after exposure to microwaves (2.45 GHz) for 40 s, volume of each solution = 100 ml.

to charge. For example, lesser size of magnesium, calcium, strontium, and barium in comparison to the corresponding members of group IA induces more temperature in their solutions despite the fact that they have double charge. To further confirm the results, a set of three ions (cobalt, copper, and nickel) having almost the same size and charge were studied (Fig. 4) and it was found that as there was no significant difference between the charge and size, the temperatures were almost similar in each case.

Urea and sugar solutions were also exposed to microwaves under similar conditions, and it was found that more temperature was achieved in comparison to metal chloride solutions. The reason is that urea and sugar can hold water molecules by weak hydrogen bonding while interaction of ions with water molecules is strong. A slight decrease in the temperature of one molar solution of urea and sugar in comparison to pure water (Fig. 5) can be because of more mass available to heat. When urea and sugar solutions were exposed to microwaves, loosely bound molecules arrange them in an oscillating field of electromagnetic radiations causing water to heat by the phenomenon 'dielectric polarization'. However, when water having ions was exposed to microwaves, less thermal effect was achieved, since not as much of free water molecules were available for dielectric polarization. Ions may not oscillate at this frequency (2.45 GHz) to heat water by the phenomenon 'ionic conduction'. Thus, water with ions will heat less. Furthermore, a decrease in the temperature is directly proportional to the size of the ion.

## 4. Conclusion

To comprehend the interactions of microwaves with dielectric materials and their conversion to thermal energy in water, the effect of ions was studied. Water samples with and without inorganic ions were exposed to microwaves in a personalized oven under similar conditions. A significant decrease in the temperature was observed with an increase in the quantity of ions that was directly proportional to the size of the ion. It can be concluded that ionic conduction cannot take place in domestic microwave ovens, rather ions suppress the dielectric polarization and less temperatures are achieved in comparison to dilute aqueous solutions or pure water.

## References

Adam, S., 1969. Microwave theory and applications. 21 Laboratory Experiments. Prentice-Hall, New Jersey.

Baden, A., 1990. Microwaves: An Introduction to Microwave Theory and Techniques, third ed. Pergamon, Oxford.

Caddick, S., Fitzmaurice, R., 2009. Microwave enhanced synthesis. Tetrahedron 65, 3325–3355.

Gabriel, C., Gabriel, S., Grant, E., Halstead, B., Michael, D., Mingos, P., 1998. Dielectric parameters relevant to microwave dielectric heating. Chem. Soc. Rev. 27, 213–224.

Hasted, J., 1973. Aqueous Dielectrics. Chapman and Hall, London.

Horikoshi, S., Serpone, S., 2009. Photochemistry with microwaves catalysts and environmental applications. J. Photogr. Sci. C. 10, 96–110.

Jauchem, J., 2008. Effects of low-level radio-frequency (3 kHz to 300 GHz) energy on human cardiovascular, reproductive, immune, and other systems: a review of the recent literature. Int. J. Hyg. Environ. Health. 211, 1–29.

Kappe, C., 2005. Microwaves in Organic and Medicinal Chemistry. Wiley-VCH, Weinheim.

Keiko, N., 2003. Effect of sodium chloride on the sample temperature and absorbed energy during microwave cooking. J. Hom. Econ. Jpn. 54, 351–356.

Kingston, H., Jassie, L., 1998. Microwave-enhanced chemistry. Fundamentals, sample preparation and applications. American Chemical Society Publishing, Washington DC.

MacKenzie, K., Dunens, O., Harris, A., 2009. A review of carbon nano-tube purification by microwave assisted acid digestion. Sep. Purif. Technol. 66, 209–222.

Menéndez, J., Arenillas, A., Fidalgo, B., Fernández, Y., Zubizarreta, L., Calvo, E., Bermúdez, J., 2009. Microwave heating processes involving carbon materials. Fuel Process. Technol. 91, 1–8.

Meredith, R., 1998. Engineers' Handbook of Industrial Microwave Heating. Institution of Electrical Engineers, London.

Metaxas, A., 1996. Foundations of Electroheat: A Unified Approach. John Wiley and Sons, United States.

Mingos, M., Baghurst, D., 1991. Applications of microwave dielectric heating effects to synthetic problems in chemistry. Chem. Soc. Rev. 20, 1–47.

Ponne, C., 1996. Interaction of electromagnetic energy with vegetable food constituents, Ph.D. Thesis. Technical University, Eindhoven.

Reich, H., 1953. Microwave theory and techniques. Van Nostrand Series in Electronics and Communications. Van Nostrand Publisher, California.

Taylor, M., Atri, B., Minhas, S., 2005. Developments in Microwave Chemistry. Evalueserve, England.

Zlotorzynski, A., 1995. The application of microwave radiation to analytical and environmental chemistry. Crit. Rev. Anal. Chem. 25, 43–76.