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Microwave heating as a new way to induce selectivity between competitive reactions. Application to isomeric ratio control in sulfonation of naphthalene.

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Abstract : *Heating rate associated with microwave heating are used to control isomeric ratio in sulfonation of naphtalene. General considerations about use of microwave heating in organic syntheses are also considered. The authors show specificities of microwave heating in term of reactivity, associated with control of very fast heating rate.*

The use of microwave irradiation to activate organic reactions has been taking a new dimension for some years now. Microwave heating uses the ability of some materials (liquids and solids) to transform electromagnetic energy into heat. This microwaves application should not be confused with gas phases reactions where microwave discharges can create a plasma and can cause dramatic fragmentation and recombinaison reactions. Microwave heating appears as "in situ" mode of energy conversion, which is very attractive for chemists.

Microwave irradiation has been used for a great variety of organic reactions as estherification, etherification, oxydation, hydrolysis, Claisen, Diels-Alder, Reformatsky, Knoevenagel and Bischler-Napieralski reactions. Many reviews [1, 2, 3, 4] have been published, and most publications describe some very important accelerations of reaction rate. Synthesis of derivatives which normally require long reflux periods can be achieved conveniently and very rapidly in a microwave-oven. Reduction time factor observed is usually close to two or three order of magnitude. In relation with these accelerations of reaction rate (rate enhancement defined as ratio between conventional reaction time and microwave reaction time), some authors have come to the conclusion that microwave heating have some "specific effects" or "non-thermal effects".

Despite the great practical interest of reduction time, these results seem to be disappointing. In majority of studied reactions, chemical reactivity is unchanged (products obtained by microwave irradiation are identical to these obtained by classical heating), and moreover no isomeric selectivity is observed. In relationship with these results, it seems that the unique interest of microwave irradiation in chemistry is reduction of reaction time. The object of this work is to prove potentiality of microwave heating to control isomeric ratio. According to us, that raises interest and induces to reconsider the role of microwave irradiation in chemistry.

ORIGIN OF RATE ENHANCEMENT

Most organic chemists use domestic oven, but the conventional chemical reflux system cannot be introduced into the microwave oven because of the circulating water coolant would strongly absorb microwave energy and microwave energy would heat it up very rapidly. Furthermore, an air condenser would not be effective in returning the flammable solvents to the reaction flask in a safe manner. Then majority of chemists prefer to use closed vessels which are transparent to microwave energy. In a sealed vessel and for a same solvent, boiling temperature is very different compared to boiling temperature at atmospheric pressure, in relation with pressure effects. In these particular conditions, consistent reductions of reaction time are not surprising. Energy density used in domestic microwave oven are sufficient to raise the temperature from ambiant to 200 °C in less than one minute, and so cause the total reaction time is reduced by a factor close to 10^3. These remarks have been already explicited by Gedye [5].

If the role played by microwave over collisionnal or mecanistic term remains unknown and obscure today, it is otherwise for temperature. Indeed the specificity and the essential interest of microwave heating are the temperature slopes induced. Consistent differences between classical heating with an oil bath and microwave heating appear in relationship with dielectric losses.

This natural tendency for thermal racing is accentuated by the implicated energy density, which is in general totally different from these energy density induced by classical heating technologies, particularly for sealed tubes or small autoclaves, as used by organic chemists. Then temperature appears as a preponderant variable.

In relation with microwave power density, we can control temporal change of temperature. For a given solvent with dielectric losses, we can choice the time to reach boiling temperature. Microwave irradiation can be used as a tool to generate heating rate faster than classical heating.

NEW DIMENSION OF MICROWAVE HEATING : SELECTIVITY

If we consider two competitive reactions, we can imagine to take advantages of this heating rate control, particularly to induce a selection between the two considered reactions. However, in order to observe such effects of selection, it is necessary to consider reactions with reaction time close to heating time. In fact, reaction time of the most usual organic reactions are close to an hour (in these conditions, boiling temperature is instantaneously obtained compared to reaction time) and what justifies to neglect such effects in the classical heating conditions with reflux. As it is explained above, most of organic reactions assisted by microwave energy are made in sealed vessels, and in these very particular conditions reaction time and heating time have the same magnitude, because of the pressure effects. Then the use of sealed vessels should permit to take advantages of heating rate to induce a selection between two competitive reactions.

A kinetic model based on Arrhenius law, taking into account the temperature slope associated with the solvents heating has been established. This model has been used for competitive reactions (parallel reversible first order reactions with a common reactive R_1). Two reagents R_1 and R_2 react to product P_1 with rate constant and activation energy respectively k_1, E_1 and k_2, E_2 (sheme 1). Concurrently R_1 and R_3 react to product P_2 with constant rate and activation energy respectively k_3, E_3 and k_4, E_4 (sheme 2). We consider temporal evolution of temperature during reaction between ambiant temperature and boiling temperature of considered solvent, here boiling temperature of 120 °C. Heating time (time to reach boiling temperature) has been choosen between 20 seconds and 15 minutes (respectively, heating rate of 5 °Cs^{-1} and 0.125 °Cs^{-1}), in relation with energy density classicaly applied to reactor. This choice of parameters corresponds to very realistic conditions.

