Microwaves Solution for Improving Woven Fabric

Drago Katovic
University of Zagreb
Faculty of Textile Technology
Croatia

1. Introduction

According to well known physical definition, electromagnetic waves are oscillating electric and magnetic fields traveling together through space. In the electromagnetic radiation spectrum, shown in figure 1, microwaves (300 MHz – 300 GHz) lie between radio wave (RF) and infrared (IR) frequencies, with relatively large wavelength (1m-1mm) (Metaxas & Meredith)

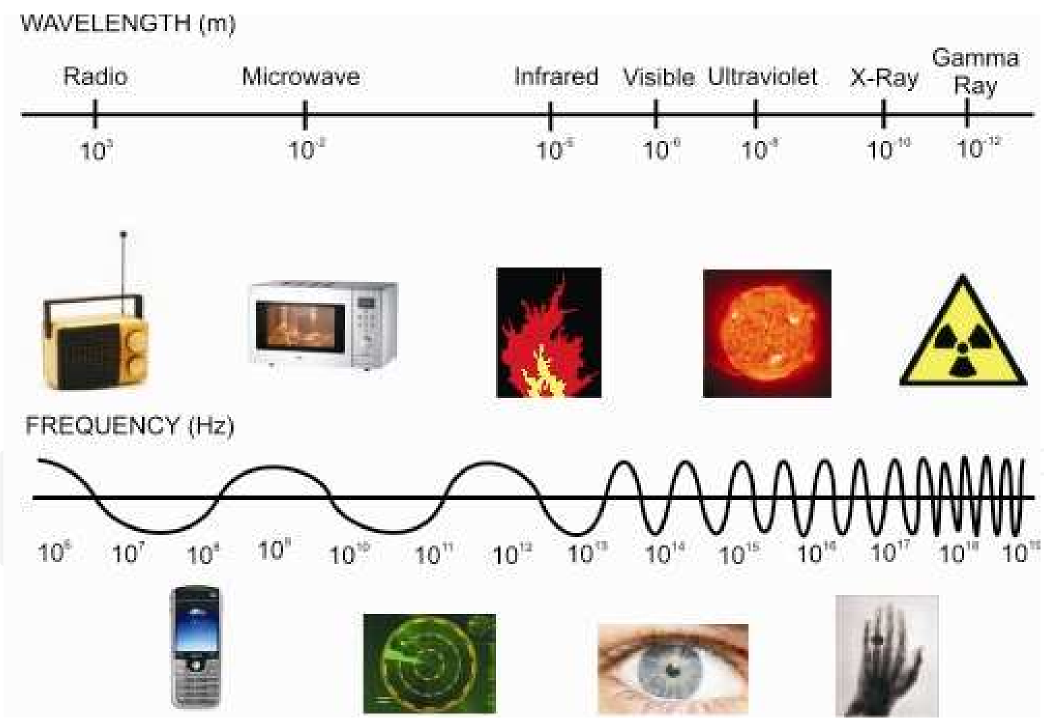


Fig. 1. Electromagnetic spectrum

Electromagnetic wave is formed by the electrical charge in the conductor that produces an electrical field in the spreading direction. The electrical field produces the magnetic filed. The so-formed magnetic field reproduces the electrical field in the space. The electrical field is perpendicular to the magnetic field, and both are perpendicular to the direction of the spreading wave.

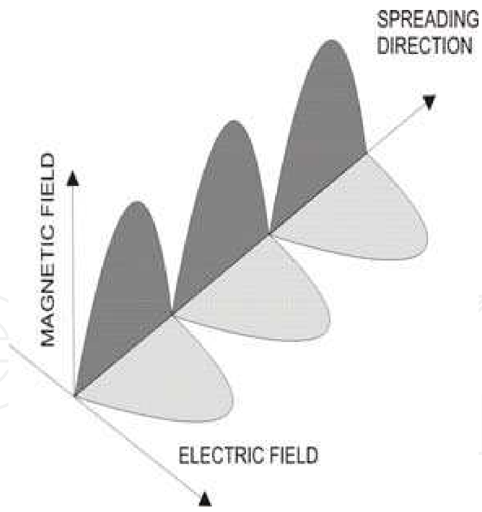


Fig. 2. Direction spread of electromagnetic wave

The energy of microwave photons is very low (0,125 kJ/mol) relative to the typical energies for chemical bonds (335-84 kJ/mol); thus microwave will not directly affect the molecular structure. They cannot change the electronic structure around atoms or among them, but they can interact with the electronic differences between atoms. However, chemical reactions can accelerate due to selective absorption of microwave energy by polar molecules, while non-polar molecules are inert to the microwave (MW) radiation (Varma 2001).

Different materials can be divided according to their response on microwave radiation:

- The materials that reflect MW radiation (stayed cold)
- The materials that are transparent to MW radiation (non-heated)
- The materials that absorb MW energy (being heated).

However, chemical reactions can be accelerated due to selective absorption of electromagnetic energy by polar molecules, while non-polar molecules are inert to the electromagnetic radiation. Besides influencing dipole water molecules, an alternating electromagnetic field also acts on partially polar molecules of textiles such as polyurethane (PU), polyacrylonitrile (PAN), or polyamide (PA)

A microwave electromagnetic field oscillating at 2.45 GHz, which is preferred frequency for heating applications, the charge changes polarity nearly 5 billion times per second. Microwave radiation is specially tuned to the natural frequency of water molecules to maximize the interactions.

Some important applications of microwaves come from their interaction with various types of material. The interaction of microwaves with dielectric materials causes a net polarization of the substance. There are several different mechanisms of polarization: electronic polarization, ionic, molecular (dipole) polarization and interfacial (space-charge) polarization. The overall net polarization creates a dipole moment. Dipole rotation is an interaction, in which polar molecules or species try to align themselves with the rapidly changing electric field of applied radiation. The motion of the molecule as it tries to orient to the field results in a transfer of energy. The second way to transfer energy is ionic conduction that occurs if there are free ions or ionic species present in the substance being heated.

The main difference between conventional heating with hot air and microwave heating is the heating mechanism. While conventional techniques heat a surface, the microwaves heat the whole volume of the treated object. During the conventional heating, the heat is generated outside the treated product and conveyed by conduction or convection. Hence, the surface is heated at first and afterwards the heat flows toward the inside, which always remains colder than the surface. The required internal temperature can be reached only by sufficient increase of the surface temperature of the material above the temperature needed for particular treatment.

