

EFFICIENCY OF MICROWAVE APPLICATORS: REZONANT, MULTIMODE AND MONOMODE

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The performances of a new microwave applicator based upon two concepts: resonance and focus of the electromagnetic field on the target are described. At resonance frequency, the cavity stores the MWs energy – therefore, no MWs are reflected back into the wave guide. The focusing capacity of the applicator is measured via ϵ energy transfer efficiency and heating uniformity. This new applicator was tested for several liquids with very different dielectric parameters behavior, namely: water, ethylene glycol, acetic acid and 2-propanol and its performance has been compared to that of the single-mode and multimode applicators.

Keywords: Process intensification, new microwave applicator, resonant applicator

1. Introduction

Process intensification can be achieved by developing new equipment and techniques that bring considerable improvements compared to the existing ones, by reducing the dimensions, accelerating the process rate, decreasing the specific consumptions, etc.[1]. The process intensification with microwaves creates additional freedom to design the equipment because it is a contactless method, so it does not require a heating surface [2]. Microwave heating technology uses electromagnetic waves, the most used frequencies being 915 MHz and 2450 MHz. This technology has specific characteristics which are unique: is selective, is heating in volume and it is very fast. A better understanding of the effectiveness of this process aiming for both optimizing the microwave heating and increasing the efficiency of energy usage is an important aspect. Electricity is first converted into microwave energy, which is then absorbed by a dielectric medium and dissipated as thermal energy [3].

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Any industrial technology should be optimized in terms of specific process requirements, to ensure a high rate of outcomes and better energy efficiency. So, any system using thermal energy for material processing needs to be adapted to the required production rate and to the material specific thermal properties of the products [4]. Literature data [3, 5] indicate that, when using a multimode applicator, microwave heating is influenced by many factors, the most important of which are: the position of the sample inside the cavity, the dielectric characteristics of the material being heated, the microwave power and the geometric parameters of the applicator used, as well as the ratio between the sample volume and the applicator volume.

A major problem in microwave heating systems with electromagnetic applicators is that resonant frequency, electromagnetic field and heating uniformity are all affected by any disturbance that may occur in the cavity. The latter can occur due to the properties of materials and changes in geometry due to changes in the position, shape and size of any objects physically present in the cavity. The relations among resonance frequency, heating uniformity, structural parameters of the cavity, load, and material properties of the load were investigated in Sturm et al. [2].

The most important characteristics for microwave heated materials are: dielectric constant (ϵ'), dielectric loss factor (ϵ'') and dissipation factor ($\tan \delta$). The dielectric constant describes the ability of the molecule to be polarized by the electric field. At low frequencies this value will reach a maximum as the maximum amount of energy can be stored in the material. The dielectric loss, ϵ'' , measures the efficiency with which the energy of the electromagnetic radiation can be converted into heat. The ratio of the dielectric loss and the dielectric constant define the (dielectric) loss tangent $= \epsilon''/\epsilon' = \tan \delta$, which describes the ability of a material to convert electromagnetic energy into heat energy at a given frequency and temperature [6, 7].

The most important types of microwave applicators are: monomode and multimode. In their simplest form, single-mode applicators consist of a section of waveguide operating at a frequency near cutoff. They usually have had holes or slots cut in them to let product in or out. Some advantages of single-mode applicators follow [8]:

- High fields are possible.
- Fields are well defined.
- Fields can be matched to product geometry.
- The applicators are useful for heating both low-loss and high-loss materials.
- The applicators are compatible with continuous product flow.
- High efficiency is possible.

The use of single-mode applicators involves some penalties that must be weighed carefully. They are product specific rather than general purpose and in operation can be very sensitive (i.e., tuned off-resonance) to changes in product properties, geometry, and position, the treated samples are very small to preserve the advantages of the single mode applicator.

