Use of Alternative Energy Sources for the Initiation and Execution of Chemical Reactions and Processes:

Microwave technology

Microwaves represent an alternative way of power input into chemical reactions and processes. Through dielectric heating, reaction mixtures are homogenously heated without contact to a wall. Reaction times are significantly reduced compared to conventionally (thermally) heated systems while maintaining acceptable yields and selectivities. A small disadvantage is the fact that chemical reactions and processes in the microwave field depend more on the employed devices and substances than in the case of thermal heating.

Introduction

Many organic chemical reactions and processes only proceed upon the addition of energy. Most often, thermal energy is used. This paper describes the use of microwaves as alternative energy sources. The amount of energy required to heat a reaction mixture Q_{th} is defined by equation 1. The consumption of electrical energy Q_{el} can be measured (eqs. 2 and 3).

$$Q_{th} = \Delta T * c_P * m \qquad (1)$$

$$P = U * I \qquad (2)$$

$$Q_{el} = P * t \qquad (3)$$

The efficiencyer η_1 according to eq. 4

$$\eta_1 = Q_{th} / Q_{el} \qquad (4)$$

indicates how much electrical energy is converted into usable thermal energy. Multiple energy conversions and transfers through boundary layers decrease the efficiency and increase the energy consumption. Upon reaching the reaction temperatures, equilibrium between introduced energy and energy losses establishes which is only influenced by the reaction enthalpy. The enthalpy, however, plays only a minor role for batch sizes used in laboratory classes (0.1 mol). For most chemical reaction the equilibrium is reached by working at reflux, i.e. part of the introduced thermal energy is constantly transferred to the cooling water by condensation of the boiling compound at the reflux condenser. Energy balances for such systems thus have to include the required cooling energy.

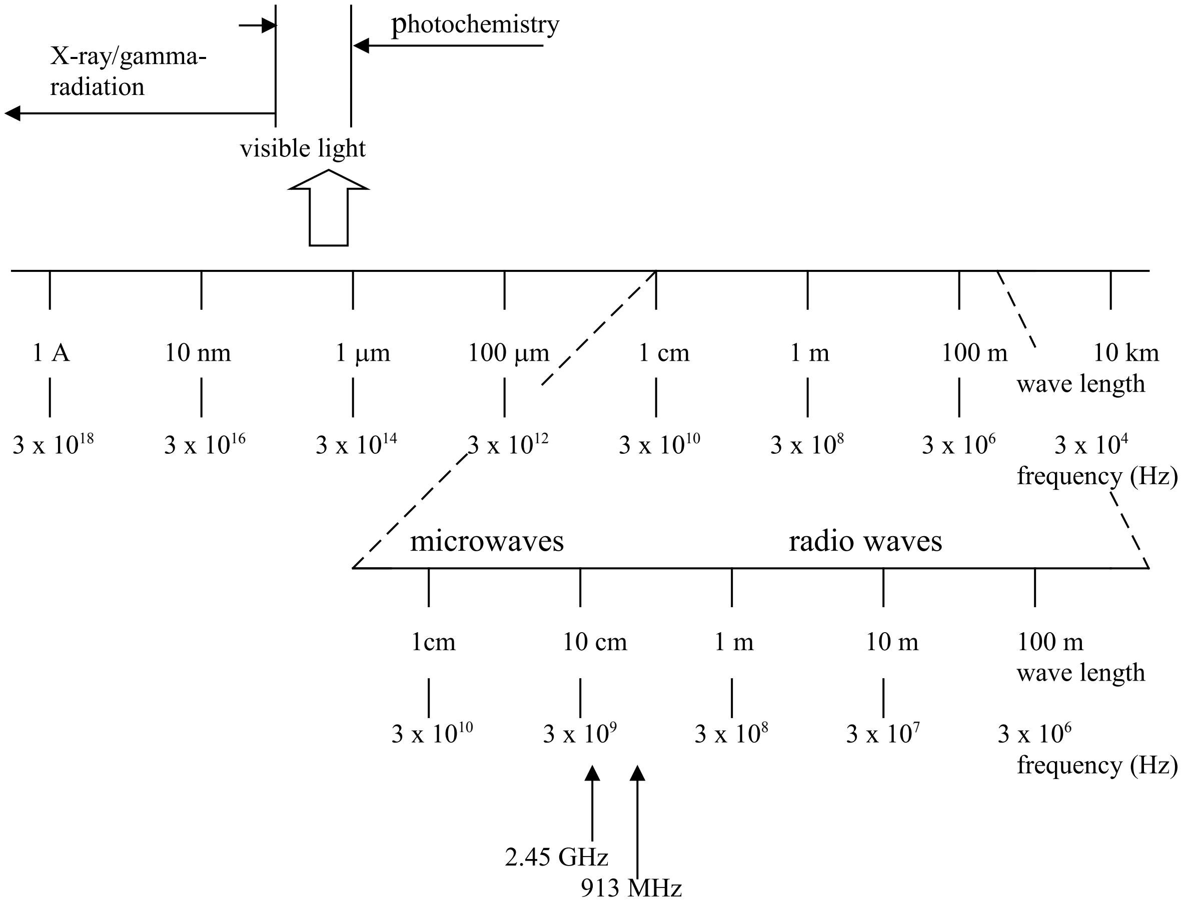
Possibilities for alternative energy input

The following list summarizes some possibilities of alternative energy input:

- chemical reactions by X-ray or gamma-radiation
- plasmachemistry
- photochemistry
- microwave-assisted chemistry
- mechanochemistry
- sonochemistry

Different frequency domains of the electromagnetic spectrum (EMS, Fig. 1) have a great influence on the energy input into chemical reactions.

