PHYSICAL AND CHEMICAL CHARACTERISTICS OF WATER IN A MICROWAVE FIELD AND MASS TRANSFER DURING THE DRYING OF DENSE TEXTILES

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Abstract

Microwave drying provides economic advantages based on optimised energy consumption and productivity deriving from the changes in physical and chemical properties of water in a microwave field: heating rate, as influenced by chemical composition, volume, the presence of the heat transformer; volume expansion, vapour pressure, rH, evaporation rate and the evaporation parameter – all measured in relation to temperature, time and power. For example, in the case of felt, energy consumption is reduced from 4-6 kWh in classical drying to 1.7-2.3 kWh during microwave drying per 1 kg of dried water. In addition, the drying period is shortened from 200-400 min. in classical drying to 60-140 min. in microwave drying. Thus, based on drying time alone, productivity increases 3 to 4 times. Each material subjected to a drying process is characterised by typical energy consumption and productivity levels.

Key words: water, field, microwave, trensfer, drying

The microwave heating of dielectrics in a cavity resonator has emerged out of the necessity to increase the power transformed into heat, by using ultra high frequencies, the intensity of the electrical field being limited due to dielectric rigidity. According to the general classification, microwaves are defined as the area of the electromagnetic spectrum ranging between f = 0.3 GHz and f = 6.10^3 GHz (λ = 0.05 - 10^3 mm); based on other definitions set the boundaries of the microwave spectrum between f = 1 and 3.10^2 GHz (λ = 1-3.10^2 mm).

Interaction effects can be thermal or non-thermal. Non-thermal effects are generated at high potential (> 100 V/cm) and at low potential. This refers to: the saturation of dielectrics, the orientation of colloidal particles, the molecular resonance of microscopic-scale biological structures, etc.

As regards thermal effects, the specific power [W/m^3] dissipated in the material is expressed by the relationship:

$$P_V = 0.5 \cdot a_{el} \cdot E^2 + 0.5 \cdot \varepsilon_0 \cdot \varepsilon'' \cdot \omega \cdot E^2 + 0.5 \cdot \mu_0 \cdot \mu'' \cdot \omega \cdot H^2 \ [W/m^3]$$

Where a_{el} – electric conductibility [S/m]; ε - electric permittivity [F/m]; μ'' - magnetic permeability [H/m]; E, H – the intensity levels of the electric field [V/m] and, of the magnetic field [A/m] respectively.

If a_{el} = 0 and μ'' = 0, :

$P_V = 0.55 \cdot 10^{-10} \cdot \varepsilon'' \cdot f \cdot E^2$

with $\varepsilon'' = \varepsilon' . tg\ \delta_{el}$ and $\mu'' = \mu' . tg\ \delta_m$.

These values define the dielectric properties of a material and characterise its behaviour under the influence of a high-frequency field (microwaves), being dependent on frequency, humidity, temperature, etc.

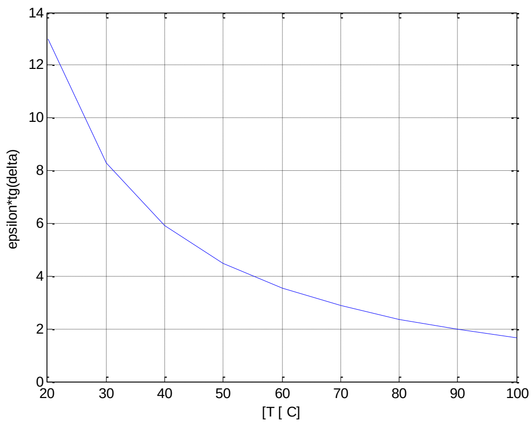

Figure 1 **Temperature dependence of product (ε'tg δel) for water at 2.45 GHz frequency.**

In the case of water, given the ranges f = 1 - 10 GHz and T = 20 -100 ^{0}C, one can calculate the following relationships:

$$tg\ \delta_{el} = \frac{1}{T}(1{,}82 . 10^{-9}\ f - 1{,}2)$$

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$$\varepsilon' = 87 - 0{,}36T$$

Product ε'tg δ_{el} reaches the maximum values at a frequency of 27.5 GHz.