Multimode applicators are often used for processing bulk materials or arrays of discrete material, whose overall dimensions are too large (larger than the wavelength of the operating frequency) to permit consideration for use in a single-mode oven. These applicators, in their simplest configuration, take the form of a metal box that is excited (driven) at a frequency well above its fundamental cutoff frequency. For example, the common home microwave oven typically has internal dimensions on the order of 30 to 40 cm., while the wavelength is 12.2 cm. The larger dimension corresponds to a cutoff frequency of about 400 MHz as compared with the operating frequency of 2.450 GHz [8]. When the electromagnetic energy, externally generated, is fed by some means into a cavity with specific dimensions, it induces an internal resonant electromagnetic field that extends throughout the entire cavity [9]. Some workloads have such a low value of loss factor ϵ'' that the heat dissipation density using monomode or multimode applicators is too low at the electric-field intensities they create. In such cases, by using resonance, the field intensity can be raised considerably, giving satisfactory heat dissipation [7]. Except for plasma generation, resonant systems have not been widely used in industrial production because of control difficulties. As the workload properties and other parameters of the system change with temperature and wear, both the cavity resonant frequency and the generator frequency drift, and power transfer falls. Retuning is necessary to restore the correct operating conditions. In most cases, this is necessary so frequently that an automatic frequency control (AFC) is required, in order to get back the applicator closer to the resonant state [10]. However, such a system involves very expensive components for controlling and adapting the microwave frequency depending on the reflected power. Our idea was to design and make an applicator that does not deviate too much from the resonant state during operation even if the frequency is maintained the same. In order to compare the efficiency of this new type of applicator (Fig. 3b), power tests were performed using this new resonant applicator and two monomode and multimode type applicators.

2. Experimental

2.1. Materials

The experiments were performed using liquids that have very different dielectric properties: distilled water, ethylene glycol (Chimopar), 2-propanol (Chemical) and glacial acetic acid (Chimreactiv). From these, two liquids have high values of tangent loss (ethylene glycol and 2-propanol), while the other two

have lower values (water and acetic acid). Fig. 1 (a, b, c) shows the dielectric properties of these selected substances in the temperature range 20-80°C, as documented in literature [11]. For the experiments with the selected liquids, three different applicators were used:

1. The monomode applicator, the one provided by SAIREM as part of the MINIFLOW 200 SS system [12], being an applicator that works in TE mode (figs. 2 and 3a).
2. The resonant applicator is a new applicator built by us (fig. 3b), being an aluminum cube with a side of 145.3 mm. In this applicator the microwaves are provided by a transition coaxial adapter to waveguide WR340.
3. The multimode applicator is adapted from a classic microwave oven, with a volume of 18 L, in which a slot was cut to mount the transition coaxial adapter to waveguide WR340 (Fig.3c).