Fig. 1: Electromagnetic spectrum



The use of radiation in the UV/Vis domain to initiate chemical reactions (150 to 800 nm) has been known for a long time. Photochemistry is an independent area of organic chemistry [2]. Photoreactions are quintessential for the existence of life on earth (photosynthesis). A number of large industrial-scale processes are initiated by UV/Vis radiation (sulfochlorination, photonitrosation, photochlorination). The energy of a photon from this part of the EMS can be used for either constructive (synthesis) reactions as well as for destructive reactions. As in many other parts of chemistry, the results of the conversions are influenced by the reaction conditions. For further details please refer to text books on photochemistry [e.g. 3].

Microwave-assisted reactions and processes: background

The foundations of microwave technology date back to the time shortly before World War II. Since the 1970s, microwaves were used in the food industry. During the 1980s, applications in the laboratory and industrial processes emerged. First chemical reactions that can be referred to as organic syntheses are reported in the year 1986 [4, 5].

Interestingly, in the case of microwave use for synthetic chemistry, an energy source was employed for research purposes that had previously been used million fold for cooking, heating of food, drying etc. [6]. DDevices designed for these purposes exhibit certain safety standards for the use of electromagnetic radiation, however, are not suitable for the conduction of chemical reaction according to GLP (good laboratory practice) requirements.

A field in which microwaves are already exhaustively used in chemical laboratories is the extraction (microwave-assisted extraction – MAE) of organic pollutants from different matrices as well as the isolation and preparation of natural products. MAE becomes more and more an alternative to conventional Soxhlet extractions, which usually involve long extraction times and high amounts of solvents. Advantages of MAE are associated with the increased boiling point of the used extracting solvent due to pressure increase [7].

Microwave-assisted reactions and processes: basics

The physical fundaments of microwave radiation are rather simple and will be briefly discussed in the following sections.

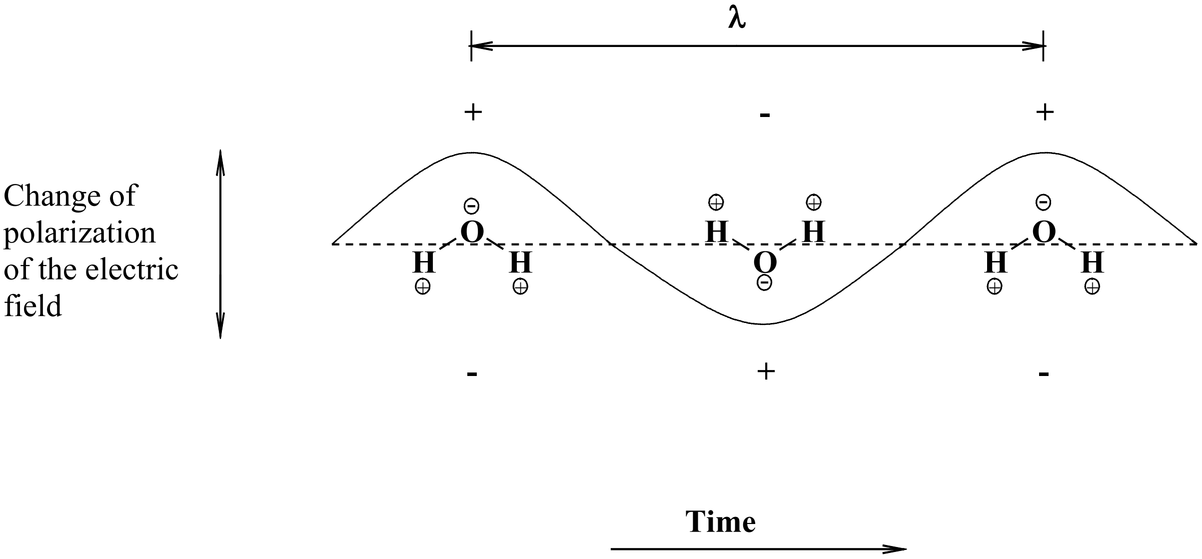
The wavelength λ_0 (often: 12.24 cm) relates to the frequency (2.45 GHz) by equation (5). The frequency indicates the number of oscillations of the electric or magnetic field per second [8].

$$\lambda_0 = \frac{c}{f} \qquad (5)$$

The action by which matter absorbs microwave energy is called dielectric heating [9]. An important property is the relative mobility of the dipoles and their capability of adjusting their orientation with the electric field. If amount and direction of the electric field change over time, the orientation of the dipoles changes as well. Molecules possessing a permanent dipole moment adjust themselves by rotation, partially or completely, in the direction of the field. In gases or liquids, molecules can rotate with field frequencies of 10^6 Hz and higher [10]. However, they cannot follow indefinitely fast inversions of the electric field. Upon irradiation with high frequencies of more than 10^8 Hz, the reorientation of the molecules does not occur simultaneously to the field inversion. Phase shift occurs and thus dielectric loss. Dielectric coefficients (permittivity) and size (mass) of the excited molecules are key factors. Field energy is transferred to the medium. Electric energy is converted into kinetic or thermal energy. This process is often described by a friction model. A large amount of polar substances shows dielectric loss in contact with microwaves [10].

A simplified depiction of the heating mechanism of polar solvents by microwave radiation is shown in Fig. 2 for the example of a water molecule. The quickly changing electric field of the microwave radiation leads to a rotation of the water molecules. As a consequence, “internal friction” takes place inside the polar medium, which results in a direct and very even heating of the reaction mixture. However, reflections and refractions on local boundaries lead to so-called “hot spots” and to the broadly discussed “superheating” effect [11].