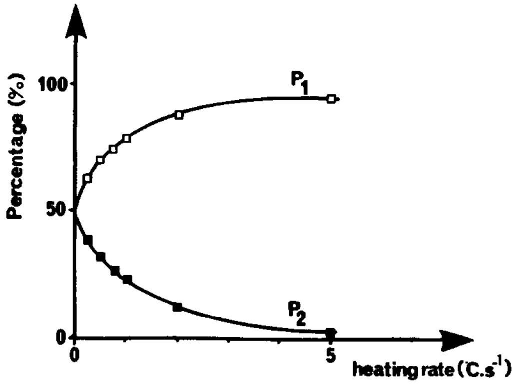
$$R_1 + R_2 \underset{k_4,E_4}{\overset{k_3,E_3}{\rightleftharpoons}} P_1 \quad \text{Scheme 1}$$

$$R_1 + R_3 \underset{k_2,E_2}{\overset{k_1,E_1}{\rightleftharpoons}} P_2 \quad \text{Scheme 2}$$

This model foresees some very interesting effects induced by heating rate of reactive medium. Firstly a consistent reduction of reaction time (between 2 and 0.2 °Cs^{-1} reaction time is reduced to a quarter). Secondly, in relation with cinetical parameters (preexponential factor and activation energy) we can foresee two very special situations.

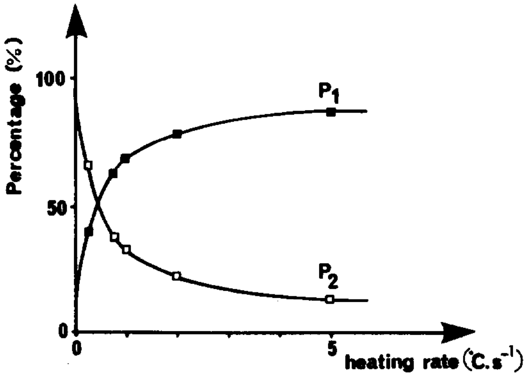
The first situation can be named "induced selectivity". This situation is described by the figure 1 that gives the concentration of P1 and P2 after reaction, versus heating rate. In classical heating conditions or very slow heating rate, we obtain a mixture of the two products P_1 and P_2. In relationship with magnitude of heating rate, we can control ratio between P_1 and P_2. In microwave heating conditions, we can strictly obtain P_1 contaminated by P_2. No selective conditions (reactive concentrations) because of side reaction, can become very selective with the use of very fast heating rate.

Fig. 1 : Percentage of P_1 and P_2 versus heating rate.



The second situation can be named "inversion". This situation is described by figure 2. In classical heating conditions we obtain essentially P_1, and in microwave heating conditions or very fast heating we obtain essentially P_2.This situation is very interesting because it forecasts change of reactivity induced by heating rate despite the same operating conditions. These results have been obtained with E_1 = 85 KJ mol^{-1}, E_2 = 80 KJ mol^{-1}, E_3 = 85 KJ mol^{-1}, E_4 = 90 kJ mol^{-1} and $K_1 = K_2 = 10^3$ $mol^{-1}s^{-1}$, $K_3 = 10^{12}$ $mol^{-1}s^{-1}$, $K_4 = 0.33$ 10^{12} $mol^{-1}s^{-1}$, (K_1, K_2, K_3, K_4, preexponential factor) initial concentrations of reagents are respectively 1 $mol.l^{-1}$ and 0.1 $mol.l^{-1}$. Numerical results presented here, correspond to values for parameters (preexponential factor and activation energy) which give optimum effect of selectivity.These numerical values obtained correspond to realistic situations.

Fig. 2 : Percentage of P_1 and P_2 versus heating rate.



APPLICATIONS : SULFONATION OF NAPHTALENE.

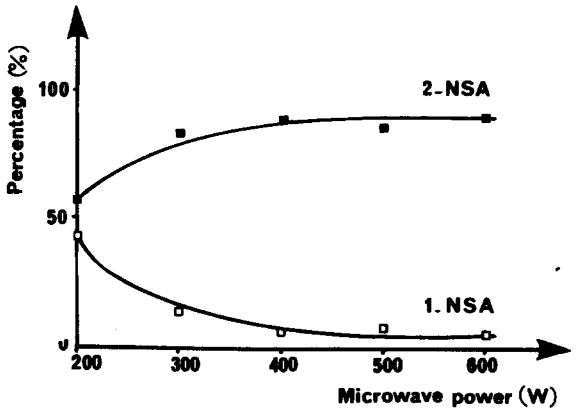
To illustrate effects forecasted by this model we have chosen a very classical reaction no denoid of industrial interests : sulfonation of naphtalene. 2-naphtalene sulfonic acid is a raw material used in the manufacture of pharmaceuticals, dyestuffs and polymers. Sulfonation of naphtalene results in a mixture composed of 1- and 2-naphtalene sulfonic, di-, tri-, and tetrasulfonic acids, and sulfones, the percentage of which depends on the conditions used for sulfonation.The reaction is of first order with respect to naphtalene in concentrated aqueous sulfuric acid. The pseudo first order constant rate raises strongly with increasing sulfuric acid concentration. The ratio of 1- to 2-naphtalene sulfonic acid decreases sligtly with increasing sulfuric acid concentation and temperature (isomeric ratio of 6 for 75% sulfuric acid and isomeric ratio of 4 for 95% sulfuric acid at 25°C).