MATERIALS AND METHODS

A laboratory set-up was assembled from commercial components, similar in principle to regular components, with maximum output power of 800 W and a frequency of 2450 MHz. Initial power (P) was set on three levels: 350, 500, 650 W. The cavity resonator features:

- reaction bowl;
- PC-linked digital thermometer for automatic recording during the charging break of the magnetron;
- pressure manometer (0 – 300 mmHg);
- ORP system for the simultaneous measurement of temperature, pH, electrode potential, connected to a PC and charged through a connection loop in the generation break of microwaves;
- pycnometer with volumetric pipette.

Materials

Measurements of the cavity resonator: L x l x H = (350 x 228 x 343) mm and volume 27.3 l.

Heating rate

The power of microwaves is a key factor with a significant influence on the heating rate. If greater power is applied, then an increased heating rate of the object subjected to heating is to be expected.

The dependence between the power of microwaves applied during heating and temperature increase can be rendered by the equation below:

$$\Delta T = \frac{P \cdot t}{\rho \cdot V \cdot c_p}$$

where: ΔT – temperature increase of the heated object;

P – power of microwaves used for heating;

ρ, V, c_p – the density, volume, specific heat (kg/m^3, m^3, and J/(kg ^{0}K), respectively), t – heating time, s.

The output efficiency of the set-up is dependent on the frequency and on the measurements and volume of the cavity typical of each set-up.

The initial power absorbed by water (IEC standard IEC 705 – 1988, V = 1000 ml, T_0 = 10 ± 2 ^{0}C) is expressed by the previous equation adjusted for the given conditions:

$$P = 4187 \cdot \frac{\Delta T}{t}$$

RESULTS AND DISCUSSIONS

Temperature : T = 63.5750 + 27.7500 t + 10.9667 P +4.3250 t P – 0.8250 t^2 – 6.8750 P^2

t – time, min.: P - power, W

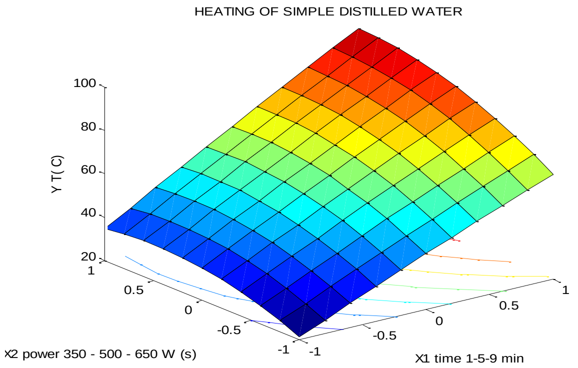

Figure 2 **Temperature**

Heating rate

dT/dt = 0.88-0.595 t – 0.0875 P -0.2075 t P – 0.0925 t^2 +0.0734 P^2

t – time, min.: P - power, W

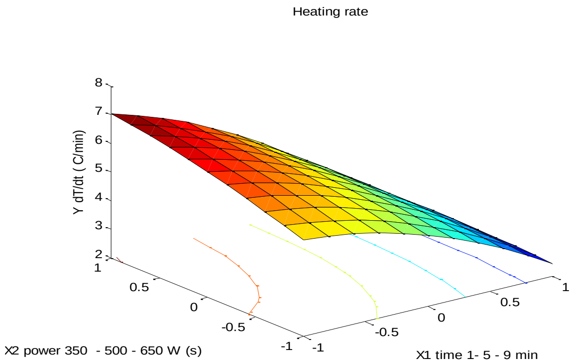

Figure 3 **Heating rate**

Heating based on a heat transformer (thermal runaway)