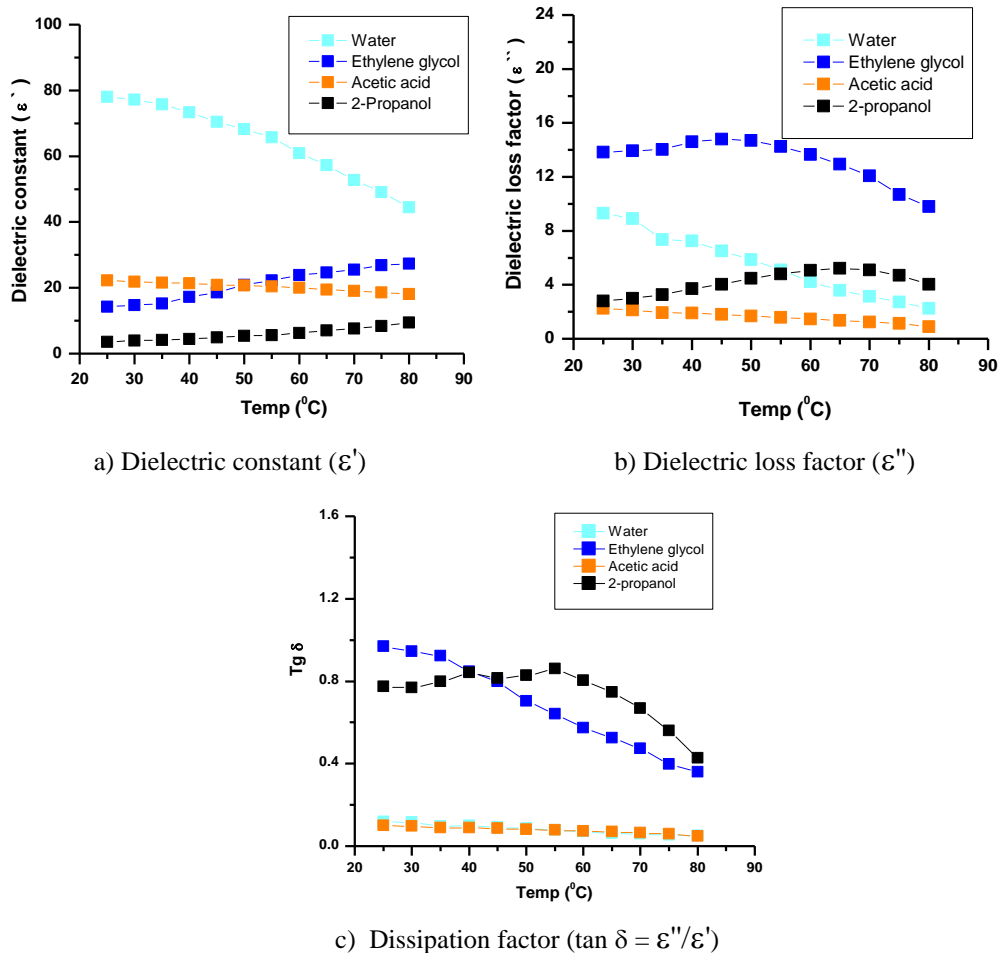


Fig 1. Dielectric properties of water, ethylene glycol, 2-propanol and glacial acetic acid [11]

In all these applicators the microwave energy is supplied by the same solid-state microwave generator (fig. 2, 6) via a coaxial cable, which allows the recording of the absorbed and the reflected power. In single-mode and resonant applicators, a sliding short-circuit device (figs. 2 and 3, 4) can also be mounted, which is a waveguide-based component used in tuning applicators for the adjustment of the resonance frequency.

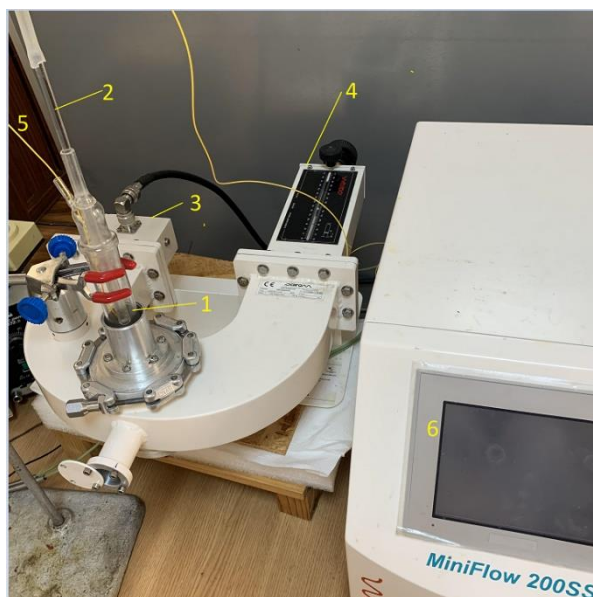


Fig. 2. Mini-Flow 200SS used with TE type cavity

1 – reactor; 2 – stirrer; 3 - transition coaxial adapter to waveguide; 4 – sliding short circuit; 5 – optical fiber; 6 – SS MW generator

