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REVIEW

Application of Microwave Techniques in Textile Chemistry

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Microwave heating techniques have been widely used in textile chemistry. This paper presents a state-of-the-art review of microwave technologies and industrial applications. The characteristics of microwave interactions with textile materials are outlined together with microwave fundamentals in the heat-setting process. Furthermore, the limitations in current understanding are included as a guide for potential users and for future research and development activities.

Key Words: Microwaves, Textile chemistry, Penetrating radiation.

INTRODUCTION

Radiation is a form of electromagnetic energy transmission and takes place between all matter provided that it is at a temperature above absolute zero. Infrared radiations form just part of the overall electromagnetic spectrum. Radiation is the energy emitted by the electrons vibrating in the molecules at the surface of a body. The amount of energy that can be transferred depends on the absolute temperature of the body and the radiant properties of the surface.

Electromagnetic radiation is a form of energy that propagates through vacuum in the absence of any moving material. We observe electromagnetic radiation as light and use it as radio waves, X-rays, etc. Here, we are mostly interested in a form of electromagnetic radiation called microwaves that can be used to heat and dry textile materials.

The word microwave is not new to every walk of life as there are more than 60 million microwave ovens in the households all over the world. On account of its great success in processing food, people believe that the microwave technology can also be wisely employed to process materials. Microwave characteristics that are not available in conventional processing of materials consist of penetrating radiation, controllable electric field distribution, rapid heating, selective heating materials and self-limiting reactions. Single or in combination, these characteristics lead to benefits and opportunities that are not available in conventional processing methods.

Since World War II, there have been major developments in the use of microwaves for heating applications. After this time it was realized that microwaves had the potential to provide rapid, energy-efficient heating of materials. The main applications of microwave heating today include food processing, wood drying, plastic and rubber treating as well as curing and preheating of ceramics. Broadly speaking, microwave radiation is the term associated with any electromagnetic radiation in the microwave frequency range of 300 MHz–300 GHz. Domestic and industrial microwave ovens generally operate at a frequency of 2.45 GHz corresponding to a wavelength of 12.2 cm. However, not all materials can be heated rapidly by microwaves. Materials may be classified into three groups, *i.e.*, conductors, insulators and absorbers. Materials that absorb microwave radiation are called dielectrics; thus, microwave heating is also referred to as dielectric heating. Dielectrics have two important properties: (a) They have very few charge carriers. When an external electric field is applied, there is very little change carried through the material matrix. (b) The molecules or atoms comprising the dielectric exhibit a dipole movement distance. An example of this is the stereochemistry of covalent bonds in a water molecule, giving the water molecule a dipole movement. Water is the typical case of non-symmetric molecule. Dipoles may be a natural feature of the dielectric or they may be induced. Distortion of the electron cloud around non-polar molecules or atoms through the presence of an external electric field can induce a temporary dipole movement. This movement generates friction inside the dielectric and the energy is dissipated subsequently as heat[1].

The interaction of dielectric materials with electromagnetic radiation in the microwave range results in energy absorbance. The ability of a material to absorb energy while in a microwave cavity is related to the loss tangent of the material. This depends on the relaxation times of the molecules in the material, which, in turn, depends on the nature of the functional groups and the volume of the molecule. Generally, the dielectric properties of a material are related to temperature, moisture content, density and material geometry.

An important characteristic of microwave heating is the phenomenon of hot spot formation, whereby regions of very high temperature form due to non-uniform heating. This thermal instability arises because of the non-linear dependence of the electromagnetic and thermal properties of material on temperature. The formation of standing waves within the microwave cavity results in some regions being exposed to higher energy than others. This results in an increased rate of heating in these higher energy areas due to the non-linear dependence. Cavity design is an important factor in the control or the utilization of this hot spot phenomenon.

Microwave energy is extremely efficient in the selective heating of materials as no energy is wasted in bulk heating the sample. This is a clear advantage that microwave heating has over conventional methods. Microwave heating processes are currently undergoing investigation for application in a number of fields where the advantages of microwave energy may lead to significant savings in energy consumption, process time and environmental remediation.

Compared with conventional heating techniques, microwave heating has the following additional advantages:

- higher heating rates;
- no direct contact between the heating source and the heated material;
- selective heating may be achieved;
- greater control of the heating or drying process;
- reduced equipment size and waste.

The benefit of microwave technology has been realized over the past decade with the growing acceptance of microwave ovens in the home. This, together with the gloomy outlook of a worldwide energy crisis, has paved the way for extensive research into new and innovative heating and drying processes. The use of microwave drying cannot only greatly enhance the drying rates of textile materials, but it may also enhance the final product quality.