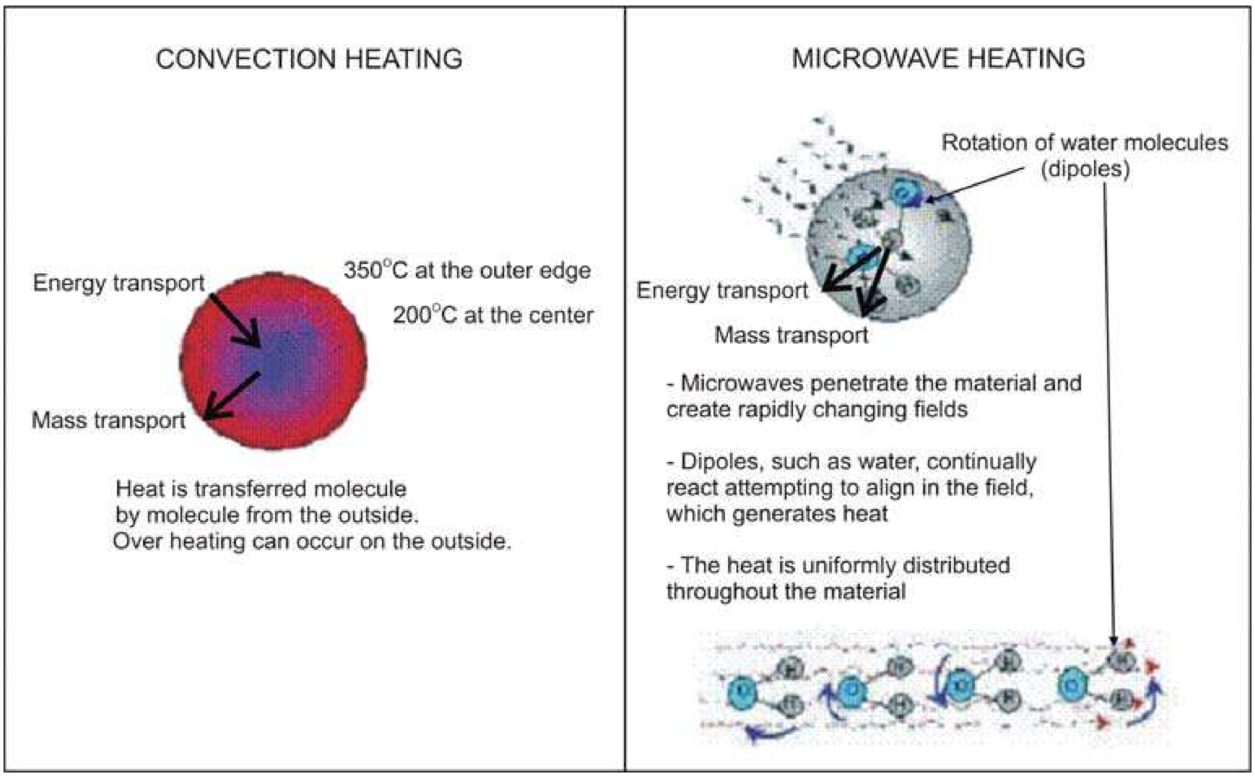


Fig. 3. Energy transfer comparison

On the contrary, in electromagnetic treatment, the heat is generated in a distributed manner inside of the material, allowing more uniform and faster heating. According to the literature (Metaxas & Meredith 1983) the energy consumption is 60-70 % lower in a case of electromagnetic treatment. For dielectric heating the generated power density per volume is calculated by

$$p = \omega \cdot \varepsilon_r'' \cdot \varepsilon_0 \cdot E^2 \tag{1}$$

where ω is the angular frequency, ε_r'' is the imaginary part of the complex relative permittivity, ε_0 is the permittivity of free space and *E* the electric field strength. The imaginary part of the complex relative permittivity is a measure for the ability of dielectric material to convert radio frequency electromagnetic field energy into heat.

What are the advantages microwave? Because volumetric heating is not dependent on heat transfer by conduction or convection, it is possible to use microwave heating for applications where conventional heat transfer is inadequate. One example is in heterogeneous fluids where the identical heating of solids and liquids is required to minimize over-processing. Another is for obtaining very low final moisture levels for product without over-drying. Other advantages include: Microwaves generate higher power densities, enabling increased production speeds and decreased production costs.

Microwave systems are more compact, requiring a smaller equipment space or footprint. Microwave energy is precisely controllable and can be turned on and off instantly, eliminating the need for warm-up and cool-down. Lack of high temperature heating surfaces reduces product fouling in cylindrical microwave heaters. This increases production run times and reduces both cleaning times and chemical costs. Microwaves are a non-contact drying technology. One example is the application of IMS planar dryers in the textile industry, which reduce material finish marring, decrease drying stresses, and improve product quality. Microwave energy is selectively absorbed by areas of greater moisture. This results in more uniform temperature and moisture profiles, improved yields and enhanced product performance. The use of industrial microwave systems avoids combustible gaseous by-products, eliminating the need for environmental permits and improving working conditions.

What are the disadvantages? Historically, the primary technological drawback to using microwave energy for industrial processing has been the inability to create uniform energy distribution. If uniform energy distribution is not present, wet regions of the target material are underexposed, and other regions are overexposed. This is analogous to the hot spots and cold spots generated in your microwave oven at home when heating or defrosting food like a potato or frozen chicken. Severe overexposure of non-uniform energy distribution may provide excessive focus of heat build up resulting in burnt material or a fire hazard. The uniformity of distribution designed into IMS microwave equipment overcomes this problem. Another disadvantage is the depth of penetration achievable using microwave energy. This is a function of microwave frequency, dielectric properties of the material being heated and its temperature. As a general rule, the higher the frequency, the lower the depth of penetration. 2,450 MHz versus 915 MHz? 915 MHz generators can provide up to 100 KW from a single magnetron. Although the cost is similar, the largest commercial 2,450 MHz units available use 30 KW magnetrons. 915 MHz generators lose about 15% efficiency in producing electromagnetic energy from electric power. However, the conversion of that energy into useful heating or drying is often greater than 95% so that the total system efficiency usually exceeds 80%. This compares with 55 to 70% total system efficiency obtainable from 2,450 MHz generators. The depth of penetration of microwave energy at 915 MHz is about three times as great as that at 2,450 MHz. With their higher total system efficiencies, 915 MHz heaters and dryers tend to have lower running costs than comparable 2,450 MHz units. One 100 KW 915 MHz generator will be about 50% cheaper than seven 15 KW 2,450 MHz units. The low power 2,450 MHz magnetrons developed from the proliferation of domestic microwave ovens are inexpensive and readily available. This makes them ideal for low flow capacity R & D applications. The size of magnetrons and wave-guides for a 2,450 MHz system is considerably smaller than those used in 915 MHz units. This makes them suitable for small-scale installations. 2,450 MHz is efficient where fast product expansion is required, such as dry frying of starch-based foods.

Today they are widely accepted and spread to mobile phones, television, wireless computer networks and some special applications such as rocket engines.

2. Microwave in textile finishing

The term "microwaves" was used for the first time in 1932nd, and its first usage was during the Second World War in radio communication and radar technology. The activity of electromagnetic field of high frequency was discovered accidentally during a radar-related research project, while testing a new vacuum tube, called a magnetron. After more then 50 years of investigation and development, the microwave heating technology is nowadays widely used in number of fields. Studies in the last decade suggest that microwave energy may have a unique ability to influence chemical processes. These include chemical and materials syntheses as well as separations (Tompsett et al. 2006). Until now, MW have been used for food preparation, chemical sludge, medical waste, organic synthesis (Cablewski et al. 1994), analytics and curing (Saito et al. 2004) of hi-tech polymers (Zubizarreta L at all). There are a number of papers dealing with synthesis of organic compounds using microwave (Varma R. 2001). Numerous chemical reaction of textile materials are discussed and presented; e.g. (Barantsev et al. 2007) substitution, additions esterfication (Satge et al (2000), transesterfications, acetylization, amidation and decarboxylation (Hou & Wang 2008). One of the advantages of using microwave radiation is its influence on the reaction kinetics. Kaynak investigated the influence of polymerization time and dopant concentraction on the absorption of microwave radiation in conducting polypyrrole coated textiles (Kaynak et al. 2009). Chang investigated microwave heating for butyrylation of wood with aim of reducing the reaction time (Chang & Chang 2003).

The effect of the sintering temperature on the structural characteristies of nanosized zirconium dioxide particles treated by microwave radiation the during process was investigated by small-angle X-ray scattering and the BET method. It was shown that the specific surface area, particle size, polydispersvity index, and surface and mass fractal dimensionality of zirconium dioxide depend on heat treatment conditions (Strizhak et al).

Microwave moisture measurement is capable of measuring the moisture application behind the padder in continuous dyeing processes and of evaluating the measured values for the padder control. They can also used to determine the residual moisture content behind the stenter exit. A defined microwave emission is thereby beamed onto the damp fabric. The proportion of microwaves, not absorbed because of its density, is measured and relates to the humidity by calibration (Rouette 2002).

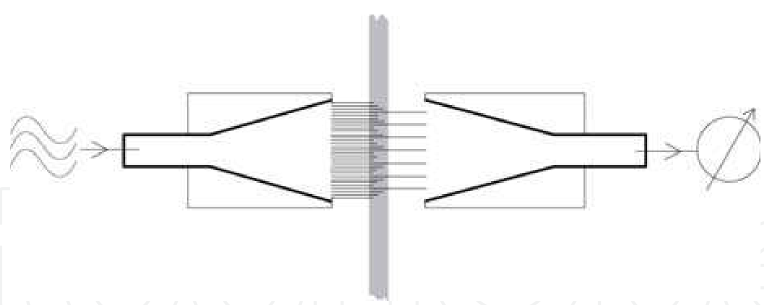


Fig. 4. Principle of moisture measurement using microwaves

The first idea of microwave application for textile finishing processes originated in 1970-es when cellulose fabrics were treated with Durable Press (DP) finishing agents and cured in microwave oven (Englert & Berriman 1974). Until now, microwave irradiation for textile finishing has been used (anonymous 1996) for the combined de-sizing, scouring and bleaching processes, dyeing (Nando & Patel 2002), printing (Neral et al. 2007), and drying processes, as well as for eradication of insects from wool textiles (Regan 1982). Microwave sterilization has many advantages in comparison with conventional methods. It is able to raise the temperature of a material in a short time and selectively heat the material. This results in the reduction of usage and the rapid completion of sterilization Bacillus subtilis (ATCC 9372) and Bacillus stearothermophilus (ATCC 7953) (Wang et al. 2005)

Although these first results microwave irradiation for textile finishing, were promising, the idea was abandoned until 1955, when Miller patented his Pre-set process without awareness of the earlier patent. Both cases involved garment microwave treatment, but they were abandoned because of efforts to control the process failed.

