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RESEARCH ARTICLE

A microwave cavity design and optimisation for a homogeneous and faster drying process inside an industrial Agitated Nutsche Filter

[version 1; peer review: 1 approved with reservations, 2 not approved]

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Abstract

Background: Nowadays the disposal or recycling of polyethylene terephthalate (PET) material is a real-world problem. The European Union's DEM3TO project aims at recycling PET to return it to the main chemical components with which it was produced. In a specific reactor, microwave radiation is used to quickly depolymerise the initial polymer. At the end of the de-polymerization process, a filtering and drying process through an agitated Nutsche filter (ANF) is necessary.
Methods: This study aims to design and develop a High Frequency (HF) cavity inside the ANF (plugin "HF-ANF") to speed up and improve the drying process. The effects studied are the efficiency of the HF cavity as a function of the heating process, the evaporation/drying process, and the mechanical mixing (due to the blades) of the mixture.
Results: During these studies it was possible to improve the efficiency of the HF plugin and allowing to absorb more than the 95% of the microwave energy into the mixture to increase the drying speed and the drying homogeneity of the ANF. In addition, the mixture was characterised to obtain the dielectric proprieties as a function of the temperature of the ANF and the concentration of the residual water.
Conclusions: The study allowed us to develop some important methodology that usually cannot to be simulated in a non-multi physics simulator. The careful modelling of certain aspects that are not normally available in EM (Electro-Magnetic) simulators, like variable geometries, mixed material, heating effect and the dielectrics characterization process are difficult and critical process but are very important steps to be undertaken in order to obtain results that can be compared with real measurements.

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Microwave heating, Microwave Cavity, Penetration depth, Dielectric mixture concentration and temperature dependencies, Dynamic impedance matching controller, Geometry dynamics emulation in an EM simulator, Dielectric modelling in temperature and miscibility



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Introduction

Nowadays, polyethylene terephthalate (PET)-based waste streams are mainly treated by means of mechanical processes. Nevertheless, only single-polymer plastic solid waste (PSW) can be properly recycled and these processes result in their progressive degradation, while the unrecyclable polymers are burnt or disposed of in landfills. However, the life cycle of PSW finishes when, after excessive degradation and contamination, wastes are not recyclable anymore and they can just be burned or disposed of with the other plastics in landfills. This disposal process doesn't allow the base material that has been used to produce PET-base plastics, to be recovered. Therefore, recovery of these parent materials is at this moment not possible due to time, cost and energy efficiency problems. Chemical processing could be considered for complete recovery of the molecules constituting the polymer, which would then be ready to be used to produce virgin PET or other material topologies based on previous molecules.

In the context of the European Union's DEM3TO project, an innovative technology is proposed to chemically process the PET. In a specific reactor, microwave radiation is used with a temperature controller to quickly depolymerise the initial polymer (PET) into its composing elements Ethylene Glycol [EG] and terephthalic acid [TPA]) without burning it[1].

In order to produce the desired molecules, once the depolymerisation has been terminated, a filtration and drying system must be adopted. Filtration and drying processes are critical operations in a variety of industrial processes such as DEM3TO that require the separation of solid matter from liquid. Due to high temperatures and use of dangerous substances, isolation, reduced product handling and environmental protection, agitated Nutsche filter (ANF) filtration and drying techniques are employed (Figure 1).

ANF allows a very high drying ratio (~1% of moisture), but the entire process is time-consuming. Additionally, ANF systems aren't able to homogeneously and quickly dry the mixture, because the heating power is performed by the vessel walls or in some cases from the agitator, but this still doesn't allow for an excellent homogeneity of humidity. Therefore, it is necessary to agitate the mixture many times to homogenise and evacuate the vapours, especially when the re-slurry process is needed, because wash quality requirements are not sufficient or long contact time is needed[2]. Therefore, standard ANF procedure is slow[3]. It can take hours to finish the drying process, but with the use of microwaves it is possible to accelerate it. This is an additional vantage of the using of electromagnetic waves, but the main objective is to heat the whole substances homogeneously thanks to the microwaves that spread out into all the mixture and not only in perimetry like electric heaters inside vessel/blades walls. For these reasons a novel cavity microwave dryer component has also been developed to address above problems and accelerate the drying process.