T=59.8000 + 28.3500 t + 10.5333 P +
+5.7000 t P – 0.7000 t^2 – 2.5500 P^2

t – time, min.: P – power, W

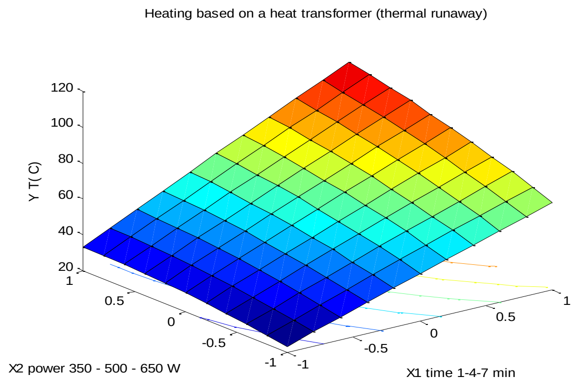

Figure 4 **Temperature**

Heating rate based on thermal runaway

dT/dt=8.3715 – 1.7490 t + 0.7510 P – 0.6215 t P – 1.7615 t^2 – 0.0815 P^2

t – time, min.: P - power, W

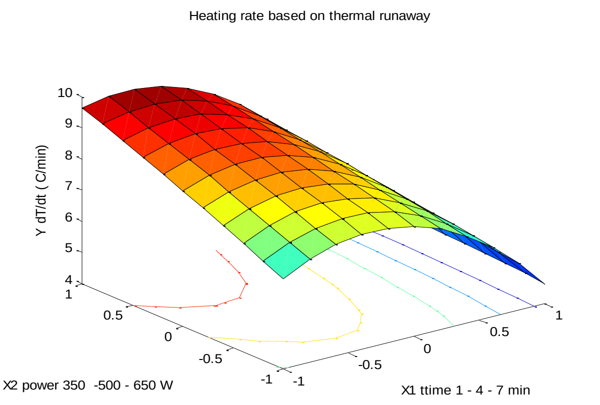

Figure 5 **Heating rate**

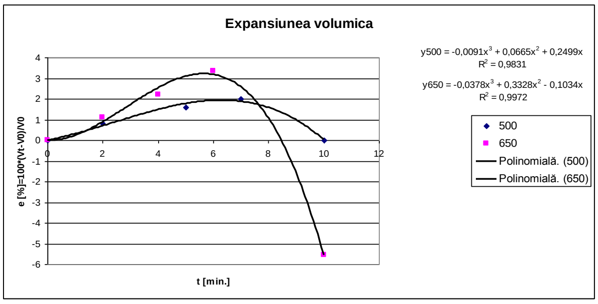

Figure 6 **Volume expansion**

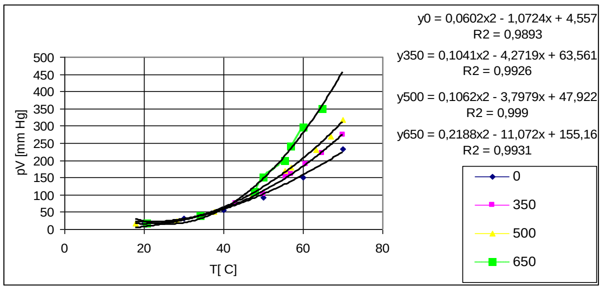

Figure 7 **Pressure of water vapours**

Dependence of vapour pressure on time and power

$p_v = 44 + 55.8333\ t + 48.6667\ P + 43.0000\ t\ P + +29.000\ t^2 + 17.5000\ P^2$

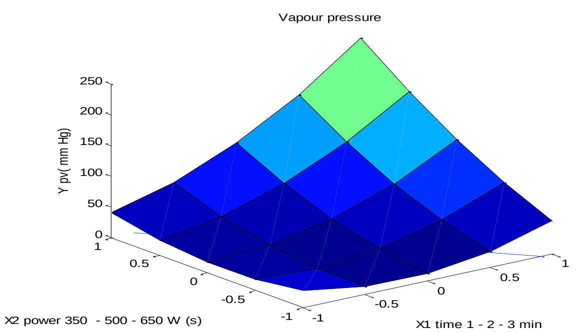

Figure 8 **Vapour pressure**

Determining the rH for polymolecular water fractions

The relative hydrogen score, rH, was first proposed to the research community (mostly inorganic chemists) by Clark in 1923, as a means to measure the actual reduction of hydrogen in an aqueous solution of simple antioxidant compounds and is based on a variant of the Nernst equation.