2.1 State of the art

The influence of three different drying methods, convection, contact and as a novelty – microwave one, on physical-mechanical parameters of yarn sizing was investigated by Katovic et al. The research was performed on 4 different types of 100% cotton yarn which had been sized on newly constructed laboratory sizing device. In this way the following parameters: sizing velocity, temperature of the sizing agent, tension and inlet moisture of the warp, outlet moisture of the warp, after drying and drying intensity were continuously controlled and regulated. The application of microwave drying method for wrap sizing showed to be good or even better in some cases, compared to the other drying methods (Katovic et al., 2008).

For microwave vacuum drying (Therdthai & Zhou 2009), three microwave intensities were applied with pressure controlled at 13.33 kPa. For hot air drying, two drying temperatures were examined. The microwave vacuum drying could reduce drying time by 85-90% compared with the hot air drying. In addition, colors change during drying was investigated. From scanning electron micrographs, the microwave vacuum dried mint leaves had a more porous and uniform structure than the hot air ones.

Microwave heating has been proved to be more rapid, uniform and efficient, and easy penetrate to particle inside. To investigate the effect of microwave irradiation on the physical property and morphological structure of cotton cellulose, cellulose fabric was treated with microwave irradiation at different condition. The morphological structures and thermal stabilities of the untreated and treated cellulose were investigated with differential structures and thermal stabilities of were investigated with differential scanning calorimetry and X-ray diffraction. The thermal stability of the treated cellulose was changed. The crystallinity and preferred orientation of the treated cotton cellulose increased (Hou et al. 2008).

The release of formaldehyde from plywood has been greatly reduced by treatment with microwave radiation. Microwave released formaldehyde from plywood samples more effectively compared to samples subjected to thermal energy from external heating. This suggests that microwaves directly activate free formaldehyde molecules, which have a polarity that is susceptible to microwaves. (Saito, Y. et al, 2004).

The influence of microwaves on the efficiency of polycarboxilic acid esterification was studied by FT-IR spectroscopy. Polycarboxilic acid is used as non-formaldehyde durable press finishing agents and maximum effects can be obtained with 1,2,3,4 butantetracaroxylic acid (BTCA) and citric acid (CA). Instead of the usual curing process performed at very high temperatures microwaves were used. Fabric resilience improved while the whiteness was not significantly lowered (Katovic & Bischof Vukusic, 2002).

The esterification involved in Durable Press (DP) finishing is one among several chemical reactions that can be improved by microwave radiation. Cotton material is usually esterified with modified 1, 3 dimethylol 4, 5 dihydroxyethylene urea (DMDHEU). In this study, a novel microwave planar device was used for simultaneous drying and curing processes. The experimental results showed that microwave-assisted textile finishing yields better results than conventional curing at tender frame. Noticeable improvements were obtained in wrinkle recovery resistance and tensile strength reduction. In addition, the influence of microwaves on formaldehyde release was investigated in order to decrease formaldehyde emission from textile material. Several different experimental methods were used in order to identify a mechanism of formaldehyde release (Katovic et al. 2002, 2005). An alternative approach to formaldehyde-releasing conventional N-methylol compounds is based on the use of non-formaldehyde durable press polycarboxlic acid (PCA) finishing agents. Another alternative approach, investigated, is using microwave energy to impart durable crease resistance to dyed cotton fabric. The bi-functional reactive dyes are used in the study, and the isocratic HPLC method is employed to quantify the PCA reacted with the cellulosic material for two different curing procedures. Shade change evaluation reveals that microwave curing has a greater influence on the dE values than conventional curing. In all other aspects, primarily wrinkle recovery and deformation resistance, microwave curing offers much better results (Katovic et al 2000) and (Bischof Vukusic et al, 2000).

A new microwave curing system was used to affect cross-linking of cotton fabric with non-formaldehyde finishes, namely, glyoxal, glutaraldehyde and BTCA along with water soluble chitosan in order to impart ease care and antibacterial properties to the fabrics (Fouda et al., 2009).

The esterification involved in Durable Press (DP) finishing is one among several chemical reactions that can be improved by microwave radiation. Cotton material is usually esterified with modified 1,3 dimethylol 4,5 dihydroxyethylene urea (DMDHEU). The experimental results obtained on a novel microwave planar device used for simultaneous drying and curing processes showed that MW-assisted textile finishing yields better results than conventional curing at stenter frame, especially for wrinkle recovery resistance and tensile strength reduction (Katovic et al., 2005).

Esterification of cellulose with fatty acids is relatively more recent than acylation of cellulose. The fatty acid esters of cellulose are potentially biodegradable plastics. Most of the undertaken studies using conventional heating resulted in long reaction times. Rapid homogeneous esterification of cellulose with long chain acyl chloride induced by microwave irradiation was studied by Satge et al. The use of microwave resulted in dramatic drop in reaction time: 1 min irradiation was sufficient, compared with 30 min to 2 days, when conventional heating is used. In this work, a systematic study of the effect of degree of substitution as the main parameter for estimating biodegradability was performed (Satge et al., 2002).

Temperature changes in conducting polypyrrole/para-toluene-2-sulfuric acid coated nylon textiles due to microwave absorption in the 8-9 GHz frequency ranges were obtained by a thermography station during simulataneous irradiation of the samples. The temperature values are compared and related to the amounts of reflection, transmission and absorption obtained with a non-contact free space transmission technique, indicating a relationship between microwave absorption and temperature increase. Non-conductive samples showed no temperature increase upon irradiation irrespective of frequency range. The maximum temperature difference around 4° C in the conducting fabrics relative to ambient temperature was observed in samples having 48 %absorption and 26.5 ± 4%reflection. Samples polymerized for 60 or 120 min with a dopand concentraction of 0.018 mol/l or polymerized for 180 min with a dopant concentraction of 0.009 mol/l yielded optimum absorption levels. As the surface resistivity decreased and the reflection levels increased, the temperature increase upon irradiation reduced (Kaynak et al., 2009).