The purpose of the research was:

- to speed up the drying process through microwaves and increase the homogeneity of heat distribution
- to analyse the trend of the S parameters (this parameter allows to calculate the efficiency of the HF system)[4], to evaluate if a dynamic controlling of the microwave impedance is needed
- to study how the power efficiency and the distribution of the humidity inside the mixture is influenced by the heating/evaporation of the liquid as a function of the concentration of the mixture and the presence of the mixer blades

The research can be summarized in:

- study the behaviour of a microwave cavity inside a ANF during the preheating phase and the drying phase (water evaporation)

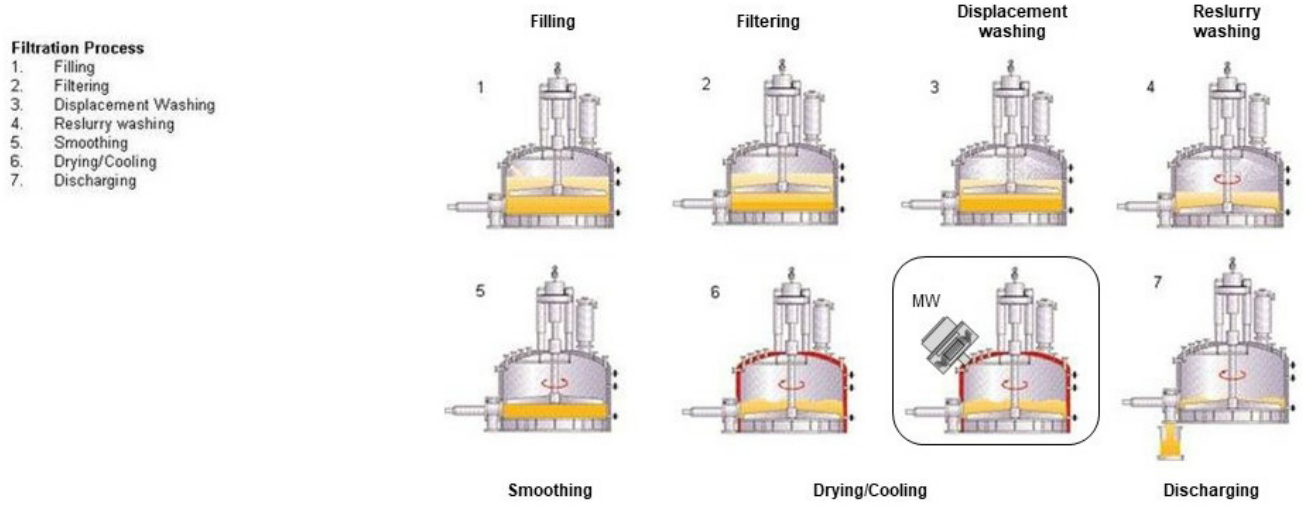

Figure 1. The traditional Agitated Nutsche Filter (ANF) phases (7) with the additional high frequency (HF) component. Copyright permissions granted. © De Dietrich Process Systems, Inc[5].

- laboratory characterisation of the dielectric behaviour of the chemical substances (TPA, EG) dissolved in water in function of temperature, water concentration and microwave (MW) frequency of the HF source (magnetron)[6]
- electromagnetic simulation of the pre-heating of the chemical substances and water up to the boiling temperature and analysis of the power efficiency of the HF source,
- electromagnetics simulation of the water evaporation (drying phase) (TPA/EG drying) and analysis of the power efficiency of the HF source and the distribution of the humidity into the mixture

Microwave dryer cavity analysis

To speed up the drying/evaporation process of the substance inside the ANF, it is necessary to create an MW cavity that allows microwaves to penetrate homogeneously and heat the mixture. Before we start discussing the use of cavities it is necessary to understand some fundamental principles and models that govern their behaviour[7]. Cavities usually work in resonant modes, however in the present case, due to the continuous variations in volume, the evaporation effect and temperature changes, it is not possible to keep the cavity in permanent resonance condition.