This reaction has been first made with microwave irradiation by R.A. Abramovitch [4, 6]. Now we want to prove the control of isomeric ratio between 1- and 2- naphtalene sulfonic acids. This reaction is in good agreement with model criterias, particularly a very fast reaction (at atmospheric pressure).

The frequent use by organic chemists of domestic oven is a result of their low cost. Moreover domestic oven is very versatile because it can accept a wide range of material loads of different dielectric losses, size and shape. A high heating rate and a short processing time are requested for this experiment, and we don't use a domestic oven, but a tuned cavity specially designed by the authors (single mode TE_{055}). We can irradiate a volume of 15 cm^3 with certitude of homogeneous electric field inside the used tube. This tube (tube diameter 20 mm) crosses the cavity and is connected to a classical reflux system. Temperature measurements are possible with a fluoroptic thermometer. After 15 minutes of irradiation, because of the great solubility of sulfonic acids in water and the consequent difficulty in cristallisation, the free sulfonic acids are not isolated but are converted directly into the sodium salts. Most of contained insoluble matters, particularly sulfones, were removed by filtering. Isomeric ratio has been estimated by the use of HPLC (Whatman Partisil ODS2 10/25 4.6 mm x 250 mm column, the eluant was prepareted by diluting 90 ml isopropanol to 2l with 0.15 M aqueous $(NH_4)_2$ SO_4). The operating conditions are flow: 3 ml/min, ambiant temperature, detection wavelenght 280 nm). Retention times are for 1- and 2- naphtalene sulfonic acids respectively 14 minutes and 19 minutes.

The figure 3 gives the change of 1- and 2-naphtalene sulfonic acid percentage after reaction versus microwave power used. That's quite possible to control isomeric ratio independently of operating conditions as reactive concentrations. These results prove isomeric control during sulfonation of naphtalene, in relationship with microwave power used.

Fig. 3 : Percentage of 1- and 2- NSA versus microwave power.



The origin of this change of selectivity results from the change of heating rate induced by the change of microwave power. At relatively high temperature (close to 130 °C) we know that production of the 2-NSA is major, compared to the production of 1-NSA. Then the more heating rate is high, the more the proportionof 2-NSA compared to proportion of 1-NSA is strong. Hence these results are not mysterious, and don't violate the thermodynamic laws. The same heating rate induced by another heating technology should give the same results. However, this experiment is not possible because of the implicated energy density by microwave heating, which is very stronger than these induced by classical heating technologies.

CONCLUSIONS

This work clearly shows the control of the proportion between 1- and 2- naphtalenesulfonic acids during sulfonation of naphtalene, and that, independently of experimental conditions (same concentrations of naphtalene and sulfonic acids). This isomeric control is induced by the control of temporal evolution of temperature.

To observe such effects of selectivity, very fast reactions as sulfonation of naphtalene are necessary (reaction time close to a few minutes). Hence, the coupling use of microwave heating and sealed-vessels seems essential to observe such effects induced by heating rate. The sealed-vessels permit consistent reduction of reaction time. Microwave heating permits to scan a large area of heating rate inaccessible by classical heating. This specificity of microwave heating results from the easy control of energy density applied and the nature of dielectric heating which is an "in situ" mode of energy conversion.

The conclusions of this work foresee very interesting potentialities in term of reactivity, associated with control of very fast heating rate. The microwave heating strictly appears as an easy way to impose very fast heating rate inaccessible by classical heating. According to the authors, it seems that the coupling use of sealed vessels and microwave heating open a new way for synthetic chemistry, particularly an original way to cinetical control. Then, the eventual and hypothetical "non thermal" effects called by some authors, doesn't appear as a necessity to justify the use of microwave in organic synthesis.

In this paper we only have shown "induced selectivity" situation. The model foresees a more interesting situation, named above "inversion". This second situation should be suitable to Diels and Alder reactions (control of ratio endo to exo, and reduction of eventual side reactions as polymerisation of cyclopentadiene).

The authors have been taking part in writing of a brochure[7] which gives instructions for the use of microwave in synthetic chemistry, and they would like to receive some proposals of very fast reactions in classical conditions (reflux).

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