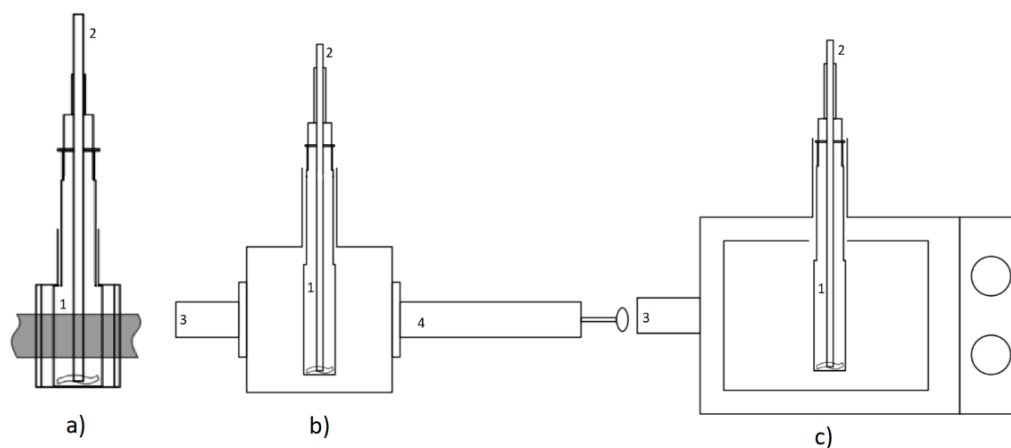


Fig. 3 Microwave applicators used: a) monomode, TE type, b) resonant cavity, c) multimode

1 – reactor; 2 – stirrer; 3 - transition coaxial adapter to waveguide; 4 – sliding short circuit

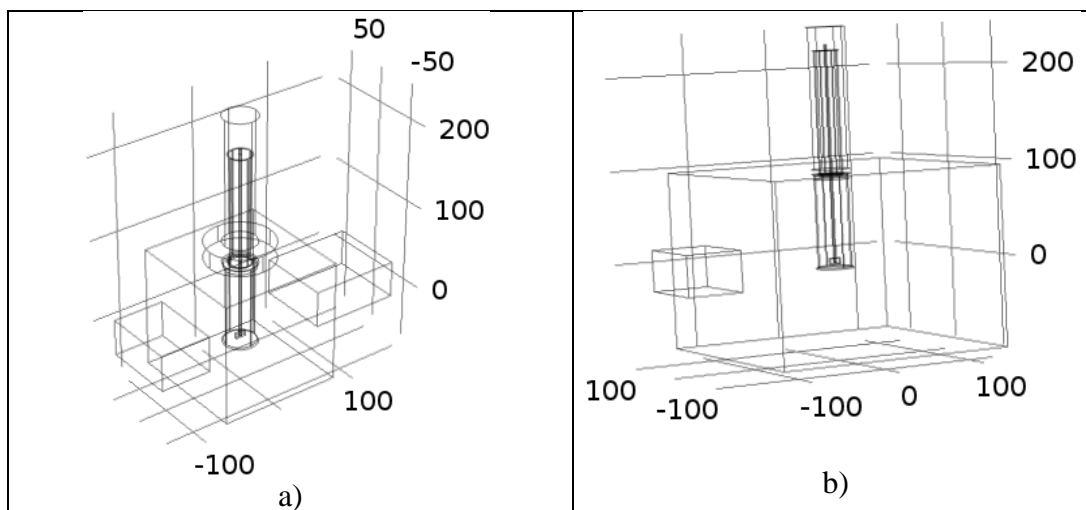
2.2. Experimental setup

The experiments were performed using the same load in all applicators (a cylindrical vessel⁵ with a useful volume of 100 mL, provided with a mechanical stirrer). After positioning the reactor symmetrically to the waveguide, the stirring is started. The initial temperature was measured with optical fiber then the SS MW generator was turned on and set to a certain power for 60 seconds. When the microwave generator is turned off the final temperature was measured.

Determinations of power losses in the load were made starting from the same temperature (25°C).

2.3. COMSOL® modeling

Using the basic building blocks from COMSOL® (Block, Cone, Cylinder and Sphere), together with the Boolean operation (Union, Intersection, Difference, Compose), the three applicators were built according to their geometrical characteristics (Fig. 4). After this first step, the geometry of each applicator was meshed, so that the solving algorithm to be able to accurately compute the electromagnetic wave field. To this end, the mesh maximum dimension should equal the tenth of the wavelength. The dielectric properties of each of the four liquids were introduced, according to literature data and the “Electromagnetic Waves, Frequency Domain” physics was used, to compute field distribution inside the applicator. The computation was done according to the “Frequency Domain” study, which uses the “multifrontal massively parallel sparse direct solver” implementation in COMSOL®, with the default options.



⁵ In subsequent work this applicator will be used to study various chemical reactions. For this reason we used the name reactor for the cylindrical vessel.