While cost presents a major barrier to wider use of microwave in textile industry, an equally important barrier is the lack of understanding of how microwaves interact with materials during heating and drying. The design of suitable process equipment is further confounded by the constraint that geometry places on the prediction of field patterns and hence heating rates within the materials. Effects such as resonance within the material can occur as well as large variations in field patterns at the textile material surface.

The phenomenon of drying has been investigated at considerable length and treated in various texts. However, in general, there is only a very small section of this literature devoted to microwave drying of textile materials.

One of the main features which distinguishes microwave drying from conventional drying processes is that because liquids such as water absorb the bulk of the electromagnetic energy at microwave frequencies, the energy is transmitted directly to the wet material. The process does not rely on conduction of heat from the surface of the textile material and thus increased heat transfer occurs, speeding up the drying process. This has the advantage of eliminating case hardening of textile material which is usually associated with convective hot air drying operations. Another feature is the large increase in the dielectric loss factor with moisture content. This can be used with great effect to produce a moisture levelling phenomenon during the drying process since the electromagnetic energy will selectively or preferentially dry the wettest regions of the solid[2].

Meanwhile, infrared heating on textile lines has been in use for many years on dyeing lines to set the dyes prior to the tenter oven and to predry a host of fabric finishes or topical coatings on fabrics. The renewed interest in infrared predrying is due in large part to the need for ever-increasing line speeds and the availability of improved infrared hardware. Infrared predrying of the dyed or finished fabric rapidly preheats and predries wetted fabrics far faster than the typical convection tenter dryer. Typically, an air dryer requires 20–25% of its length just to preheat the wetted fabric to a temperature where water is freely evaporated. The infrared preheater/predryer section takes over this function in a fraction of the length required in the convection dryer. For dyed fabrics, infrared predryers are typically vertical in configuration and are generally mounted on the line prior to the tenter frame. The systems consist of arrays of electric infrared emitters positioned on both sides of the fabric. The emitters are typically controlled from the fabric temperature. The evaporative load on the predryer dictates how much energy is required and how many vertical sections the predryer must be. With today's more efficient and higher powered emitters most predryers are one or two passes. In applications where two-sided heating is not required, such as latex backcoatings, an infrared predryer can be enclosed around pin and clip tenter frames immediately prior to the tenter oven. As a result, line speeds are increased as the added energy accelerates the heating or drying process that has previously taken place only inside the oven. Heat setting operations can benefit from preheating as well.

It should be noted that controlling shade variations and shade shifts in dyed fabrics has typically been problematic for manufacturing engineers. Without predrying, the likelihood of shade variation from one side of the fabric to the other increases. Dyestuffs tend to migrate to the heated side of the fabric as it passes through the oven. The migration is due partly to gravity and partly to fluid dynamics. Dyed fabrics come onto the tenter frame at usually 50 to 80% wet pickup. Optimum product quality requires that wet pickup be reduced to the 30 to 60% range with equal water removal from both sides of the fabric. The predryed fabric is then presented to the horizontal tenter oven with the dyes "locked in" to position. Additional quality benefits can be realized on topical finishes or coatings. Rapid heating with infrared immediately after coating applications tends to keep the coating from deeply wicking into the fabric. For example, the infrared predrying of foamed on fluorochemical finishes for stain resistance tend to keep the coating more towards the surface of the fabric where they do the most good[3].

Background

This section reviews the basic principles of physics pertaining to microwave heating.

Energy: Energy is the capacitance to do work and work is defined as the product of a force acting over a distance, that is,

$$E = W = F \cdot x \tag{1}$$

where E = energy, W = the equivalent work, F = force that performs the work, x = distance a mass is moved by the force.

Atomic particles: All matter is composed of atoms. Atoms, in turn, consist of nuclei surrounded by orbiting electrons. The nucleus consists of positively charged protons and uncharged neutrons. The surrounding electrons are negatively charged. In neutral atoms, the number of protons in the nucleus equals the number of electrons, resulting in a zero net charge.

Electrostatic forces: If some electrons are removed from a piece of material, the protons will outnumber the electrons and the material will take on a positive charge. Similarly, if some electrons are added to a piece of material, the material will take a negative charge. On the other hand, if a negatively charged object is brought near a positively charged object, each will experience a force pulling them together.

Columb's law: If two charges of magnitudes q_1 and q_2 are separated by a distance r, each will feel a force of magnitude

$$F = k\frac{q_1 q_2}{r^2} \quad (2)$$

It is clear from eqn. (2) that the force is proportional to the magnitude of each charge and inversely proportional to the square of the distance between them.

Electric fields: Electrostatic force is defined as "force at a distance" [eqn. (1)]. If a charge Q and a test charge q is placed a distance r away from it, Q will push on q across that distance. The magnitude of push will depend on the magnitudes of Q, q and r.