Fig. 2: Energy transmission by microwaves for the example of water



Coupling in of microwave energy in the medium depends on the dielectric properties of the substance to be heated, i.e. how strongly microwaves are impeded on their passage through the substance [10]. A measure for this property is the relative dielectric coefficient εr, which is characteristic for each substance and state. ε_r is related to C (the capacity to store electric energy) by equation (6):

$$\varepsilon_r = \frac{C}{C_0} \qquad (6)$$

For electromagnetic fields, ε_r is extended by an imaginary part i ε_r'' according to eqation (7) ($i^2 = -1$):

$$\varepsilon_r = \varepsilon_r' + i\varepsilon_r'' \qquad (7)$$

The dielectric loss factor ε_r'' (also called dynamic dielectric coefficient) is obtained from the comparison of irradiated microwave power and the actual power absorbed by the sample. ε_r'' depends on the electric conductivity σ and the frequency *f* by equation (8):

$$\varepsilon_r'' = \frac{\sigma}{2\pi f} \qquad (8)$$

In a reaction system, the degree of coupling is determined by the ε_r' and ε_r'' and is called dissipation factor D = tan δ, equation (9):

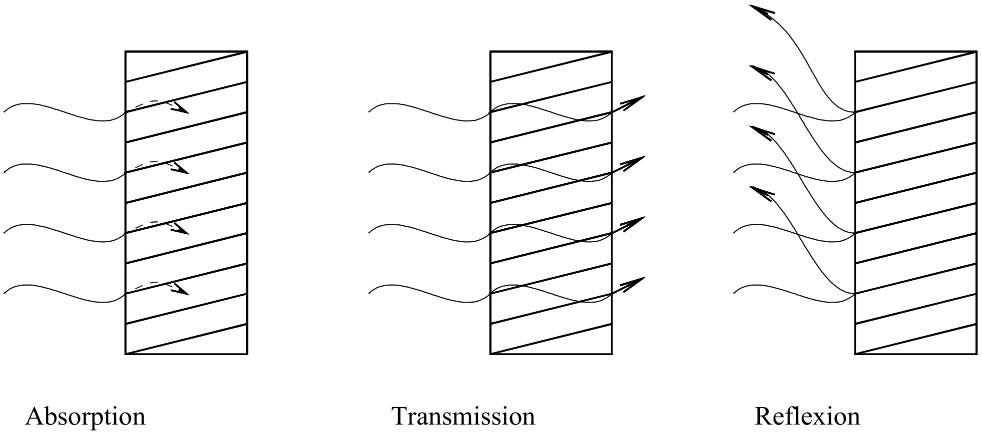
$$D = \tan\delta = \frac{\varepsilon_r''}{\varepsilon_r'} \qquad (9)$$

$$\tan \delta \sim \frac{1}{x} \qquad (10)$$

The dissipation factor defines the ability of a medium to convert electromagnetic energy into heat for a given frequency and temperature. It can also be understood as a measure of the penetration depth of microwave radiation into the material and is inversely proportional to x (equation (10)). By definition, penetration depth is the value at which still 37% (1/e) of the initially irradiated microwave power is present. Since both, the penetration depth as well as the dissipation factor, are strongly temperature dependent, they have to be considered when planning industrial reactors. Depending on the energy coupling in (ion conduction or dipole rotation), the dissipation factor depends on different factors and is directly proportional to the ion concentration, ion size, microwave frequency, and viscosity of the reacting medium. The dissipation factor of water and most organic substances decreases with increasing temperature, i.e. the coupling in of microwave energy into water worsens at high temperatures. Thus, the penetration depth of microwave radiation increases.

Dielectric coefficients for a number of substances such as organic and inorganic compounds, e.g. plastics, ceramics, waxes, glasses and food, are documented in the literature (cf. [12]). For common organic substances, temperature dependence of the dielectric coefficient is known [12]. However, comprehensive knowledge is still missing.

Fig. 3: Interaction of microwave radiation with matter



The interaction of electromagnetic radiation with matter is characterized by three different processes: absorption, transmission, and reflection (Fig. 3, [13]). Substances with high dielectric properties show strong absorption of microwaves and thus strong heating of the material. That means that ε_r'' and tan δ are large and the penetration depth of microwaves into the medium is small. Optimal coupling in of energy into the system prevails.

If microwave radiation is reflected on the material surface, none or only small energy coupling in takes place. In most cases, temperature increase can then be neglected. This is especially true for metals having a high electric conductivity. In order to prevent microwave radiation from reaching outside the microwave device, the interior of the microwave is covered with metal surfaces (Faraday cage). Since interactions also take place with the boundary surfaces, irradiated energy is "extinct" very quickly in an empty microwave system (heating of the boundary surfaces of the microwave space) and no decay periods can be measured.

Nonpolar substances show only little interaction with penetrating microwaves and therefore are suitable as materials to construct reactors. These materials include quartz, highly purified aluminum oxide (corundum), some specialty glasses, and mostly plastics. While polyethylene and polypropylene are only suited for external parts of the reactors, due to their low softening point, fluorocarbon polymers with their high temperature and chemical resistance can be used for parts that have direct contact with the hot reaction mixtures.

Due to the widespread use of microwaves in the communication sector, international treaties only permit few selected frequencies for other applications [6]. So-called ISM frequencies are summarized in Tab. 1.