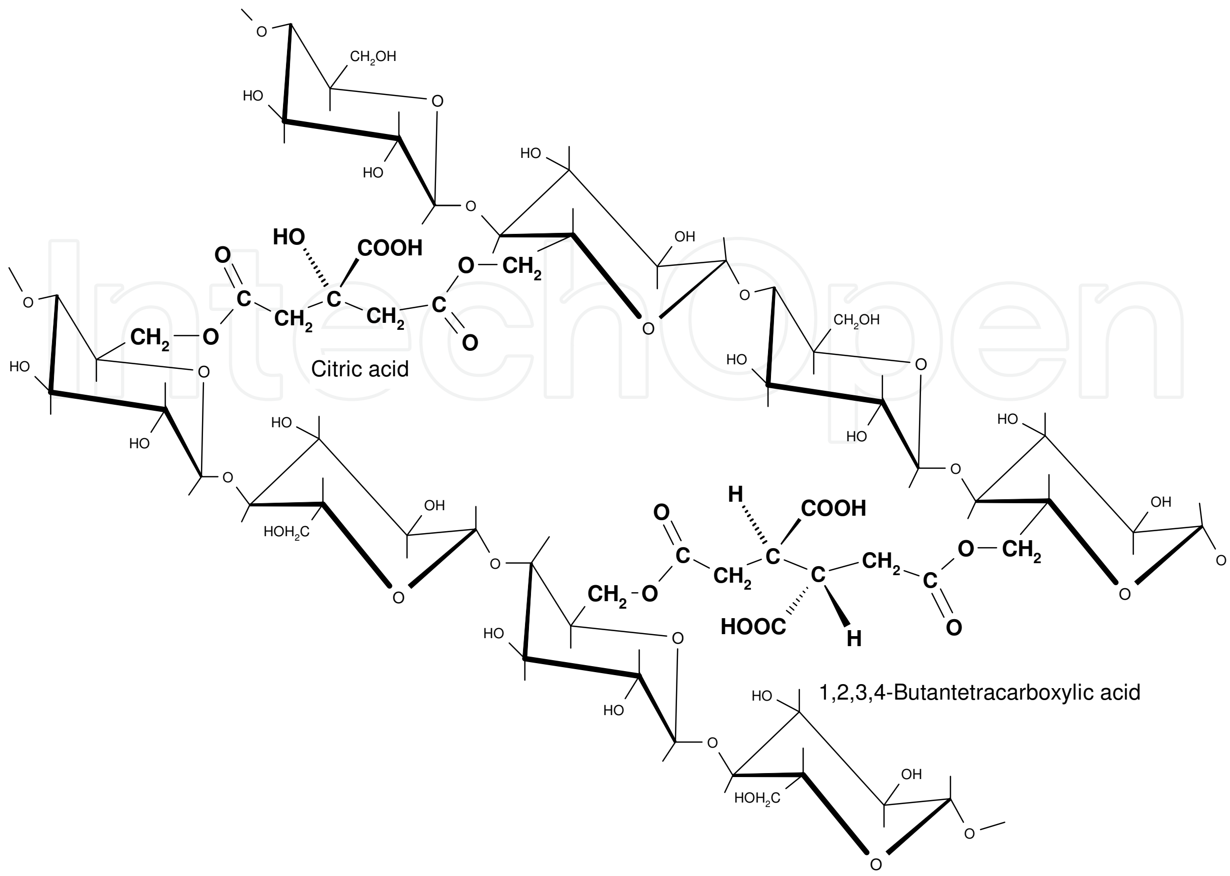


Fig. 5. Cross-linking via ester linkages of CA and BTCA with cellulosic chains

The important possibility of conducting sol-gel synthesis of oxide systems on the surface of para-aramid fibres under the effect of microwave radiation was demonstrated. Selection and control of the basic process parameters (duration and intensity of exposure to electromagnetic radiation, concentration of salts and carbamide) allow regulation of the effectiveness of interaction of reaction system with the microwave fields and eliminating degradation of the polymer (Barantsev et a., 2007).

Results of water- and oil-repellency obtained on planar MW apparatus have been compared with the ones obtained using conventional curing treatment. Simultaneous drying and curing processes have been conducted with MW at planar microwave device for the first time. Microwave technology offers better effects than conventional curing at stenter frame. Only in the case of durability to washing, cotton material treated with microwaves has shown a decrease. Lower effects, primarily caused by de-orientation of fluorocarbon chains, have been improved with thermal re-activation performed after washing and dry cleaning. Greatest advantages of the microwave device constructed are lower production costs and the elimination of separate drying procedure. In this way, conventional treatment, which might cause uneven effects, is eliminated (Bischof Vukusic et al., 2004). The influence of microwave pre-treatment on the UV protective properties of white polyester woven fabrics was investigated. The fabric samples for shade structures of various construction characteristics have been air dried and dried using laboratory microwave device. The impact of microwave pre-treatment has been verified after microwave untreated and treated samples examination and micro-structural changes of the fabrics treated influenced by intra- and inter- structural PES multifilament yarn changes attributed to specific character of the

treatment applied. It was found that changes mentioned, confirmed with obtained results of fabric mass per unit area, fabric thickness, yarns diameter, percent cover, volume porosity and air permeability, have a strong influence on UVA and UVB transmission trough the fabrics. Synergistic influence on the UV protection effect obtained by unconventional pre-treatment and agents based on organic UV absorbers has also been evaluated (Tomljenovic & Katovic 2008).
The efficiency of microwave fixation of prints of the reactive dye applied to a cotton fabric using the digital print technology has been investigated. The results of the fixation of prints with saturated steam and hot air were compared with the characteristics of the microwave-fixed prints. The effects of time and microwave power on change in characteristics of impregnated textile substrates were teed. Based on the results obtained it may be concluded that the characteristic of microwave-fixed prints comparable with the characteristics of digital prints are of reactive dyes fixed by classic methods (Neral et al. 2007).
This paper deals with calibration and standardization of microwave oven, selection of energy level, configuration and placement of fabric swatch in the oven and fixation time to get optimum results viz., shade closest to that obtainable by the cold pad-batch method. Both vinyl sulphone as well asheterobifunctional dyes have been studied. The major finding has been that high energy and low exposure time in microwave oven gives comparable results to those by pad batch method in terms of K/S values, bleaching in post-dyeing wash-off and dry wet rub fastness. Several bulk trials have been taken successfully (Nanda & Patel 2002).
Thermosetting is an important part of the finishing of thermoplastic poly (ethylene terephthalate) (PET) fabrics and garments that confers stability in dimensions and shape as well as appropriate hand to the final product. Conventional thermosetting methods for PET include hot air and steaming treatments. In the present work we used solid state NMR as well DSC methods in order to investigate any differences in the behavior of PET chips when annealed with either a conventional or microwave technique. (D'Arrigo et al. 2002).

2.2 Electromagnetic devices in textile finishing

There are three types of devices for microwave processing of flexible materials. The device based on the resonant cavity principle can be used on discontinuing principle. Therefore it is suitable for lab research of small quantities of textile materials. The major part of the research was conducted on this type of a device. Devices based on the open resonator and waveguide applicator principle operate according to a continuing principle, and they are still being tested. These devices for microwave textile finishing are prevalently laboratory apparatus. Their main problem is reduced spreading of microwaves into the environment through gaps for flexible material. The only devices using electromagnetic waves that are used in textile industrial applications are radio-frequency dryers.

2.2.1 Resonant cavity

The frequencies used in microwave ovens were chosen based on two constraints. The first is that they should be in one of the industrial, scientific, and medical (ISM) frequency bands set aside for non-communication purposes. Three additional ISM bands exist in the microwave frequencies. Two of them are centered on 5.8 GHz and 24.125 GHz, but are not used for microwave cooking because of the very high cost of power generation at these frequencies. The third, centered on 433.92 MHz, is a narrow band that would require expensive equipment to generate sufficient power without creating interference outside the

band, and is only available in some countries. For household purposes, 2.45 GHz has the advantage over 915 MHz in that 915 MHz is only an ISM band in the ITU Region while 2.45 GHz is available worldwide.
Most microwave ovens allow users to choose between several power levels. In most ovens, however, there is no change in the intensity of the microwave radiation; instead, the magnetron is turned on and off in duty cycles of several seconds at a time. This can actually be heard (a change in the humming sound from the oven), or observed when microwaving airy foods which may inflate during heating phases and deflate when the magnetron is turned off. For such an oven, the magnetron is driven by a linear transformer which can only feasibly be switched completely on or off. Newer models have inverter power supplies which use pulse width modulation to provide effectively-continuous heating at reduced power so that foods are heated more evenly at a given power level and can be heated more quickly without being damaged by uneven heating.
The cooking chamber itself is a Faraday cage which prevents the microwaves from escaping. The oven door usually has a window for easy viewing, but the window has a layer of conductive mesh some distance from the outer panel to maintain the shielding. Because the size of the perforations in the mesh are much less than the microwaves' wavelength, most of the microwave radiation cannot pass through the door, while visible light (with a much shorter wavelength) can.
This type of device has precisely determined dimensions depending on the characteristics of microwaves. Until now, the use of different types of resonant cavities has been tested for the purpose of microwave treatment and one of them is a domestic oven. A magnetron operating most often in the 2.45 GHz band (ISM) generates microwave power between a few hundred watts and few kilowatts, depending upon the application. It is connected by means of a waveguides to resonant cavity oven, which contains the materials to be heated or dried: food, wood, paper, plastics chemicals textiles, building materials. A mode stirrer distributes the microwave energy among the different resonant modes of the cavity, ensuring homogeneous heating. Main problems related to the use of such resonant cavities are the