Another way to look at this is to say that Q creates a field in the space that surrounds it. At any point in that space, the field will have a strength E that depends on Q and r. If a test charge is placed at some point in the space, the field at that point will push on it with a force depends on the field strength E at that point and on q. To make these two explanations mathematically equivalent, we separate eqn. (2) into two parts; thus

$$F = k\frac{Qq}{r^2}\left(k\frac{Q}{r^2}\right)(q) \quad (3)$$

The second part is simply the charge of the second particle. The first part we call E, the field strength at distance r away from Q:

$$E = \left(k\frac{Q}{r^2}\right) \quad (4)$$

Now the force on q can be defined in terms of the field strength times the magnitude of q:

$$F = E \cdot q \quad (5)$$

A microwave oven consists of three major parts:

- The magnetron is the device that generates the microwaves.
- Waveguides direct these waves to the oven cavity.
- The oven cavity holds the material to be heated so that microwaves can impinge on them.

Magnetron: It generates microwaves and consists of the following parts:

(a) Central cathode: The cathode is a metal cylinder at the centre of the magnetron coated with an electron-emitting material. In operation, the cathode is heated to a temperature high enough to cause electrons to boil off the coating.

(b) Outer anode: There is a metal ring called an anode around the magnetron maintained at a large positive potential (voltage) relative to the cathode. This sets up an electrostatic field between the cathode and anode that accelerates the electrons toward the anode.

Magnetic field: A strong magnetic field is placed next to the anode and cathode in such an orientation that it produces a magnetic field at right angles to the electrostatic field. This field has the effect of bending the path of the electrons so that, instead of rushing to the anode, they begin to circle in the space between the cathode and anode in a high-energy swarm.

Resonant cavities: They have been built into the anode. Random noise in the electron swarm causes occasional electrons to strike these cavities are such that most radiation frequencies die out. Microwave frequencies, on the other hand, bounce around the cavities and tend to grow, thus getting their energy from the magnetron, passes through the wave guides and enters the cavity.

However, not all materials can be heated rapidly by microwaves. Materials are reflected from the surface and therefore do not heat metals. Metals in general have high conductivity and are classed as conductors. Conductors are often used as conduits (waveguide) for microwaves. Materials which are transparent to microwaves are classed as insulators. Insulators are often used in microwave ovens to support the material to be heated. Materials which are excellent absorbers of microwave energy are easily used and are classed as dielectric.

Microwaves from part of a continuous electromagnetic spectrum that extends from low frequency alternating currents to cosmic rays shown in Table-1.

TABLE-1
THE ELECTROMAGNETIC SPECTRUM

Region	Frequencies (Hz)	Wavelength
Audio frequencies	$30–30 \times 10^3$	10 mm–10 km
Radio frequencies	$30 \times 10^3–30 \times 10^{11}$	10 km–1 m
Infrared	$30 \times 10^{11}–4 \times 10^{14}$	1 m–730 nm
Visible	$4 \times 10^{14}–7.5 \times 10^{14}$	730 nm–0.3 nm
Ultraviolet	$7.5 \times 10^{14}–1 \times 10^{18}$	400 nm–0.3 nm
X-rays	$> 1 \times 10^{17}$	< 3 nm
Gamma rays	$> 1 \times 10^{20}$	< 3 nm
Cosmic rays	$> 1 \times 10^{20}$	< 3 nm

In this continuum, the radio-frequency range is divided into bands as depicted in Table-2. Radio-frequency energy has several possible benefits in textile processing. Substitution of conventional heating methods by radio-frequency techniques may result in quicker and more uniform heating, more compact processing machinery requiring less space and less material in process at a particular time. Radio-frequency energy has been used for many years to heat bulk materials such as spools of yarn. Bands 9, 10 and 11 constitute the microwave range limited on the frequency side by high frequency and on the high frequency side by the infrared. These microwaves propagate through empty space through empty space at the velocity of light. The frequency ranges from 300 MHz to 300 GHz.

TABLE-2
FREQUENCY BANDS

Band	Designation	Frequency limits
4	Very low frequency (VLF)	3–30 kHz
5	Low frequency (LF)	30–300 kHz
6	Medium frequency (MF)	300 kHz–3MHz
7	High frequency (HF)	3–300 MHz
8	Very high frequency (VHF)	30–300 MHz
9	Ultra high frequency (UHF)	300–3 GHz
10	Super high frequency (SHF)	3–30 GHz
11	Extremely high frequency (EHF)	30–300 GHz

Pertinent electromagnetic parameters governing microwave heating

The loss tangent can be derived from materials complex permittivity. The real component of the permittivity is called the dielectric constant whilst the imaginary component is referred to as the loss factor. The ratio of the loss factor to the dielectric constant is the loss tangent. The complex dielectric constant is given by:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{6}$$

where ε is the complex permittivity, ε' is the real part of dielectric constant, ε'' is the loss factor and $\varepsilon'/\varepsilon'' = \tan\delta$ is the loss tangent.