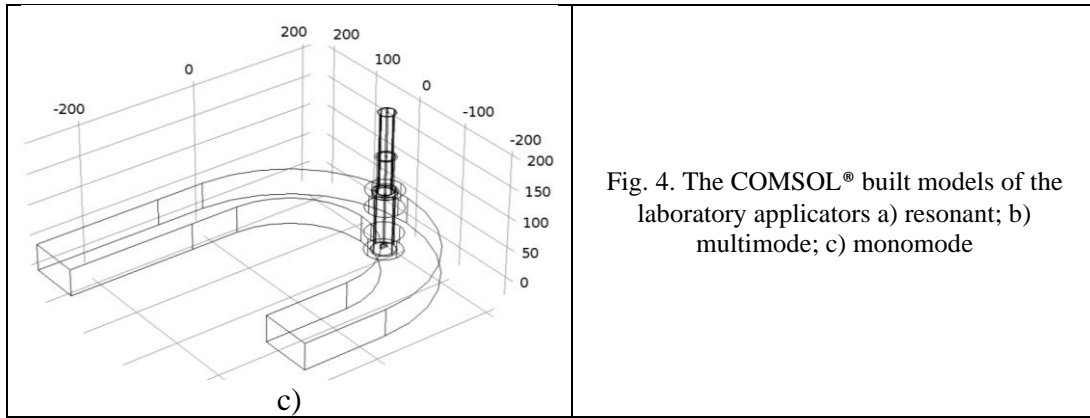


Fig. 4. The COMSOL® built models of the laboratory applicators a) resonant; b) multimode; c) monomode

4. Results and discussion

The energy transfer efficiency (η_L) in the liquid expected to be heated can be expressed as the ratio of power losses in the load P_L to the total power loss, P . The total power loss is expressed as a sum of ohmic losses determined by eddy currents obtained by reflection loss of the electromagnetic waves within the resonator walls (P_R), power loss of the load (P_L) and power loss of the coupling port (P_C) [4]:

$$P = P_R + P_L + P_C \quad (1)$$

$$\eta_L = \frac{P_L}{P} = \frac{Q}{Q_L} \quad (2)$$

The Q factor is a measure of the efficiency of electromagnetic storage in the applicator. It is correlated with the existing loss mechanisms and is given by the ratio between stored and lost energy [4].

$$Q = \frac{\text{Stored energy}}{\text{Power loss} \cdot \text{Oscillation period}} \quad (3)$$

For the experiments performed in this work, power losses in the load (P_L) were calculated by the equation (4). Because short irradiation times were used, the temperature increases in the reactor (ΔT) were small and for this reason lost power was neglected ($P_{\text{lost}} = P_R + P_C$) [4].

$$P_L = \frac{m \cdot C_p \cdot \Delta T}{\text{Time}} + P_{\text{lost}} \quad (4)$$

where:

m - mass of liquid in the reactor, g;

ΔT - temperature difference, ($^{\circ}\text{C}$) recorded after the working time: 60 s

C_p - specific heat, ($\text{J} / \text{g} \cdot ^{\circ}\text{C}$);

Time - is the time of microwave heating (s).

Table 1 shows the values obtained for the power losses in the load, for the three types of applicators, when the power provided by the solid-state microwave generator was 25W. The results in the table are consistent with the literature information: the higher the loss tangent ($\tan \delta$), the better the conversion of microwave energy into heat [13]. Regarding the type of applicator, it can be seen that our resonant applicator adapts well to all liquids used (reflected power is zero) and allows attaining the best values for energy transfer efficiency.

Table 1

Power absorbed for the 4 liquids tested in the 3 microwave applicators

Liquids	Applicator type	P_L	Reflected power	Energy transfer efficiency
		W	W	
Ethylene glycol	Multimode	20.11	0.29	0.81
	Resonant	24.17	0.00	0.97
	Monomode	21.03	2.10	0.92
2-propanol	Multimode	21.29	1.72	0.91
	Resonant	22.86	0.00	0.91
	Monomode	21.15	0.00	0.85
Water	Multimode	18.14	1.02	0.76
	Resonant	21.33	0.00	0.85
	Monomode	19.72	2.80	0.89
Acetic acid	Multimode	16.61	5.00	0.83
	Resonant	21.78	0.00	0.87
	Monomode	20.9	0.00	0.84