Table 1: ISM frequencies permitted by international treaties (ISM – frequencies for **i**ndustrial, **s**cientific and **m**edical use)

Frequency	Wave length
433.92 MHz ± 0.2 %	69.14 cm
915 MHz ± 13 MHz (*)	32.75 cm
2450 MHz ± 50 MHz	12.24 cm
5800 MHz ± 75 MHz	5.17 cm
24125 MHz ± 125 MHz	1.36 cm

(*) not permitted in Germany

For a few years, technical microwave, especially for the use in chemical applications, have been developed and improved the possibilities of carrying out microwave-assisted reactions. The great advantages associated with these microwaves stimulated an interest of transferring this technology to the industrial scale. While discussing about the advantages of microwave-assisted power input into chemical reactions and process, one always must consider that the energy of microwaves is far too small to initiate chemical reactions in the sense of the collision theory. Tab. 2 lists different bond energies and relevant frequencies.

Table 2: Comparison between bond energies of selected covalent bonds and the energy content of microwave photons of different frequencies [14, 15]

	Energy [eV]
C-C – bond	3.61
C=C – bond	6.35
C-O – bond	3.74
C=O – bond	7.71
C-H – bond	4.28
O-H – bond	4.80
Hydrogen bond	0.04 – 0.44
Microwaves f = 300 MHz	1.2×10^{-6}
Microwaves f = 2.45 GHz	**1.0×10^{-5}**
Microwaves f = 300 GHz	1.2×10^{-3}

Technical possibilities for carrying out microwave-assisted reactions and separations

A number of manufacturers (e.g. Hitachi, Panasonic, Sharp, Siemens) produces worldwide different types of household microwave ovens, which differ in size, power, and equipment. All of them, however, have a closed, microwave-tight cavity (Pic. 1). Most of these household microwave ovens operate with a radiation of 2.45 GHz. The reason for the selection of this wavelength is the inexpensive manufacturing of magnetrons that produce this microwave radiation. In household microwave ovens, the homogeneity of the microwave field is relatively small but sufficient for its intended purpose of heating food. The field distributions of the same devices already alter from on serial number to the next and are thus incomparable.

Pic. 1: Example of a household microwave oven

First experiments on microwave-assisted syntheses were performed in such systems. The used devices exhibit a certain safety standard for working with electromagnetic radiation; however, they are only partly suitable for performing chemical reactions. The setting and control of experimental parameters is restricted to power input and the irradiation time (assuming an equidistant power distribution). The measurement of pressure and temperature poses enormous problems. Therefore, comparison with conventional reactions is difficult and often leads to speculations of non-thermal (or microwave) effects. Reactions are only controlled by power input without a temperature limitation.

The use of household microwave ovens for chemical reaction in the laboratory and for educational purposes cannot be recommended due to safety reasons.

In another development field, microwaves have been used for 15 years to perform decomposition reactions, primarily in the sample preparation for elementary analysis procedures (AAS, ICP-MS). A number of methods in this area have been adopted by the US Environmental Protection Agency (EPA) as standard methods [16].

For this purpose, microwave devices were built possessing the required safety standards for handling electromagnetic radiation and aggressive chemicals at high pressures and temperatures. These systems also work at frequencies of 2.45 GHz and are controlled by special software.

Two trends can be observed in the development of microwave systems for organic chemistry:

One trend features the development of small devices or special applications. Small devices allow for small-scale reactions in the mmol-range in short times (few minutes) and with comparatively high power input. They have small microwave cavities (approx. 1 L) or openings for the reactor directly in the wave guide, which often allow only for the use of small sealed reactors in the shape of GC-vials. Organic chemists can use these systems if they are only looking for a yes/no-answer considering the course of the reaction. If precise and reproducible reaction conditions, kinetics, or scale-up to 0.1 mol products (factor 100) are required, these systems fail. From an educational point of view, these devices often represent “black boxes” and are therefore only of minor value for teaching purposes. Examples of such devices include the EMRYS line from Personal Chemistry (S) with different degrees of automatization, the Synthewave line from Prolabo (F) (no longer existing) with real “monomode” systems, and the Discovery system from CEM (U.S.). Some microwave systems available for organic syntheses are summarized in Tab. 3.

In addition to the previously mentioned systems, another modular system is offered commercially (ETHOS system from MLS GmbH / Milestone srl). Depending on the specific requirements, the system allows for flexible reaction engineering by using different reactors in one basic device. Advantages of microwave energy can be exploited while reaction parameter can always be precisely controlled. In this modular system reactions can be carried out from the mmol to the mol-scale. Furthermore, a transition from batch reaction to continuous systems can be envisioned and has been proven for some reaction types [17, 18]. Derived form the basic system, a system for beginners with simplified measurement equipment is offered (PRAKTIKA). Maximal power is 1000 W (800 W for the PRAKTIKA-System), which can be regulated in 10 W increments.

Tab. 3: Comparison between available microwave systems for synthesis

	Household microwave R-220A Sharp	Emrys ™ Creator Fa. Personal Chemistry	Discovery ™ Fa. CEM	ETHOS ™ MR Fa. MLS / Milestone
Irradiation mode	multimode	monomode	monomode	multimode
max. power	800 W pulsed	300 W non pulsed	300 W, non pulsed	1000 W pulsed or non pulsed
Cavity	15.7 L	approx. 1 L	approx. 1 L	42.8 L
max. power density inside the empty oven	approx.50 W/L	approx. 300 W/L	approx. 300 W/L	approx. 23 W/L
Reaction scale	max. 100 g for dry reactions	< 20 g	< 50 g	up to 3000 g depending on the reactor

The devices feature different temperature measurement methods, multiple control parameters for energy input, and specially designed reactors for handling chemicals safely. Applications in the area of synthetic chemistry can use all reactors known from conventional lab glassware. In general, all metal parts must be avoided inside the microwave device. Exceptions will be discussed later.