Knowledge of a materials dielectric properties enables the prediction of its ability to absorb energy when exposed to microwave radiation. The average power absorbed by a given volume of material when heated dielectrically is given by the equation:

$$P_{av} = \varpi \varepsilon_0 \varepsilon''_{eff} E^2_{rms} V \tag{7}$$

where P_{av} is the average power absorbed (W); ϖ is the angular frequency of the generator (rad/s); ε_0 is the permittivity of free space; ε''_{eff} is the effective loss factor; E is the electric field strength (V/m) and V is the volume (m^3).

The effective loss factor ε''_{eff} includes the effects of conductivity in addition to the losses due to polarization. It provides an adequate measure of total loss, since the mechanisms contributing to losses are usually difficult to isolate in most circumstances.

Another important factor in dielectric heating is the depth of penetration of the radiation because an even field distribution in a material is essential for the uniform heating. The properties that most strongly influence the penetration depth are the dielectric properties of the material. These may vary with the free space wavelength and frequency of the propagating wave. For low loss dielectrics such as plastics ($\varepsilon'' \ll 1$) the penetration depth is given approximately by:

$$D_P = \frac{\lambda_0 \sqrt{\varepsilon'}}{2\pi \varepsilon''_{eff}} \quad (8)$$

where D_P is the penetration depth; λ_0 is the free space wavelength; ε' is the dielectric constant and ε''_{eff} is the effective loss factor.

The penetration depth increases linearly with respect to the wavelength and also increases as the loss factor decreases. Despite this, however, penetration is not influenced significantly when increasing frequencies are used because the loss factor also drops away maintaining a reasonable balance in the above equation.

As the material is heated, its moisture content decreases leading to a decrease in the loss factor. It can be seen from equation (8) that the decrease in loss factor causes in the penetration depth of radiation.

Microwaves cause molecular motion by migration of ionic species and/or rotation of dipolar species. Microwave heating a material depends to a great extent on its "dissipation" factor, which is the ratio of dielectric loss or "loss" factor to dielectric constant of the material. The dielectric constant is a measure of the ability of the material to retard microwave energy as it passes through; the loss factor is a measure of the ability of the material to dissipate the energy. In other words "loss" factor represents the amount of input microwave energy lost in the material by being dissipated as heat. Therefore, a material with high "loss" factor is easily heated by microwave energy. In fact, ionic conduction and dipolar rotation are the two important mechanisms of the microwave energy loss (*i.e.*, energy dissipation in the material). Non-homogeneous material (in terms of dielectric property) may not heat uniformly, that is, some parts of the materials heat faster than others. This phenomenon is often referred to as thermal runway.

Continuous temperature measurement during microwave irradiation is a major problem. Luxtron fluoroptic or accufiber can be employed to measure temperature up to 400°C but are too fragile for most industrial applications. An optical pyrometer and thermocouple can be employed to measure higher temperatures. Optical pyrometers, such as thermovision infrared camera, only records surface temperature, which is invariably much lower than the interior sample temperature. When a thermocouple (metallic probe) is employed for temperature measurements, arcing between the sample and the thermocouple can occur leading to temperature measurements, arcing between the sample and thermocouple can occur leading to failure in thermocouple performance. A recent development is the ultrasonic temperature probe, which covers temperature up to 1500°C.

In summary, microwave heating is unique and offers a number of advantages over conventional heating such as: non-contact heating; energy transfer, not heat transfer; rapid heating; material selective heating; volumetric heating; quick start-up and stopping; heating starts from interior of the material body; higher level of safety and automation.

A glossary[4] of microwave heating system is given in Table-3.

TABLE-3
GLOSSARY OF MICROWAVE HEATING SYSTEM[4]

Applicator or cavity	A closed space where a material is exposed to microwaves for heating
Choke	Barriers placed at entrance and exit of the applicator to prevent leakage of microwaves.
Circulator	A three port ferrite device allowing transmission of energy in one direction but directing reflected energy into water load (dummy load) connected at the third port.
Coupling	The transfer of energy from one portion of a circuit to another.
Dielectric	It is a measure of a sample's ability to retard microwave energy as it passes through.
Dielectric loss or loss factor	It is a measure of a sample's ability to dissipate microwave energy.
Hertz (Hz)	1 Hz = 1 cycle.
Magnetron	An electronic tube for generating microwaves.
Single mode applicator	Dimension of applicator or cavity is comparable with the wave length of microwave.
Multimode applicator	An applicator dimension is large in relation to the wave length of incident microwaves.