The rH range is from 0 to 42, with 28 being the median value. Below the 28 point reduction occurs, and oxidation above the 28 value. The extreme values, 0 and 42, indicate the maximum reduction and oxidation rates, respectively.

$$rH = \left(\frac{E + 200}{30} + 2pH \right)$$

E – recorded potential, in mV; E_0 – potential of the reference electrode, 244.2 mV (calomel), which is dependent on temperature.

$E = E_i\ (t) + [244.2 - 0.72 * (T_i - 25)]$;

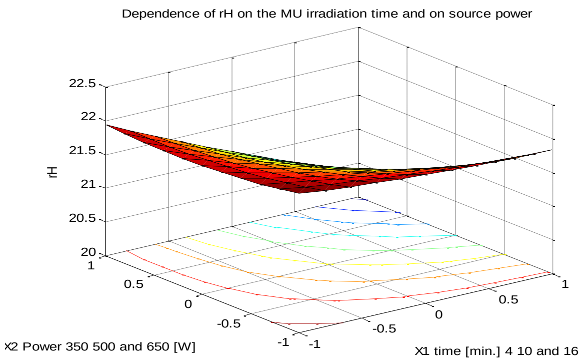

Figure 9 **rH in relation to time and power**

The regression equation:

rH=21.4112-0.4525 t-0.4015 P-0.3407 t*P+ +0.0441 t^2+0.0959 P^2

t – time, min ; P – power, W;

rH decreases from 22.0646 (4 min and 350 W) to **20.3566 (15 min. and 650W).**

Modelling the water evaporation process

For the various initial power values (P_0 = 350, 500, 650 W), after different irradiation periods, t (min.), water temperature, T (^{0}C), was measured and the Matlab software environment was used for mathematical calculations and graphical representations of the dependencies:

- mass loss by evaporation, M(g);
- water mass evaporated, M (%), in relation to t (min.) and P (W) ;
- evaporation rate, dM/dt (%-min.), in relation to t (min.) and P (W) ;
- evaporation rate, dM/dt (%/min.) in relation to the water mass evaporated, M /%) for power values P = 350, 500 and 650 W;
- the initial evaporation parameter, k (min^{-1}) in relations to P (W);
- the evaporation parameter for volume 4 x 250 ml.

Mass loss by evaporation

M_{ev} (%) = 29.1400 +29.5467 t +8.9533 P + 8.73550 t P -5.0300 t^2+3.7600 P^2

t - time, min; P – power, W; volume 500 ml.

Irradiation volume: 500 ml water.

Evaporation rate

dM_{ev}/dt [%/min.] = 0.9931 – 0.1304 t+0.1538 P + +0.0881 t P – 0.2981 t^2 +0.4900 P^2

dM/dt [%/min.] = 0.9850 – 0.0300 M +0.2983P + +0.0950 M P -0.27 M^2 – 0.1150 P^2

Initial evaporation parameter, k_{ev} [(%/min)/%]