Experimental conditions of a microwave experiment depend on the technical data of the microwave device. In order to develop precise instructions for the safe use of microwave reactions in the scope of the organic chemical lab class, a microwave device had to be chosen as reference. All experiments were performed with an ETHOS device from MLS GmbH, Leutkirch, Germany. This device fulfills all safety and technical requirements for laboratory experiments. The following sections refer to this device and its accessories only. In principle, all microwave experiments described in NOP can be carried out with devices from different manufacturers. Power and experimental parameters, technical and safety instructions have to be verified and adapted accordingly.

Pic. 2 shows the basic device (ETHOS MR from MLS GmbH, Leutkirch, Germany) with a reflux apparatus. The sole difference to a regular reflux apparatus is the glass connection tube, which connects the vessel inside the microwave cavity with the reflux condenser outside the microwave field. The apparatus can be easily extended by adding tap funnels, water separators, distillation bridges, or precision glass stirrers, which are commonly added outside the microwave device using Claisen stillheads.

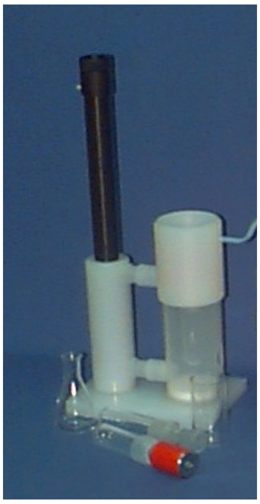
Pic. 2: Microwave system ETHOS MR with reflux apparatus (temperature measurement with fiber optic sensor)

Experiments summarized in Tab. 4 were carried out with this device. As a comparison, conventionally conducted reactions are listed as well.

In addition to "regular" reflux apparatuses, special reactors with internal air cooling were developed. Single and multiple reactors are available. Thus, group work is possible in addition to reaction optimization. Pic. 3 shows a single reactor, an 8-segment rotor, and a 15-segment rotor with 20 mL reaction vessels. Temperature measurement can be performed by fiber optic or IR sensors. Air cooling is achieved by ventilation of the microwave cavity and special inlets.

Pic. 3: Reactors with internal air coolers for the use in technical microwave systems of the ETHOS or PRAKTIKA type

Pic. 3a: Single reactor



Pic. 3b: 8-segment reflux rotor MMR 8 with faseroptischer Temperaturmessung

Pic. 3c: 15-segment reflux rotor for group experiments and parallel syntheses

With these reactor systems, experiments requiring reflux as well as parallel syntheses can be carried out on the 1 – 10 mmol-scale. Cooling is advantageous by using the ventilation inside the microwave system or the specific air supplies for air cooling of the reactors. The use of air-cooling, however, requires some knowledge on microwave energy and controlling microwave-assisted reactions, and thus should be reserved for advanced lab classes.

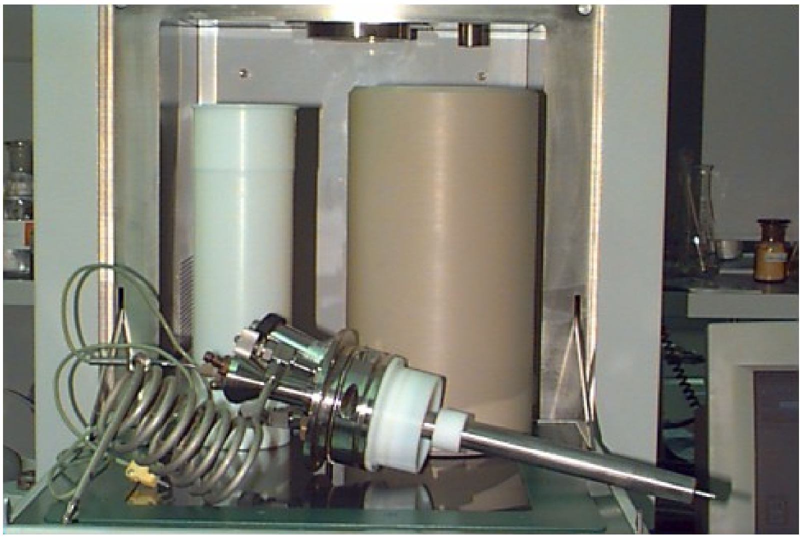
Several simple pressure reactors are available to extent the temperature range above the boiling point of the employed solvent. These reactors were primarily developed for decompositions but are very useful for organic syntheses as well, Pic. 4.

Pic. 4: Pressure reactors for the use in technical microwave systems of the ETHOS and PRAKTIKA type

Pic. 4a: 6-segment high-pressure reactor

Pic. 4b: 36-segment pressure reactor

Pic. 4c: Microwave autoclave with 500 mL reaction vessel (mechanical or magnetic stirring, inert/reaction gas feed, internal cooling)



Pic. 4 depicts single reactors as well as rotors with integrated multiple reactor systems. They can be used for reaction optimization by varying the molar composition as well as for group experiments in the organic lab classes. Plastic or glass reactors can be used for reaction volumes of up to 50 mL and, depending on the material, for temperatures up to 280 °C and pressures of 40 bar. Pressure and temperature measurements are performed in a lead vessel. Experiments conducted in these reactors are summarized in Tab. 5. For comparison purposes, experiments with conventional methods are also listed.

For the transfer of experiments from reflux apparatuses to pressurized systems it is necessary to precisely know the course of reactions and the associated physical data. The same holds true for scale-up and the transfer to continuously operated processes.