Basic concepts of microwave heating

As it was mentioned earlier, microwaves are electromagnetic waves having a frequency ranging from 300 MHz and 0.3 THz. Most of the existing apparatuses, however, operate between 400 MHz and 60 GHz, using well defined frequencies, allocated for industrial, Scientific and Medical (ISM) applications. Among them, the 2.45 GHz is widely used for heating applications, since it is allowed word-wide and it presents some advantages in terms of costs and penetration depth.

It was also mentioned earlier, that quantitative information regarding the microwave-material interaction can be deduced by measuring the dielectric properties of the material, in particular of the real and imaginary part of the relative complex permittivity, $\varepsilon = \varepsilon' - j\varepsilon''_{eff}$ where the term ε''_{eff} includes conduction losses, as well as dielectric losses. The relative permeability is not a constant and strictly depends on frequency and temperature. A different and more practical way to express the degree of interaction between microwaves and materials is given by two parameters; the power penetration depth (D_P) and the power density dissipated in the material (P), as defined earlier in a simplified version as follows:

$$D_P = (\lambda_0\sqrt{\varepsilon'})/2\pi\varepsilon'', \qquad P = 2\pi f \varepsilon_0 \varepsilon''_{eff} E^2_{rms} \tag{9}$$

where $\varepsilon = \varepsilon' - j\varepsilon''_{eff}$ is the complex permittivity of the material under treatment, λ_0 is the wavelength of the radiation, f is its frequency, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the permittivity of empty space and E_{rms} is the electric field strength inside the material itself. It should be noted that P and D_P can only give quantitative and often misleading information, especially when it is critical to determine the temperature profiles inside the material. Others are the variables involved, however from this two parameters can be deduced most of the peculiarities which make the microwave heating a unique process[5].

First of all, it can be noticed the existence of temperature profile inversion with respect to conventional heating techniques. The air in proximity of the materials during the heat treatment, in fact, is not a good microwave absorber so that it can be considered that the atmosphere surrounding the material is essentially at low temperature. *Vice-versa*, the material under treatment, interacting in a stronger way with the electromagnetic field, heats up and reaches higher temperature. The result, in most cases, the surface temperature of the sample is lower than inside the material itself. This effect is more pronounced for poor heat conducting materials.

Since the given formulations for D_P and P show a strong dependence upon the real and imaginary part of the material permittivity for multiphase systems having components with quite different permittivities, a strong selectivity of the microwave heating process is expected. Power, in fact, is transferred preferentially to glossy materials (high ε''_{eff}) so that it can be possible to raise the temperature of just a single phase or component, or to spatially limit the heat treatment to the material, without involving the surrounding environment. These peculiarities can be particularly useful when treating composite materials. The rapid variations of the permittivity as a function of temperature is responsible for a not always desirable phenomenon, the thermal runaway, that is to say the rapid and uncontrollable overheating of parts of the material under processing. Considering a low thermal conductivity material, whose permittivity increases as the temperature rises, in particular ε'' increasing the temperature growing, it will be subject to gradient of temperature, being colder in the regions where heat is rapidly dissipated or the field strength is lower and hotter in the remaining zones. These zones, presenting higher values of ε'' and thus of P, will start absorbing microwaves more than the cold ones, further rising their temperature and consequently the local value of ε'', strengthening the phenomenon.

Finally, dielectric heating is penetrating, depending on the operating wavelength, and permits to directly heat treat the surface and the core of the body, without waiting for the heat to reach the core of the sample by means of conduction, particularly time-taking for low thermal conductivity materials like most polymers are. In these materials, the penetration depth is high, of the order of some tens of centimetres thus facilitating the processing of large bodies, too[6].

Heat and mass transfer classical equations

The conservation of mass and energy for a textile material give the following equations:

$$\frac{\partial X}{\partial t} = D_n \nabla^2 X \tag{10}$$

$$C_{pn} \rho_n \frac{\partial T}{\partial t} = \nabla(K_n \nabla T) + Q(r, z, t) \tag{11}$$

where n = 1 *and* 2 refers to the inner and outer layer of materials and D is diffusivity, X the moisture content (kg/kg dry basis); k the thermal conductivity (W/m K); ρ the density (kg/m^3); C_p the heat capacity (J/kg K) and Q is the microwave source term (W/m^3).