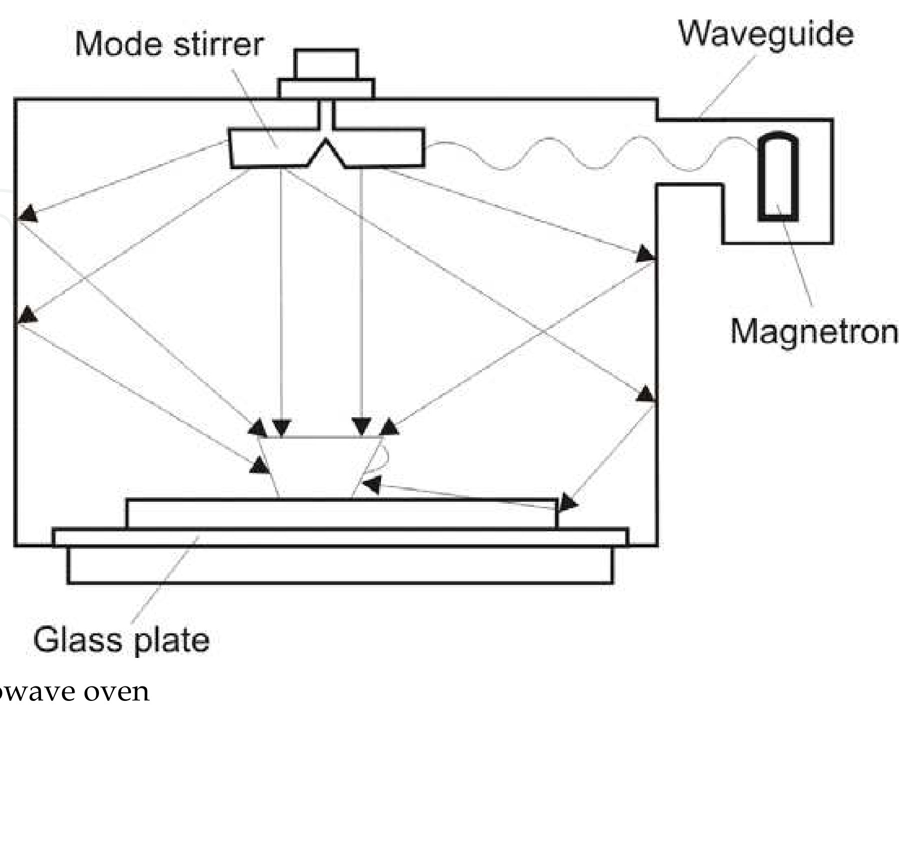


Fig. 6. Microwave oven

non-uniform energy distribution and possible MW leakage from the door seals in the case of inadequate chokes. The distribution of microwave energy within the cavity is always imperfect and the rotator (turntable) will cause the passage of the material through hotter and cooler spots, averaging out the exposure to microwaves. (Thewlis & Barnold 1999), (Hong & Thompson 1998), (Enderling 1988).

2.2.2 Open-resonator

The second reported microwave drying machine consist of many drying cells (17 in their prototype machine), which are positioned above the moving textile material. Each of the drying cells is based on the idea of an open resonator. These cells have their own magnetron placed in a waveguide holder. This applicator, which derives from the Fabry-Perot open resonator, has a magnetron as a source of high electromagnetic power. Dried textile material is located in the middle plane between the parallel conductive plates and the distance between these plates is equal to 3/2 λ. The use of this device is mostly for drying in the factory production of fabrics. This type of semi industrial dryer was developed at the Czech Technical University, Prague, Research Institute of Textile Machines Liberec and Technical University of Liberec (Pourova & Vrba 2006) (Vrba et al. 2005).
In their research of the open applicator they determined the position of the magnetron. In the same manner they also found the distribution of the electric field strength in drying textile materials. This applicator has a magnetron as a source of high electromagnetic power, placed in the waveguide holder. The power of the used magnetrons is 800 W and its working frequency is 2.45 GHz.
Their drying resonant system is optimized by criteria to create the maximum electric field strength in the plane of the drying textile. They described this structure by means of an oriented graph, which is represented in the Figure 8.
Drying resonant system is optimized by criteria to create the maximum electric field strength in the plane of the dying textile. We can describe this structure by means of an oriented graph, and we can also create a diagram of the electromagnetic waves inside this structure. By modifying the diagrams we can arrive at the resulting expression for calculating the E-field strength in the textile plane:

a) b)

Fig. 7. Open-resonator a) Interior the microwave drying machine, b) Prototype of semi-industrial microwave drying machine

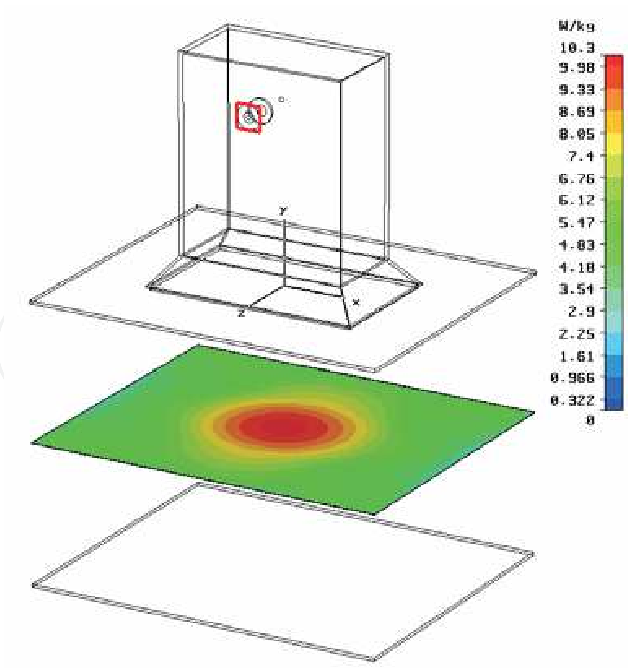


Fig. 8. Distribution of electric field strength in one applicator

$$E(l,p_2,\alpha_{tex}) = \sum_{n=0}^{\infty} p_1^n (p_2 + \delta_2 e^{-x})^n \cdot e^{-j\beta l(l+2n)} \tag{2}$$

parameters p_2 and α_{tex} are given by the dielectric properties of the textile, so we can write the electric field strength depended on relative permittivity ε_{tex} and loss factor tg δ_{tex} as follows

$$E(l,p_2,\alpha_{tex}) = \frac{e^{(j\beta l + \alpha_{tex}\cdot t)}}{e^{(j\beta l + \alpha_{tex}\cdot l)} - p_1 p_2 \cdot e^{(\alpha_{tex}\cdot t)} - p\sqrt{1-p_2^2}} \tag{3}$$

Electric field strength with respect to distance l and to relative permittivity ε_{tex} (tg δ = 0.566)
Were p_1 is reflection coefficient of metallic plate; p_2 is reflection coefficient of textile; α_{tex} is attenuation factor of textile; β is phase constant of free space; tg δ_{tex} - loss factor; l is distance between reflective plate and textile; t is thickness of textile; δ is $\sqrt{1-p^2{}_2}$ – transmission factor; e^- is $e^{(j-\alpha_{tex}\, t)}$ – absorption in textile; ε_{tex} – relative permittivity

2.2.3 Waveguide applicator

Waveguide are metallic tube, in the section-plane rectangle or circle. They transport electromagnetic energy from magnetron that runs along the waveguide. Waveguides work according to the principle of waves reflecting from the waveguide from one part to another. Fields in the waveguide can bee seen as a group of planar waves. They reflect from one part to another part, distributing in the direction of waveguide shown in the figure 9.
There are two characteristic wave lengths:

- one in the direction of vertical with the waveguide:

$$\lambda_n = \lambda / \cos\theta \tag{4}$$

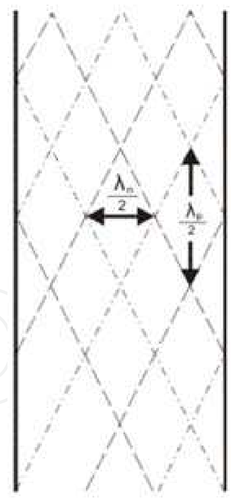
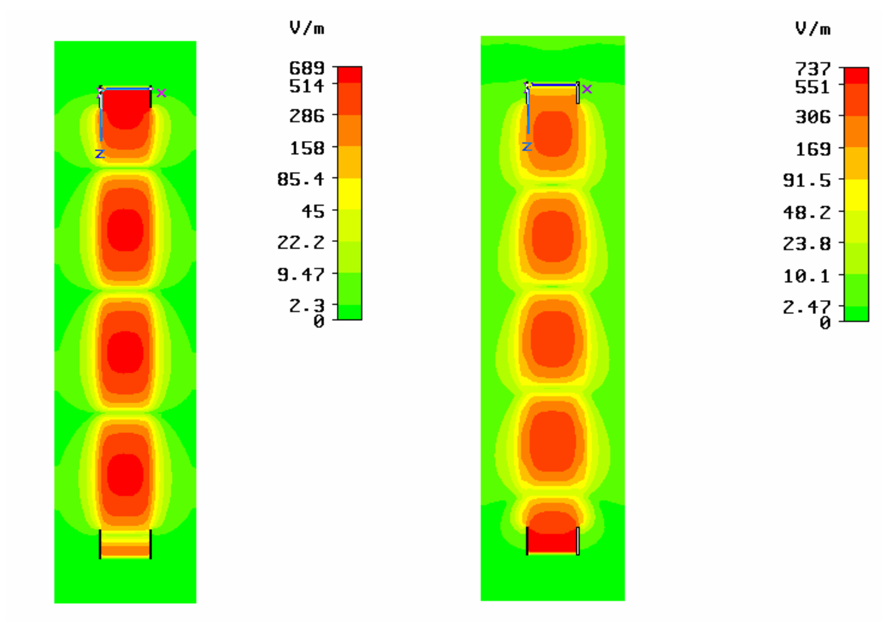


Fig. 9. Characteristic wave length in waveguide



a) b)

Fig. 10. 2D distribution of electric field strength in one waveguide a) without the textile material, b) with textile material

- one in the direction of parallel with the waveguide:

$$\lambda_p = \lambda / \sin\theta \qquad (5)$$

Were λ is wave length appointed signal; λ_{n} - is wave length in the direction vertical with the waveguide; λ_p I wavelength in the direction parallel with waveguide; θ is entrance angle (angle of incidence).