The first simulations (Figure 2) that have been performed in our study shows that working in resonance mode for this specific application is impractical, because of the resonance frequencies variations due to the resonator (ANF geometry) behaviours changes. In fact, as can be seen from the simulation, the resonant frequency is strongly influenced not only by the size of the resonant cavity but also by its characteristics such as for example, in this specific case, the amount of material presents as well as its composition (dielectric proprieties).

When the water into the cavity changes its concentration, the equivalent permittivity constant decreases the quality factor that is related to the heating efficiency of the system. Therefore, to maintain an acceptable efficiency, it is necessary to adapt the excitation frequency to the new resonant frequency of the cavity. Generally, resonant mode is used to measure permittivity constant of material and not for this kind of application[8].

In conclusion, the cavity will be used to allow microwave penetration inside the medium.

In general, when a microwave penetrates a material, its propagation speed changes in function of the material's dielectric proprieties. The following formula describes this speed reduction[9]:

$$\lambda_{diel} = \lambda_0 \cdot \frac{1}{\sqrt{\varepsilon_r}} = \frac{C}{f_0} \cdot \frac{1}{\sqrt{\varepsilon_r}} \qquad \text{(Eq 1)}$$

Where:

- C = *Speed of the light* = ~300'000 $\left[\frac{km}{s}\right]$
- ε_r = *Relative permettivity of the material* [–]
- f_0 = *Frequency of the wave into the vacuum* [Hz]
- λ_0 = *Wave-lenght of the wave into the vacuum* [m]
- λ_{diel} = *Wave-lenght of the wave into the medium* [m]

Another important parameter that must be taken into account during the development of the dryer is the penetration depth[10]. This parameter determines the attenuation of an electromagnetic (EM) wave within a given dielectric substance. The penetration depth is defined as the length with a signal attenuation of *1/e* (37%) (Eq. 2)[11]:

$$D_p @ \frac{1}{e} \cong \frac{C_0}{4\pi f_{diel}} \cdot \sqrt[2]{\frac{2}{\varepsilon'_r}} \cdot \left[\sqrt[2]{1+\tan(\delta)^2} - 1\right]^{-1/2} \qquad \text{(Eq 2)}$$

Where:

- C_0 = *Speed of the light*
- ε'_r = *Real component of the relative permettivity of the material* [–]
- f_{diel} = *Frequency of the wave into the medium* [Hz]
- $D_{p@\frac{1}{e}}$ = *Penetration depth for a signal attenuation of* 37% [m]

In some case it is also possible to use the penetration depth for an attenuation of the 50% (Eq. 3)[12]:

$$\boldsymbol{D_{p@0.5} \cong \frac{3.31 \cdot 10^7}{f_{diel} \cdot \sqrt[2]{\varepsilon'_r} \cdot \tan(\delta)}} \qquad \text{(Eq 3)}$$

Where:

- ε'_r = *Real component of the relative permettivity of the material* [–]
- f_{diel} = *Frequency of the wave into the medium* [Hz]
- $D_{p\ @\ 0.5}$ = *Penetration depth for a signal attenuation of* 50% [m]

Theoretically, the dielectric height must be infinite to absorb all the microwave signals; however, an absorption equal to 99% is sufficient to estimate the theoretical height. Through some rearrangements it is possible to evaluate minimum material depth in order to quasi-absorb (99%) the microwave signal (*Eq* 4–*Eq* 5):

$$\boldsymbol{D_p(\mu) = D_{p@0.5} \cdot \log_2\left(\frac{1}{1-\mu}\right)}$$
$$\mu = \frac{P_{abs}}{P_{in}};\ \mu = 1 - \frac{P_{out}}{P_{in}} \qquad \text{(Eq 4)}$$

Where:

- P_{abs} = *Absorbed power into the medium* [W]
- P_{in} = *Input power* [W]
- P_{out} = *Output power* [W]

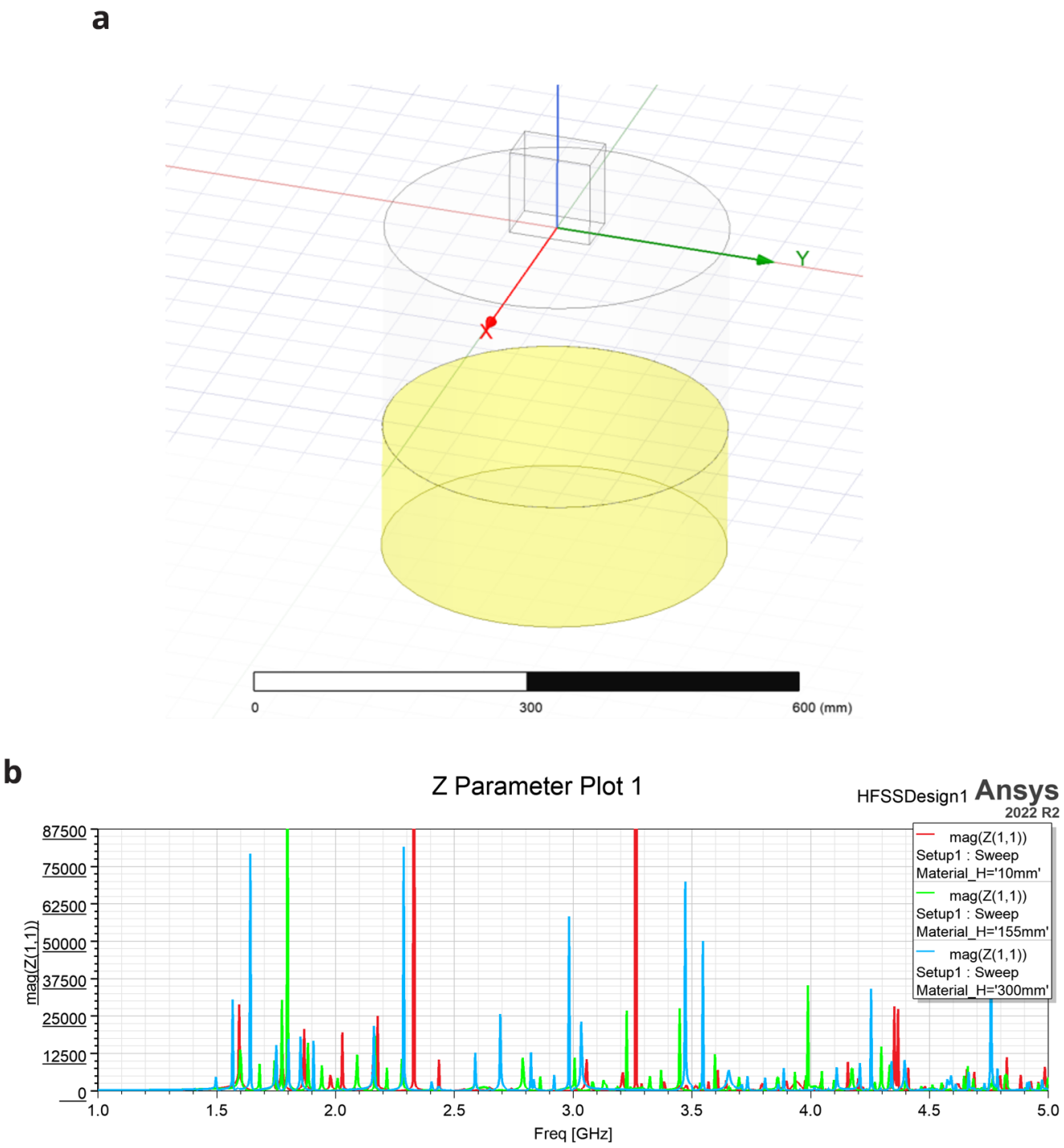

Figure 2. Ansys - 3D High Frequency Electromagnetic Simulation Software (HFSS). (**a**) Cylindrical cavity model (resonator) with variable mixture volume (yellow) from 10mm to 300mm (red, green and blue plots), cavity height of 400 mm, cavity diameter of 385 mm, mixture dielectric constant (Ɛr) = 4. (**b**) Resonant mode – resonant frequencies (impedance change) vs mixture content (cavity height, material_H variable). All permissions granted, author's own figure.