In addition to chemical reactions, a number of thermal separations or combinations with chemical reactions can be carried out in the microwave field without problems. Examples are extractions, different types of distillations (rectification, reactive distillation, steam distillation), drying, calcining, and recrystallization. Special reactors were constructed for these purposes (Pic. 5).

Pic. 5: Hot extraction filtration system

Advantages of the microwave-assisted processes are less time consumption, more precise temperature control directly in the distillation bottom of the extractor, and the controllable energy input.

Table 6 summarizes some examples of thermal separations in the microwave field. The examples show that the use of microwaves in the synthesis lab is not restricted to reactions only but can be used for other processes requiring higher temperatures. Therefore, technical microwave systems are required and, due to technical insufficiencies, house hold microwave ovens are not suitable.

Experimental instructions for reactions and processes in the microwave field

Studying the literature on microwave-assisted experiments, it is noticeable that in only few cases the reaction conditions are described in such detail that they can be reproduced without greater problems in the same system as described or in other systems. Mostly, important facts are missing such as the batch size, maximal temperature, and power input.

The same data are necessary for all other processes as well, e.g. work-up or reaction mixtures. While the use of conventional energy sources is mostly standardized, microwave-assisted reactions or separations are strongly dependent on experimental conditions and employed substances. This has to be accounted for by a precise description of experimental conditions.

Table 4: Comparison between microwave-assisted and conventional syntheses (reflux apparatus)

Microwave-assisted reaction	**Microwave-assisted reaction (literature)**	**Conventional reaction, literature and own experiments**
Toluene nitration: ● T: ice bath + max. 60 °C ● t: 0.5 h + 1 min ● batch size: 100 mmol ● molar ratio: 1 : 1.5 ● activator: sulfuric acid ● yield: 88%		● T: ice bath + room temperature ● t: 0.5 h + 2h ● batch size: 100 mmol ● molar ratio: 1 : 1.5 ● activator: sulfuric acid ● yield: 75% [1
Acetalization of 3-nitrobenzaldehyde with glycol: ● T: 130 °C ● t: 50 min ● batch size: 100 mmol ● molar ratio: 1 : 1.5 ● catalyst: p-toluenesulfonic acid ● yield: 91%		● T: reflux with cyclohexane ● t: 2 – 3 h ● batch size: 100 mmol ● molar ratio: 1 : 1.1 ● catalyst: p-toluenesulfonic acid ● yield: 92% [2]
Friedel-Crafts-acylation: fluorescein synthesis: ● T: 220 °C ● t: 30 min ● batch size: 135 mmol ● molar ratio: equimolar ● catalyst: none ● yield: 82%		● T: 170 °C ● t: 10 h ● batch size: 135 mmol ● molar ratio: equimolar ● yield: 73% [3] ● T: 180 – 210 °C ● t : 1-2 h ● batch size: 0.1 mol ● molar ratio: equimolar ● catalyst: $ZnCl_2$ (50 mmol) ● yield: quantitative [4]
Synthesis of copper phthalocyanine: ● T: 200 °C ● t: 30 min ● batch size: 4.5 mmol ● molar ratio: 18.4 : 3.6 : 1 ● catalyst: $(NH_4)_2MoO_4$	● T: unknown ● t: 4.5 – 7 min ● batch size: 0.05 mol ● molar ratio: 18.4 : 3.6 : 1	● T: 200 °C ● t: 30 min ● batch size: 4.5 mmol ● molar ratio: 18.4 : 3.6 : 1 ● catalyst: $(NH_4)_2MoO_4$

● yield: 93%	● catalyst: $(NH_4)_2MoO_4$ ● yield: 86% (household microwave oven) [5]	● yield: < 10% [6]
Knoevenagel condensation: ● T_1: 110 °C / 20 min ● T_2: 140 °C / 5 min ● batch size: 0.25 mol ● molar ratio: equimolar ● catalyst: AcOH/piperidine (15/30 mmol) ● on-pot reaction ● yield: 72%		● T: 110 °C ● t: 2 – 6 h ● batch size: 0.5 mol / 150 mL benzene ● molar ratio: equimolar ● catalyst: AcOH/piperidine (30/60 mmol) ● Dean-Stark-apparatus ● yield: 75 % [6,7]
Acetylsalicylic acid: ● T: 140 °C ● t. 60 sec ● batch size: 0.2 – 1.0 mol ● molar ratio: 1 : 1.2 ● catalyst: none ● yield: 92%	● T: 120 – 130 °C ● t: 90 sec ● batch size: 15 – 150 mmol ● molar ratio: 1 : >1 ● catalyst: none ● yield: no data [8]	● T: 140 °C ● t: 2 h ● batch size: 1 mol ● molar ratio: 1 : 1.2 ● catalyst: H_2SO_4 ● yield: 85%
Condensation of benzoin with urea: ● T: 150 °C ● t: 11 min ● batch size: 94 mmol ● molar ratio: 1 : 3.5 ● yield: 74%	● T: unknown ● t: 3 – 5 min ● batch size: 10 mmol ● molar ratio: 1 : 3.5 ● yield: 65% (household microwave oven) [10]	● T: 180 °C ● t: 60 min ● batch size: 4.7 mmol ● molar ratio: 1 : 3.6 ● yield: 70% [6,11]

References (Tab. 4):

[1] S. Hünig, G. Märkl, J. Sauer; Integriertes organisches Praktikum; Verlag Chemie, Weinheim **1979**

[2] Integriertes Organisch-Chemisches Praktikum, Regensburg, **2000**, Versuch-Nr. 4.1.1.3