The empirical model for calculating moisture diffusivity as a function of moisture and temperature,

$$D = \frac{1}{1+X} D_0 \exp\left[-\frac{E_0}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right] + \frac{1}{1+X} D_i \exp\left[-\frac{E_i}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right] \quad (11)$$

where D (m^2/s) is the moisture diffusivity; X the moisture content (kg/kg dry basis); T (°C) the material temperature; T_r a reference temperature and R = 0.0083143 kJ/mol K is the ideal gas constant, D_0 (m^2/s) the diffusivity at moisture X = 0 and temperature $T = T_r$, D_i (m^2/s) the diffusivity at moisture $X = \infty$ and temperature $T = T_r$; E_0 (kJ/mol) the activation energy of diffusion in dry material at X = 0 and E_i (kJ/mol) is the activation energy of diffusion in wet material at $X = \infty$. The proposed model may use the estimated parameters in Table-3.

TABLE-3
NUMERICAL VALUES FOR WOOL (BASED ON DATA FROM VARIOUS AUTHORS)

Diffusion coeff. of water vapour (1st stage):	$(1.04 + 68.20W_c - 1342.59W_c^2) \times 10^{-14}$, $t < 540$ s
Diffusion coeff. of water vapour (2nd stage):	$1.6164[1 - \exp\{-18.163\exp(-28.0W_c)\}] \times 10^{-14}$, $t \geq 540$ s
Diffusion coeff. in air:	$2.5e^{-5}$
Volumetric heat capacity of fibre:	$373.3 + 4661.0W_c + 4.221T$
Thermal conductivity of fibre:	$(38.49 - 0.720W_c + 0.113W_c^2 - 0.002W_c^3) \times 10^{-3}$
Heat of sorption:	$1602.5\exp(-1172W_c) + 2522.0$
Porosity of fibre:	0.92
Density of fibre:	1300 kg/m^3
Radius of fibre:	$1.03\ e^{-5}$ m
Mass transfer coeff.:	0.137 m/s
Heat transfer coeff.:	99.4 W/m^2 K

Initial conditions At time t = 0: $T = T_0(r, z)$ $X = X_0(r, z)$,

Boundary conditions: $\left.\frac{\partial X}{\partial t}\right|_{(r=0,\,H/2=0,\,t)} = 0$, $\left.\frac{\partial T}{\partial t}\right|_{(r=0,\,H/2=0,\,t)} = 0$

Fig. 1 shows that there is an increase in drying rate because of the microwave power density.

This can be attributed to the effect of microwave on moisture by rapidly increasing the moisture migration to the surface and increased evaporation. A comparison of these drying curves demonstrates improvement in drying times, under microwave heating. Nevertheless, the results show significant improvement in average drying times over the conventional heating method.

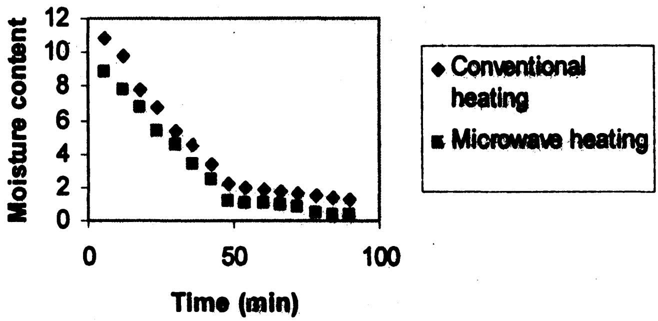

Fig. 1. Comparison of conventional and microwave on average moisture content

Heat and mass transfer exponential model

It has been recognized that microwaves could perform a useful function in textile drying in the levelling out of moisture profiles across a wet sample. This is not surprising because water is more reactive than any other material to dielectric heating so that water removal is accelerated. An exponential model presented here[7] can be used to describe the drying curves.

$$X = (a - X_{eq.}) \exp(-bt^{d}) + X_{eq.} \tag{12}$$

and its derivative form:

$$(-dX/dt) = b\, dt^{(d-1)}X \tag{13}$$

Parameters a, b, d can be determined by regression by the least square method. The quantities b and d vary with the experimental conditions and are drying coefficients. X is the moisture content of the drying material, dX/dt is the drying rate and t is the drying time. Parameter a represents the initial moisture content. The incident power strongly influenced the drying kinetics of a textile sample, reducing the drying time by raising the microwave heating power.

Combined microwave and convective drying of carpet

It should be noted that because of the higher temperature and pressure gradients generated during combined microwave and convective drying, greater care must be taken not to damage the textile material to be dried, whilst still taking advantage of the increased drying rates provided by the microwave environment. To fully understand the heat and mass transfer phenomenon occurring within the material during combined microwave and convective drying, it is required to analyze the moisture, temperature and pressure distributions generated throughout the process. It was shown by Ilic and Turner[8] that a theory based on a continuum approach led to the following equations of motion governing the drying of a slab of material.