k_{ev}= 0.0284 - 0.0189 t - 0.0031 P + 0.0044 t P – -0.0214 t^2 + 0.0123 P^2

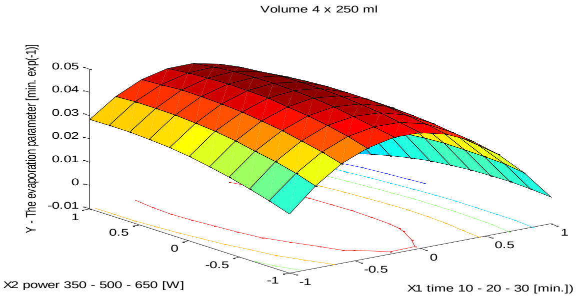

Figure 10 **The evaporation parameter**

Table 1

Materia l	Designation of characteristic	Value
Felt	thickness, m specific mass, kg/m^2	0.014 0.2
BM	thickness, mm specific mass, kg/m^2	0.05 1.0
bm	thickness, m specific mass, kg/m^2	0.03 1.5

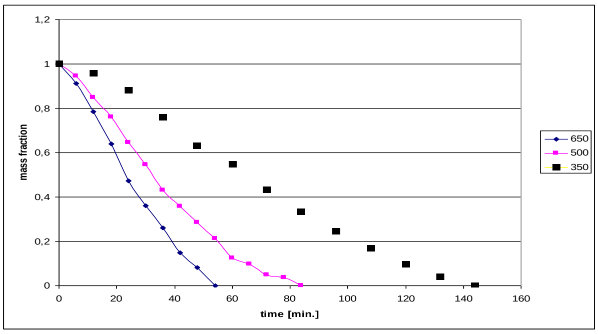

Figure 11 **Microwave drying of felt**

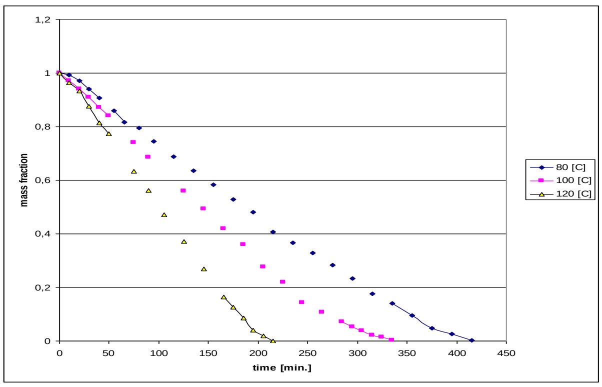

Figure 12 **Convection drying of felt**

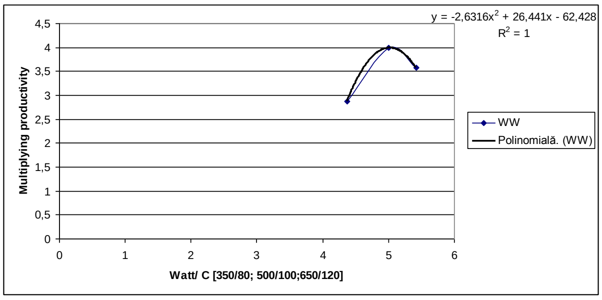

Figure 13 **Multiplying productivity**

CONCLUSIONS

Microwave drying presents economic advantages derived from optimised energy consumption and increased productivity. For instance, in the case of felt, energy consumption is reduced from 4-6 kWh in classical drying to 1.7-2.3 kWh during microwave drying per 1 kg of dried water. In addition, the drying period is shortened from 200-400 minutes in classical drying to 60-140 minutes in microwave drying. Therefore, based on drying time alone, productivity increases 3 to 4 times.

Each material subjected to a drying process exhibits typical energy consumption and productivity levels.

REFERENCES

DONCEAN, Gheorghe 2010 - *„Procedee speciale în tehnologia chimică textilă. Îndrumar de laborator”*, Editura Performantica, Iaşi.

BUTNARIU, R, and DONCEAN, Gh. 2007, 2008, 2009 - “Tehnologii neconvenționale pentru finisarea materialelor textile”, volumele I, II, III, Editura Performantica, Iaşi,

DONCEAN, Gh. 2000 - “*Optimizarea proceselor în tehnologia chimică textilă”,* Editura Performantica, Iaşi,