Another very important aspect of our resonant applicator is the uniformity of the heating in the reactor. The ideal conditions are those in which the liquid in the reactor is heated evenly within its whole volume. In order to determine the heating uniformity, the data obtained in COMSOL® were processed for modeling these three types of applicators. Heating uniformity can be expressed as an Irregularity index defined as the ratio between the standard deviation and the mean value. The smaller the Irregularity index, the more uniform heating will be in the considered liquid. Fig. 5 shows the Irregularity index for the three applicators. It can be noticed that on our new resonant applicator the lowest values of Irregularity index are obtained for all the studied liquids. In monomode and resonant applicator it is possible to better adapt the load by changing the position of the Sliding short circuit. The optimal position will depend on the dielectric properties of the liquid in the reactor. Because these properties vary with temperature, we have different curves for the two temperatures studied (25 and 50°C).

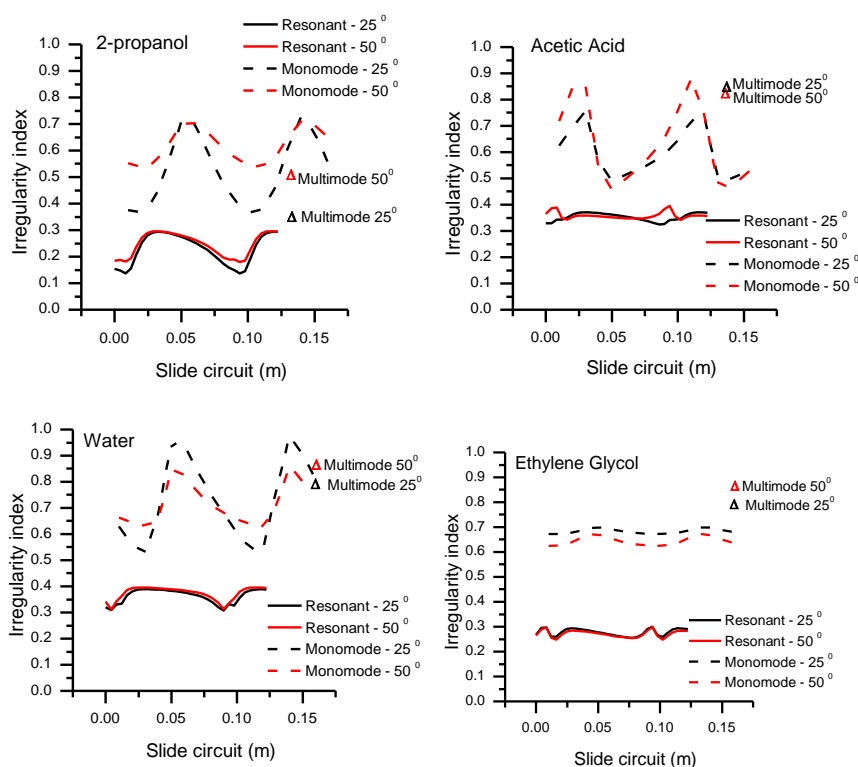


Fig 5. Irregularity index for the studied liquids, at 25 and 50 °C - for single-mode and resonant applicators depending on the Short circuit position and for the multimode applicator the point value

In the case of two liquids, water and 2 propanol, it is visible that the differences between the values modeled on the monomode applicator are significantly higher than those obtained in the case of the resonant applicator, at the positions of the Sliding short circuit where the minimum values of Irregularity index are. Another important advantage of our new resonant type applicator is that when the temperature increases, the uniformity of the heating does not decrease.

6. Conclusions

A new type of applicator (resonant applicator, fig. 3b) was designed, built and tested in our laboratory and compared with two types of applicators, monomode and multimode (commercially available). The evaluation was made based on the energy transfer efficiency (determined calorimetrically) and the uniformity of the heating (determined by modeling in COMSOL®).

The experiments performed using these three different microwave applicators: resonant build be us, monomode and multimode applied to the same reactor loaded with identical volume for four different liquids: water, ethylene

glycol, isopropyl alcohol and acetic acid, shown that the *our new resonant applicator* offer features that are better than those of commercially applicators, in terms of the heating uniformity as well as for energy transfer efficiency. These features are due to the low losses in the cavity walls and to the possibility to reach critical coupling conditions in a large variety of samples and operating conditions.

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