Total mass: $$\frac{\partial}{\partial t}(\phi S_g \rho_g + \phi S_W \rho_W) + \nabla\cdot(\chi_g \rho_g V_g + \chi_W \rho_W V_W) = 0 \tag{14}$$

Total liquid: $$\frac{\partial}{\partial t}(\phi S_g \rho_{gv} + \phi S_W \rho_W) + \nabla\cdot(\chi_g \rho_g V_{gv} + \chi_W \rho_W V_W) = 0 \tag{15}$$

Here, S is the volume saturation, ϕ is the porosity, ρ [kg m^{-3}] is the density of the fibre and χ is the surface porosity.

Total enthalpy:

$$\frac{\partial}{\partial t}\Bigg(\phi S_g \rho_{gv} h_{gv} + \phi S_g \rho_{ga} h_{ga} + \phi S_g \rho_{ga} h_{ga} + \phi S_W \rho_W h_W$$
$$+ (1-\phi)\rho_s h_s - \phi \rho_W \int_0^{S_W} \Delta h_W(S)\, dS\Bigg)$$
$$+ \nabla\cdot(\chi_g \rho_{gv} V_{gv} h_{gv} + \chi_g \rho_{ga} V_{ga} h_{ga} + \chi_W \rho_W V_w h_W)$$
$$= \nabla\cdot((K_g X_g + K_W \chi_W + K_s(1-\chi))\nabla T) + \phi \qquad (16)$$

where ϕ is the internal microwave power dissipated per unit volume, K [m^2] is permeability and h [J kg^{-1}] is the averaged enthalpy. In equation (16) the effects of viscous dissipation and compressional work have been omitted.

The equations (14–16) are augmented with the usual thermodynamic relations and the following relations.

Flux expressions are given as follows:

Gas flux:

$$\chi_g \rho_g V_g = \frac{K K_g(S_W)\rho_g}{\mu_g(T)}[\nabla P_g - \rho_g g] \qquad (16a)$$

Here, g [m s^{-2}] is the gravitational constant and K_g is the relative permeability of gas.

Liquid flux:

$$\chi_W \rho_W V_W = -\frac{K K_W(S_W)\rho_W}{\mu_W(T)}[\nabla(P_g - P_C(S_W, T)) - \rho_W g] \qquad (16b)$$

where K_W is the relative permeability of water and μ [H m^{-1}] is the permeability of free space.

Vapour flux:

$$\chi_g \rho_{gv} V_{gv} = \chi_g \rho_{gv} V_g - \frac{\chi_g \rho_g D(T, P_g) M_a M_v}{M^2} \nabla\left(\frac{P_{qv}}{P_g}\right) \qquad (16c)$$

Here, V [m s^{-1}] is the averages velocity and M [kg mol^{-1}] is the molar mass.

Air flux:

$$\chi_g \rho_{ga} V_{ga} = \chi_g \rho_g V_g - \chi_g \rho_g V_{gv} \qquad (16d)$$

Relative humidity (Kelvin effect):

$$\psi(S_W, T) = \frac{P_{gv}}{P_{gvs}(T)} = \exp\left(\frac{2\sigma(T) M_v}{r(S_W)\rho_W RT}\right) \qquad (17)$$

where ψ is the relative humidity and $P_{gvs}(T)$ is the saturated vapour pressure given by the Clausius-Clapeyron equation.

Differential heat of sorption:

$$\Delta h_W = RvT^2 \frac{\partial(\ln \psi)}{\partial T} \tag{18}$$

Enthalpy-Temperature relations:

$$h_{ga} = C_{pa}(T - T_R) \tag{19}$$

$$h_{gv} = h^0_{vap} + C_{pv}(T - T_R) \tag{20}$$

$$h_W = C_{pW}(T - T_R) \tag{21}$$

$$h_s = C_{ps}(T - T_R) \tag{22}$$

The expressions for K_g, K_W are those given by Turner and Ilic[8] and μ_g, μ_W have had functional fits according to the data by Holman[9]. The diffusivity given by Quintard and Puiggali[10] and the latent heat of evaporation given by

$$h_{vap}(T) = h_{gv} - h_W \tag{23}$$

After some mathematical manipulations[11–14], the one-dimensional system of three non-linear coupled partial differential equations which model the drying process in a thermal equilibrium environment are given by[15–20]:

$$a_{s1}\frac{\partial S_W}{\partial t} + a_{s2}\frac{\partial T}{\partial t} = \frac{\partial}{\partial Z}\left[K_{S1}\frac{\partial S_W}{\partial Z} + K_{T1}\frac{\partial T}{\partial Z} + K_{P1}\frac{\partial P_g}{\partial Z} + K_{gr1}\right] \tag{24}$$