This drying system for the treatment of flexible textile material consists of rectangular waveguides centrally slotted in order to obtain planar passage of textile mater in wide state (Katovic et al. 2008). With proper design of the waveguides and supporting equipment, a specific environment (at the particular wavelength) can be created in order to provide controlled distribution of the microwave energy, making it possible to achieve uniform exposure to material passed through a channel. The leakage of microwave energy is inherently small due to the fact that waveguide slots are oriented along the waveguide line of symmetry, and therefore they cannot act as efficient slot antennas. Furthermore, in this way the material lies in the maximum of the electric field that assures effective coupling to the flowing microwave energy. In a case that request for slots symmetry is fulfilled, only the load (textile material) which passes through the waveguides has an influence on energy loss. The amount of microwave energy absorbed by the textile in each waveguide pass depends on the material thickness and moisture content. This laboratory drying system for the treatment of flexible textile material consists of 6 rectangular waveguides (4 x 8 cm) centrally slotted in order to obtain planar passage of textile material in a wide state.

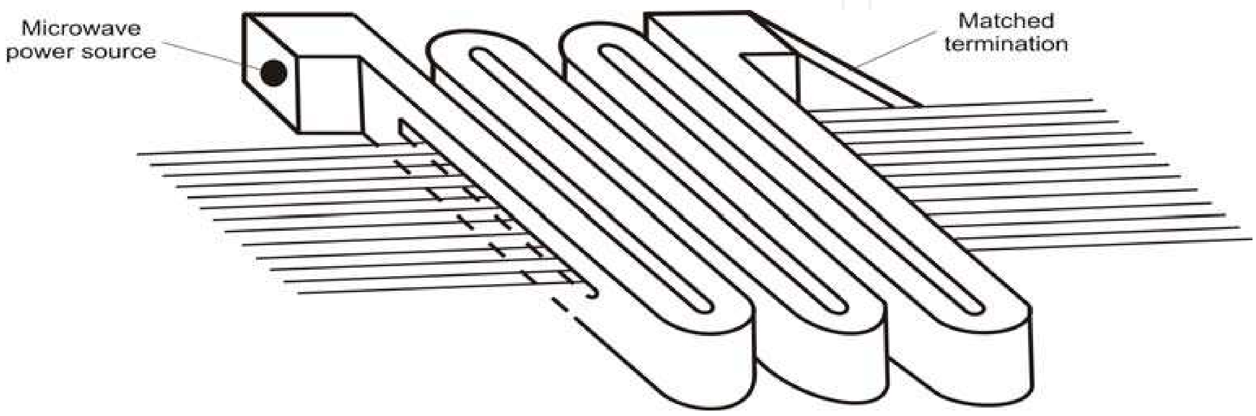


Fig. 11. Scheme of the textile material passing through the waveguides

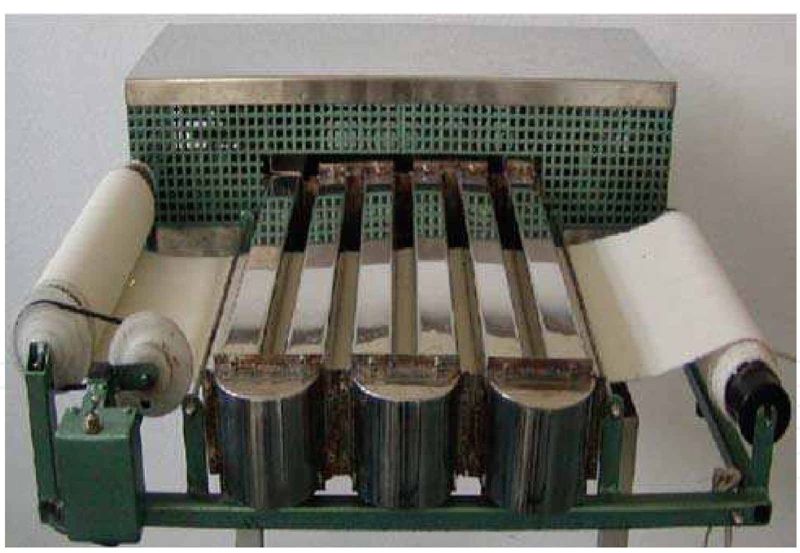


Fig. 12. Laboratory microwave device for the treatment of textile materials

In a case of single pass applicator, exponential decay of electric field might cause non-uniform heat distribution.
To prevent this negative tendency, the material is passed through a number of waveguide passes. In order to
obtain a uniform absorption of microwave energy on the whole material an even number of waveguides must always be used. Number of waveguides used depends on the desired speed of the textile material passing and the amount of water on the material. Due to special

design of waveguide slot for textile materials there is only minimal leakage of microwave energy into the environment. Namely, passing of the textile material through the waveguides leads to transition of the part of energy out of the waveguide together with the material. In order to reduce this energy transition as much as possible, waveguide slots are elongated and beveled which enables the return of microwave energy into the waveguide. Reduced energy is guided through the waveguide to the absorber of microwave energy (water) (Katovic et al. (2005).

Fig. 13. The modular microwave unit

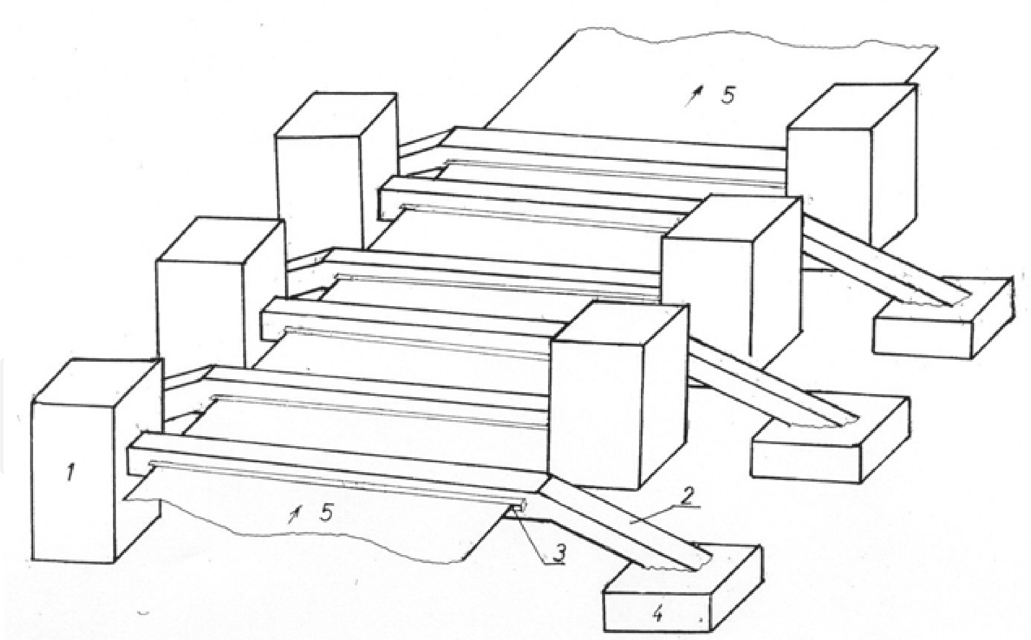


Fig. 14. Modular microwave units
1. Microwave unit box 2. Waveguides 3. Slots 4. Absorber of microwave energy (water)
5. Textile material.