[3] J. O. Metzger, personal communication, Oldenburg **2000**

[4] W. Gattermann, „Die Praxis des organischen Chemikers“, Verlag de Gruyter, Berlin - New York **1982**, 584-595

[5] A. Shaabani, *J. Chem. Res. (S)*, **1998**, 672-673

[6] Testreaktionen, FSU Jena, ITUC, Jena **2002**

[7] Autorenkollektiv, „Organikum: organisch-chemisches Grundpraktikum", 20., bearb. und erw. Aufl., korr. Nachdruck, Wiley-VCH, Weinheim **1999**, 502

[8] A. K. Bose, B. K. Banik, N. Lavlinskaia, M. Jayaraman, M. S. Manhas, *CHEMTECH*, **1997**, 18-24

[9] Lit. [7] 444-445

[10] J.-C. Feng, Qu.-H. Meng, Y. Liu, L. Dai, *Org. Prep. Proc. Int.* **1997**, *29*, 687-689

[11] B. K. Yong, S. K. Chung, K. L.Chang, *J. Heterocyclic Chem*. **1994**, *31*, 1653-1656

Table 5: Examples for the use of pressurized reactors in microwave-assisted reactions compared to conventional reactions

Microwave-assisted reactions	**Conventional reactions, literature and own experiments**
Biginelli reaction: ● T: 110 °C ● t: 20 min ● batch size: 0.1 mol ● 3% urea excess ● molar ratio: 1.03 : 1 : 1 ● catalyst: HCl/EtOH 25 mL ● yield: 75%	● T: 80 – 90 °C ● t: 4 – 8 h ● batch size: 0.01 – 1 mol ● high urea excess ● molar ratio: different ● catalyst: HCl/EtOH ● yield: 78% ● T: 25 °C ● t: 12 h ● batch size: 0.05 mol ● 50% urea excess ● molar ratio: 1.5 : 1 : 1 ● catalyst: HCl/EtOH 5 mL ● yield: 70% [2]
Fischer-glycosidation of glucose with methanol: ● T: 140 °C ● t: 40 min ● batch size: 27 mmol ● molar ratio: 1 : 37 ● catalyst: acetyl chloride ● yield: quantitative [3]	● T: 70 – 75% ● t: 8 – 24 h ● batch size: 0.01 – 10 mol ● molar ratio: different ● catalyst: different acids ● yield: 80% [2,4]
Polycondensation of ε-caprolactam: ● T: 200 °C ● p: 50 mbar ● t: 45 min ● batch size: 25 mmol ● H_2O: 10 – 25 mmol ● yield: 80%	● T: 250 °C ● p: >1 bar (ampoule) ● t: 4 h ● batch size: 25 mmol ● catalyst: HCl (1 drop) ● yield: not determined [5]

References (Tab. 5):

[1] P. Biginelli, *Gazz. Chim. Ital*. **1893**, *23*, 360-416

[2] Testversuche, FSU Jena, ITUC, Jena **2001-2002**

[3] M. Nüchter, B. Ondruschka, W. Lautenschläger, *Synth. Commun*. 2001, *31*, 1277-1283

[4] K. Hill, W. von Rybinski, G. Stoll (eds.), "Alkyl Polyglycosides", VCH, Weinheim **1997**, 1-22

[5] Autorenkollektiv, „Organikum: organisch-chemisches Grundpraktikum", 20., bearb. und erw. Aufl., korr. Nachdruck, Wiley-VCH, Weinheim **1999**, 625

Table 6: Examples of microwave-assisted separations

Microwave-assisted process	**Application**
Reactive distillation	**Reactor**: glass distillation apparatus with packed column T: up to 150 °C, vacuum up to 100 mbar Batch size: up to 2 L reaction mixture ● conversion of higher carbon acids with acetic anhydride to acetic acid and higher carbon acid derivatives ● reactive esterification of tert. alcohols with carbon acid anhydrides
Steam distillation	**Reactor**: glass distillation apparatus Time: 30 min for 250 mL destillate No additional steam source required (phenol nitration) ● isolation of ethereal oils (lavender, hemp)
Rectification	**Reactor**: glass distillation apparatus with packed column T: up to 150 °C, vacuum up to 100 mbar Batch size: up to 2 L reaction mixture ● purification of carbon acid anhydrides
Extraction I	**Reactor**: 6-segment high pressure reactor [1] T = 120 °C, t < 20 min Sample preparation for the determination of aromatics in soil
Extraction II	**Reactor**: hot extraction filtration system Hot extraction of products Isolation of natural products from plants
Recrystallization or hot extraction at ambient pressure	**Reactor**: reflux apparatus

References (Tab. 6):

[1] a) U. Nüchter, B. Ondruschka, H. G. Struppe, M. Nüchter, *Chem. Technik* **1998**, 50, 249-252,
b) C. Struppe, M. Nüchter, B. Ondruschka, *Chem. Technik* **1999**, *51*, 127-129

References:

[1] Autorenkollektiv, “Organikum: organisch-chemisches Grundpraktikum”, 20., bearb. und erw. Aufl., korr. Nachdruck, Wiley-VCH, Weinheim **1999**, 13-17

[2] a) *http://www.chemie.uni-hamburg.de/oc/marga/pages/englisch_0006pag.html* b) *http://www.chemlin.net/chemistry/photochemistry.htm*

[3] a) H. G. O. Becker, “Einführung in die Photochemie”, Thieme –Verlag Stuttgart 1983

b) M. Klessinger, “Lichtabsorption und Photochemie organischer Moleküle”, 1. Aufl., VCH, Weinheim, New York 1989

c) J. Mattay, A. Griesbeck (Eds.) “Photochemical Key Steps in Organic Synthesis”, VCH, Weinheim, New York **1994**

d) D. Wöhrle, M. W. Tausch, W.-D. Stohrer “Photochemie. Konzepte, Methoden, Experimente”, Wiley-VCH **1998**