$$a_{T1}\frac{\partial S_W}{\partial t} + a_{T2}\frac{\partial T}{\partial t} = \frac{\partial}{\partial Z}\left(K_e\frac{\partial T}{\partial Z}\right) - \phi\rho_W h_{vap}\frac{\partial}{\partial Z}\left[K_S\frac{\partial S_W}{\partial Z} + K_T\frac{\partial T}{\partial Z} + K_P\frac{\partial P_g}{\partial Z}K_{gr}\right]$$
$$+\left[\phi\rho_W C_{pW}\left(K_{S2}\frac{\partial S_W}{\partial Z} + K_{T2}\frac{\partial T}{\partial Z} + K_{P2}\frac{\partial P_g}{\partial Z} + K_{gr2}\right)\right]\frac{\partial T}{\partial Z} + \Phi(S_W, T) \tag{25}$$

$$a_{P1}\frac{\partial S_W}{\partial T} + a_{P2}\frac{\partial T}{\partial t} + a_{P3}\frac{\partial P_g}{\partial t} = \frac{\partial}{\partial Z}\left[K_S\frac{\partial S_W}{\partial Z} + K\frac{\partial T}{\partial Z} + K_{P3}\frac{\partial P_g}{\partial Z} + K_{gr3}\right] \tag{26}$$

The capacity coefficients a_{S1}, a_{T1}, a_{P1} and the kinetic coefficients $K_{S1}, K_{T1}, K_{P1}, K_{gr1}$ all depend on the independent variables: saturation S_W, temperature T and total pressure P_g. The boundary conditions are written in one dimension as[21–22]:

At z = 0 (Drying surface):

$$K_{S1}\frac{\partial S_W}{\partial Z} + K_{T1}\frac{\partial T}{\partial Z} + K_{P1}\frac{\partial P_g}{\partial Z} + K_{gr1} = \frac{K_m M_V}{R\phi\rho_W}\left(\frac{P_{gV}}{T} - \frac{P_{gV0}}{T_0}\right) \tag{27a}$$

$$K_e\frac{\partial T}{\partial Z} - \phi\rho_W h_{vap}\left(K_S\frac{\partial S_W}{\partial Z} + K_T\frac{\partial T}{\partial Z} + K_P\frac{\partial P_g}{\partial Z} + K_{gr}\right) = Q(T - T_0) \tag{27b}$$

$$P_g = P_a \tag{27c}$$

At z = L (impermeable surface):

$$K_{S1}\frac{\partial S_W}{\partial Z}+K_{T1}\frac{\partial T}{\partial Z}+K_{P1}\frac{\partial P_g}{\partial Z}+K_{gr1}=0 \tag{28a}$$

$$K_e\frac{\partial T}{\partial Z}-\phi\rho_W h_{Vap}\left(K_S\frac{\partial S_W}{\partial Z}+K_T\frac{\partial T}{\partial Z}+K_P\frac{\partial P_g}{\partial Z}+K_{gr}\right)=0 \tag{28b}$$

$$(K_{S1}-K_S)\frac{\partial S_W}{\partial Z}+(K_{T1}-K_T)\frac{\partial T}{\partial Z}+(K_{P1}-K_{P3})\frac{\partial P_g}{\partial Z}+(K_{gr1}-K_{gr3})=0 \tag{28c}$$

Initially:

$$T(z,0)=T_1 \tag{29a}$$

$$P_g(z,0)=P_0 \tag{29b}$$

$$\frac{\partial P_c}{\partial Z}=-\rho_W g \tag{29c}$$

Fig. 2 shows a comparison of convective drying with or without microwaves[23]. Whilst for convective drying there are definite constant rate and falling rate periods when microwaves are added the form of the curves changes[24, 25].

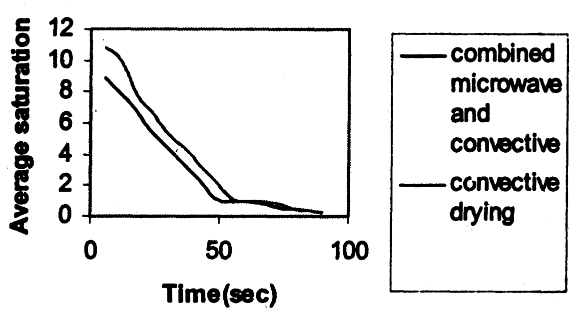

Fig. 2. Average saturation profiles in time for drying with or without microwaves

Conclusion

From the earlier discussions, it will be clear that there are a lot of factors that have to be considered before employing microwave irradiation for textile materials. Blind applications of microwave energy in textile chemistry will usually lead to disappointment. On the other hand, wise application of this technology will have greater benefits that have been anticipated. In general, the savings achieved through application of microwave techniques in textile chemistry will be other than energy as the saving in this respect would not be enormous. The benefits will be in time saving, increased process yield, environmental compatibility, space savings and unique characteristics of the textile products.

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