For paper manufacturing, textiles, and other flat materials, American company Industrial Microwave System (IMS) offer an exceptional improvement over other drying alternatives.

A completely scalable configuration of slotted separated waveguides in combination with high power microwave generators can accommodate materials up to 5 cm in thickness and 10 m wide. Because of the efficiency of microwaves along with the uniform energy distribution, production speed can be dramatically increased and product quality improved.

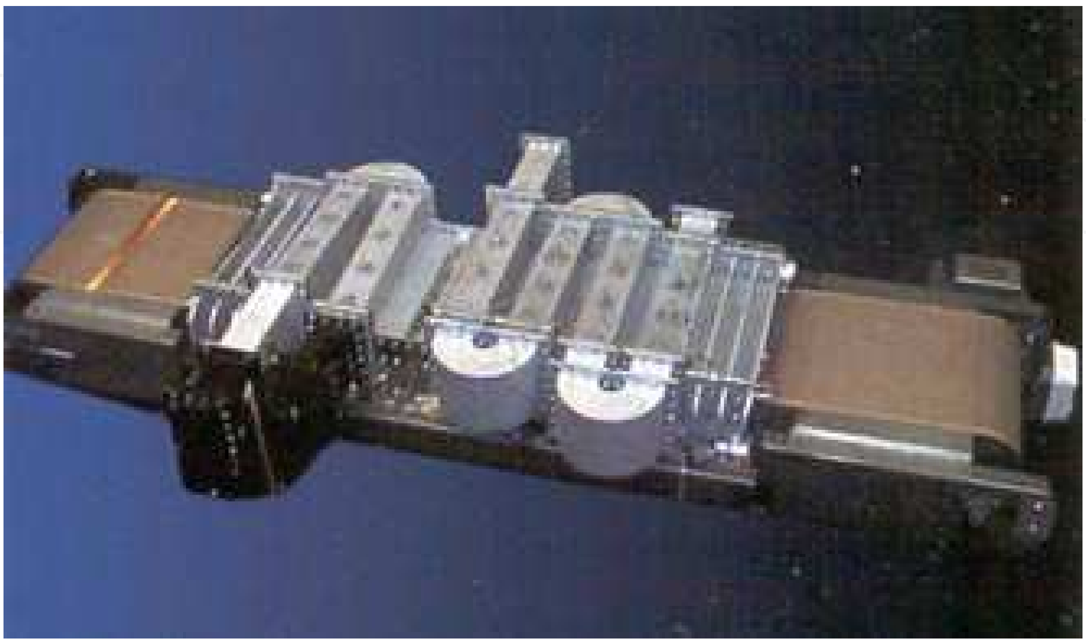


Fig. 15. IMS Planar System (prospect of company *Industrial Microwave System*)

3. Radio frequency dryers

Radio frequency (RF) and microwaves (MW) are forms of electromagnetic energy but differ in operating frequency and wavelength. Both are allocated specific bands of operation by international governments. Industrial radio frequencies typically operate between 10 and 30 MHz with wavelengths of 30 to 10 meters. Radio frequency dryers are operating with power from 10 till 100 kW. Generally speaking, the efficiency of power utilization is far lower in a RF generator than a microwave unit, although the initial capital cost per KW of power output is higher. Selection of RF or microwave heating will depend on product physical properties and required process conditions for a particular application. Where penetration depth in excess of 15 cm is required and control of uniformity of heating is not a major issue, radio frequency offers a good solution. However, where uniformity of drying and moisture control is essential. For planar applications requiring belt widths in excess of 100 cm, where edge-to-edge uniformity is essential, control of microwave energy is superior to RF. Low moisture levels and high production belt speeds, such as those encountered in the textile industry, are far better suited to IMS microwave heating due to their characteristics of control and response time respectively. Electromagnetic waves have been used in the textile industry finishing the purpose of drying of thick materials, performed at radio frequency (RF) dryers, which are operating at different frequencies between 10 and 30 MHz. In textile processing, radio frequency waves are used in dryers for thick and multi-layered materials. In these machines, energy is transferred by means of two metal electrodes plates, between which the fabric is transported on a conveyer belt. An alternating electric field is created between the electrodes, with alternating voltage created by on RF generator.

Under the influence of the alternating electric field, dipole water molecules start vibrating, which causes them to heat up and be transformed into water vapor. A wet fabric submitted to a radiofrequency fields absorbs the electromagnetic energy, so that its internal temperature increases. If a sufficient amount of a energy is supplied, the water is converted into steam, which leaves the product; that is to say, the wet product is dried. Radiofrequency dyers have some specific design and construction features which allow their users to obtain the maximum benefits from the radio frequency technology in terms of quality of the dried products, reduced operating cots flexibility and reliability. The RF generators are of the „lumped components“ type, having high efficiency (Q quality factor) and outstanding reliability. The cooling system of triodes is made up of a double water circuit; it is designed to allow the longest possible life of the triodes and does not require periodic maintenance operation. The RF power adjustment is accomplished by means of a semi-automatic circuit which controls the power supplied to the product being dried through a variable capacitor, located in the generator. The electrode is fixed or automatically positioned at pre-set heights. The range of power density for textile industry is from is 3 (nylon) to 18 kW/m^2 (cotton, viscose) of electrode surface.

Fig. 16. Radio frequency dryer (Prospect of company *Stalam*)

4. Future development

The main advantage of the microwave energy application is that the energy consumption is 60-70 % lower respect to conventional heating treatments. Another advantage is its influence on the reaction kinetics: a reaction that takes place in two days under conventional treatment methods terminates after a few minutes applying MW energy.

Recent studies have documented a significantly reduced time for fabricating zeolites, mixed oxide and mesoporous molecular sieves by employing microwave energy. In many cases, microwave syntheses have proven to synthesize new nanoporous structures. By reducing the times by over an order of magnitude, continuous production would be possible to replace batch synthesis. This lowering of the cost would make more nanoporous materials readily available for many chemical, environmental, and biological applications. Further, microwave syntheses have often proven to create more uniform (defect-free) products than from conventional hydrothermal synthesis.

The main disadvantage of a wide application of microwave energy in textile finishing is the negative influence of electromagnetic irradiation on the environment. It means that preventive security measures are needed to be developed prior to microwave energy use on a larger scale. The exposure to an excessive level of radiation can produce hazards. The microwave radiation is non-ionizing, its main effect being of a thermal nature, commonly used in applications. The body absorbs radiation and automatically adapts to the resulting temperature increase, excess heat being removed by the blood flow. However, should the radiation become too intense, the thermal balance no longer could be restored by the body processes, and burns would then occur. As microwaves tend to heat deeply into the body, one might fear deep burns would occur while the surface temperature remained acceptable. There exists a certain radiation threshold, beyond which irreversible changes do occur. A considerable number of studies were carried out to determine this threshold. No permanent effect was observed for power level lower than $100 mW/cm^2$. Severe overexposure of non-uniform energy distribution may provide excessive focus of heat build up resulting in burnt material or a fire hazard. Another disadvantage is the depth of penetration achievable using microwave energy. This is a function of microwave frequency, dielectric properties of the material being heated and its temperature. As a general rule, the higher the frequency, the lower the depth of penetration.