Microwave-assisted reactions and processes:

[4] R. Gedye, F. Smith, K. Westaway, H. Ali, L. Baldisera, L. Laberge, J. Rousell, *Tetrahedron Lett.* **1986**, *27*, 279-283

[5] R. J. Giguere, T. L. Bray, S. M. Duncan, G. Majetich, *Tetrahedron Lett.* **1986**, *27*, 4945-4949

[6] *https://www.pueschner.com/basics/phys_basics_en.php*

[7] a) K. Ganzler, I. Szinai, A. Salgó, *J. Chromatogr*. **1990**, *520*, 257-262, b) V. Lopez-Avila, R. Young, J. Benedicto, P. Ho, R. Kim, W. F. Beckert, *Anal. Chem*. **1995**, *67*, 2096-2102

[8] D. M. P. Mingos, D. R. Baghurst “Applications of Microwave Dielectric Heating Effects to Synthetic Problems in Chemistry” in: Microwave Enhanced Chemistry (Eds.: H. M. Kingston, St. J. Haswell) ACS, Washington (DC) **1997**, 3-53

[9] D. M. P. Mingos, D. R. Baghurst *Chem. Soc. Rev.* **1991**, *20*, 1-47

[10] C. Gabriel, S. Gabriel, E. H. Grant, B. S. J. Halstead, D. M. P. Mingos, *Chem. Soc. Rev.***1998**, *27*, 213

[11] D. R. Baghurst, D. M. P. Mingos *J. Chem.. Soc., Chem. Commun*. **1992**, 674-677

[12] D. R. Lide, in: CRC Handbook of Chemistry and Physics, 76th ed.; CRC press: Boca Raton, Ann Arbor, London, Tokyo **1992**, Sec. 6, 193-215

[13] W. Lautenschläger, I. Flöter, G. Schwedt, *LaborPraxis* – Juli/August **1998**, 42-44

[14] P. W. Atkins “Physical Chemistry”, Oxford University Press, **1990**, 938

[15] D. A. C. Stuerga, P. Gaillard, *J. Microwave Power and Electromagn. Energy* **1996***, 31,* 87-113

[16] *EPA Method 3015*: MICROWAVE ASSISTED ACID DIGESTION OF AQUEOUS SAMPLES AND EXTRACTS

EPA Method 3051: MICROWAVE ASSISTED ACID DIGESTION OF SEDIMENTS, SLUDGES, SOILS, AND OILS

EPA Method 3052: MICROWAVE ASSISTED ACID DIGESTION OF SILICEOUS AND ORGANICALLY BASED MATRICES

[17] M. Nüchter, B. Ondruschka, A. Jungnickel, U. Müller, *J. Phys. Org. Chem.* **2000**, *13*, 579-586

[18] M. Nüchter, U. Müller, B. Ondruschka, A. Tied, W. Lautenschläger**,** *Chem. Ing. Tech.* **2002**, *74*, 910-920

Selected reviews and books on the topic of "microwave-assisted reactions and processes"

1) Reviews

a) R. N. Gedye, F. E. Smith, K. Ch. Westaway, *Can. J. Chem*. **1988**, *66*, 17-34

b) R. A. Abramovitch, *Org. Prep. Proc. Int.* **1991**, *23*, 685-711

c) A. G. Whittaker, D. M. P. Mingos *J. Microwave Power and Electromagn. Energy* **1994**, *29,* 195-219

d) S. Caddick, *Tetrahedron* **1995**, *51*, 10403-10432

e) Ch. R. Strauss, R. W. Trainor, *Aust. J. Chem.* **1995**, *48*, 1665-1692

f) K. C. Westaway, R. N. Gedye, *J. Microwave Power and Electromagn. Energy* **1995**, *30*, 219-229

g) A. K. Bose, B. K. Banik, N. Lavlinskaja, M. Jayaraman, M. S. Manhas, *CHEMTECH* **1997**, 18, 479-488

h) S. A. Galema, *Chem. Soc. Rev*. **1997**, *26*, 233-238

i) R. N. Gedye, J. B. Wei, *Can. J. Chem.* **1998**, *76*, 525-537

j) Ch. R. Strauss, *Aust. J. Chem*. **1999**, *52*, 83-96

k) R. J. Varma, *Green Chem.* **1999**, *1*, 43-55

l) N. Elander, J. R. Jones, S.-Y. Lu, S. Stone-Elander, *Chem. Soc. Rev*. **2000**, *29*, 239-249

m) L. Perreux, A. Loupy, *Tetrahedron* **2001**, *57*, 9199-9223

n) P. Lidström, J. Tieney, B. Wathey, J. Westmann, *Tetrahedron* **2001**, *57*, 9225-9283

2. Books

a) R. van Eldik , C. D. Hubbard (Eds.), “Chemistry Under Extreme or Non-classical Conditions”, John Wiley & Sons and Spektrum Akademischer Verlag Co-Publication: New York and Heidelberg, **1997**;

b) H. M. Kingston, St. J. Haswell (Eds.), “Microwave Enhanced Chemistry” , ACS, Washington (DC) **1997**

c) A. Loupy (Ed.), “Microwaves in Organic Synthesis” Wiley-VCH, Weinheim, New York 2002

d) B. L. Hayes “Microwave Synthesis”, CEM Publishing, Matthews (NC) 2002