5. References

Anonymus (1996). Microwave Processes for the Combined Desizing, Scouring and Bleaching of Grey Cotton Fabrics, *J.Text. Institute*, 3, *pp. 602-607,* ISSN 0400-5000

Barantsev, V.M., Larionov, O.S., Pavlov, N.N. (2007). Prospects for modification of para-aramid fibres with metal complex salts in conditions of microwave expositure, *Fibre Chemistry* 39, *pp.193-196*, ISSN 0018-3830

Bischof Vukusic, S., Schramm, C., Katovic, D. (2003). Influence of Microwaves on Nonformaldehyde DP Finished Dyed Cotton Fabrics, *Textile Research Journal, 73, pp.733-738*, ISSN 0040-5175

Bischof Vukusic, S., Katovic, D. (2004). Textile finishing treatments influenced with microwaves, *The Textile Institute 83rd World Conference,* Shangai, *China, pp.1165-1169,* ISBN 1-8703-7261-1

Bischof Vukusic, S., Katovi D., Flincec Grgac S. (2004). Effect of microwave treatment on fluorocarbon finishing, *Colourage Annual, 51, pp.1000 -1004,* ISSN 0010-1826

Cablewski, T. et al (1994). Development and Application of Continuous Microwave Reactor for Organic Synthesis, *J. Org.Chem 59 pp. 3408 – 3412,* ISSN022-3263

Chang, H-T., Chang S-T.: (2003) Improvements in dimensional stability and lighfastnedd of wood by butyrylation using microwave heating *J.Wood Sci (2003) 49 p.455-460* ISSN 1435-0211

D'Arrigo, Focher, B., Pellacani, G.C., Cosentino, C.Torri, G. (2002). Textiles Thermosetting by Microwaves, *Macromol. Symp. 180 pp. 223-239*, ISNN 1022-1360

Enderlig, R., (1988). US Patent 4,907,310

Englert, R.D., Berriman, L.P. (1974), Curing chemically treated cellulosic fabrics, *US Patent 3846845, 1974. 1112*

Fouda, M. El Shafei, A., Hebeish, A. (2009). Microwave curing for producing cotton fabrics with care and antibacterial properties, *Carbohydrate Polymers 77, pp. 651-655,* ISSN 0144-8617

Hong, S., Thompson, D. (1998), Canadian Patent CA 2 235 439

Hou, A., Wang, X., Wu, L. (2008). Effect of microwave irradiation on the physical properties and morphological structures of cotton cellulose, *Carbonate Polymers 74 pp. 934-937,* ISSN 0144-8617

Katovic, D., Bischof Vukusic, S., Soljacic, I., Stefanic, G. (2000). Application of Electromagnetic Waves in Durable Press Finishing with Polycarboxylic Acid, *AATCC International Conference & Exhibition, Winston-Salem, NC, USA, 17-20 September 2000, CD-ROM,*

Katovic, D., S. Bischof Vukusic, (2002), Application of Electromagnetic Waves in Durable Press Finishing with Polycarboxylic Acid, *AATCC Review 2 (2002) 4,pp. 39-42*, ISSN 1532-8813

Katovic, D. Bischof Vukusic S., Versec, J. (2002), The application of microwave energy in Durable Press Finishing, *International Textile Clothing & Design Conference Dubrovnik 6-9 October (2002) 283-287*, ISBN 953-96408-8-1

Katovic, D., Bischof Vukusic, S. Flincec Grgac, S. (2005). Application of Microwaves in Textile Finishing Processes, *Tekstil 54(7) 313-318,* ISSN 0492-5882

Katovic, D., Bischof Vukusic, S., Hrabar, S., Bartolic, J. (2005). *Microwaves in Chemical Finishing of Textiles* 18th International Conference on Applied Electromagnetics and Communications 12-14 October (2005), Dubrovnik, 255-25, ISBN 953-6037-44-0

Katovic, D., Kovacevic, S., Bischof Vukusic, S., Schwarz, I., Flincec Grgac, S. (2007), Influence of Drying on Psysico-mechanical Properties of Sized Yarn, *Tekstil 56,8, pp .479 - 486,* ISSN 0492-5882

Katović, D. Kovacevic, Bischof Vukusic, S., Schwarz I., Flincec Grgac, S. (2008). The Effect of Microwave on Warp Sizing, *Textile Research Journal 74, pp. 353-360,* ISSN 0040-5175

Kaynak A., Hakansson E., Amiet A. (2009) The influence of polymerization time and dopant concentration on the absorption of microwave radiation in conducting polypyrrole coated textiles, *Synthetic Metals 159 (2009) pp.1373-1380,* ISSN 0379-6779

Metaxas, A.C., Meredith, R.J. (1983). Industrial Microwave Heating, *Peter Peregrinus, pp. 111-150,* ISBN 0-90604-889-3, London

Nanda, R., Patel, G. (2002). *Microwave oven*: *A tool for quick response in shade development and lab-to bulk shade translation in reactive dyeing* 7th International & 58th All India Textile Conference, Mumbai 14 -15 Dec 2002 pp. 83-88

Nanda, R., Patel, G. (2002). Microwave Oven: A tool for guide response in shade translation in reactive dyeing, *Colourage* 49,12, *pp.83-88, ,* ISSN 0010-1826

Neral, B., Sostar Turk, S., Schneider, R (2007). Efficiency of Microwave Fixation of Digital Prints of the Reactive Dyestuff, *Tekstil 56, 6, pp.358-367,* ISSN 0492-5882

Pourova, M., Vrba, J. (2006). Microwave Drying of Textile Materials and Optimization of Resonant Applicator *Acta polytechnica 46 5, pp. 3-7,* ISSN 0323-7648

Reagan, B.M. (1982), Eradication of insects from wool textiles, *Journal of the American Institute for Conservation 21, 2, pp. 1-34,* ISSN 0197-1360

Rouette, H.K. (2001). Encyclopedia of Textile Finishing, *Springer-Verlag, Berlin Heidelberg pp. 1399-1401,* ISBN 3-540-65031-8

Saito,Y., Nakano,K., Shida S., Soma,T., Arima, T. (2004). Microwave-enhanced release of formaldehyde from plywood *Holzforschung 58, pp. 548-551,* ISSN 1437-434

Satge,C., Verneuil, B., Brandland, P. Granet, R. Krausz P., Rozier, J., Petit, C. (2002). Rapid homogeneneous esterification of cellulose induced by microwave irradiation Carbonate *Polimers 49 pp. 373-376,* ISSN 1385-772

Strizhah, P.E., Tripol`shii A.I., Gurnik T.N., Tuzikov, F.V., Moroz, E.M. Konstandinova, T.E., Tuzikova,N.A., Kol`ko, V.P., Danilenko,I.A. Gorban, O.A. (2008). Effect of temperature on the structural characteristics ofd zirconium dioxide nanoparticles produced under conditions of microwaver treatment, *Theoretical and Experimental Chemistry,44, 3, p.144-148,* ISSN 0040-5760

Therdthai, N., Zhou,W., (2009). Characterzation of microwave vacuum drying and hot air drying of mint leaves (Mentha cordifolia Opiz ex Fresen), *Journal of Food Engineering 91 pp.482-489,* ISBN 0260-8774

Thewli, R., Barnoldswick (1999). European Patent EP 0 974 693 A1 (1999)

Thiry, M. (2000), The Magic of Microwave, *Textile Chemist and Colorist–American Dyestaf Reporter 32, 10, pp. 2-4,* ISSN 0040-490

Tomljenovic, A., Katovic, D. (2008). *Microwaves – solution for improving Polyester woven fabric UV protective properties* 4 rd International Textile, Cloting & Design Conference October 5th to 8th 2008; Dubrovnik, 898-903 ISBN 978-953-7105-26-6

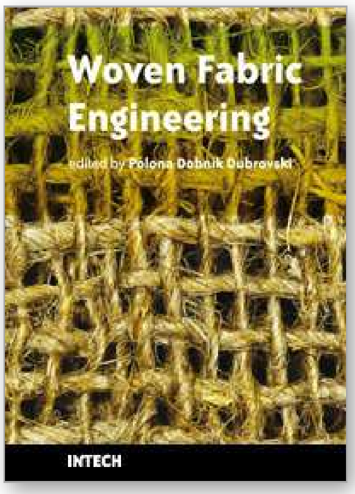
Tompsett G., Conner W.C., Yngresson K.S. (2006). Microwave Synthesis of Nanoporous Materials *ChemPhysChem 7,296-319* ISSN 1439-764

Varma, R. (2001). Solvent- free accelerated organic syntheses using microwaves, *Pure Appl. Chem 73, pp.193- 198* ISSN 0033-4545

Vrba, J., Stejskal, M., Klepl, R., Richter, A., Pourova, M., Žak, O., Herza, J., Oppi, L. (2005). *Microwave Drying Machine for Textile Materials* European 35th Microwave Conference ISBN 2-9600551-2-8

Wang H., Takashima H., Miyakawa Y., Kanno Y. (2005) Development of catalyst materials being effective for microwave sterilization *Science and Technology of Advanced Materials 6 pp. 921-926* ISBN 1878-5514

Zubizarreta, L.,Arenillas,A, Menéndez,J.A., Pis,J.J., Pirard,J.P., Job,N. (2008). Microwave Drying as an effective method to obtain porous carbon xerogels, *Journal of Non-Crystalline Solids 354 pp. 4024-4026,* ISSN 0022-3093



Woven Fabric Engineering
Edited by Polona Dobnik Dubrovski

ISBN 978-953-307-194-7
Hard cover, 414 pages
Publisher Sciyo
Published online 18, August, 2010
Published in print edition August, 2010