Therefore, assuming a total absorbed power of 99%:

$$D_{p@0.99} = D_{p@0.5} \cdot \log_2\left(\frac{1}{1-0.99}\right) \cong \frac{2.2 \cdot 10^8}{f \cdot \sqrt[2]{\varepsilon_r'} \cdot \tan(\delta)} \quad \text{(Eq 5)}$$

According to this value it still possible to choose the correct cavity diameter for the model.

Once the size of the reactor has been determined, it is possible to calculate the total power absorbed in the dielectric material (V_{loss}) by integrating the Volume Loss Density ($V_{loss\ density}$) with the mixture volume using the Electromagnetic simulator Ansys™ HFSS™ (Ansys Electromagnetics version R2020 – R2) . An alternative freely available Finite Element Method (FEM) electromagnetic simulator is Elmer FEM. The simulators allow users to compute the surface loss density (W/m^2) (Eq. 6) which comes from metallic losses, and the volume loss density (W/m^3) which comes from dielectric losses. This simulation results can be used to simulate the total absorbed power on metals and dielectrics[13].

$$V_{loss} = \int_0^V V_{loss\,density} \cdot d_V \quad \text{(Eq 6)}$$

Where:

- V_{loss} = *Absorbed power into the material* $[W]$
- $V_{loss\ density}$ = *Absorbed power into the material per unit volume* $[W/m^3]$

TPA/H_2O mixture dielectric proprieties

The dryer simulations and analysis were carried out with water and TPA (terephtalic acid) that emulate the industrial mixture that needs to be dried in the industrial process. Table 1 shows the initial concentrations and characteristics of the mixture at 30°C according to the specifications provided by the partners of the DEMETO project[14].

In order to simulate the heating and evaporation effect with MW (Microwave) energy fed into the dryer, the dielectric constant and the loss tangent factor of the mixture must be estimated. Unfortunately, this constant estimation depends on many factors[15], such as:

- Concentration (percentage between water and TPA acid)
- Physical state (liquid, solids, vapours)
- Miscibility or stratification
- Temperature
- Microwave frequency

Table 1. Mixture characteristics. TPA, terephtalic acid.

Parameter	Water	TPA
Mixing concentration	80%	20%
Mass density [kg/m3]	997.00	1520.00
Dielectric constant	~75	~1.5
Tangent loss factor	~0.13	~0.07

For these reasons, it was necessary to carry out a characterization of the substance, prior to running process simulations[16]. More specifically, in the intended application, the reactor in the drying phase will:

- heat the mixture up to the boiling temperature of the water (temperature variation - preheating phase),
- evaporate the mixture based on the mass of water (variation of the volumetric concentration of the mixture - evaporation phase).

Therefore, for these phases it will be necessary to know the dielectric properties as a function of temperature and volume (concentration of water in the mixture). For this research project it was decided to use a microwave frequency of 2.45GHz, because it is a frequency allowed for radio-frequency process heating that is included on ISM radio bands[17].

Mathematical model design

Using the following formulas, the relative theoretical dielectric constant and loss factor can be calculated[18]:

$$\varepsilon_r = \sqrt[2]{(\varepsilon_r')^2 + (\varepsilon_r'')^2} \quad \text{(Eq 7)}$$

$$\tan(\delta) = \frac{\varepsilon_r''}{\varepsilon_r'} \quad \text{(Eq 8)}$$

Where:

- ε_r' = *Real component of the relative permettivity* [–]
- ε_r'' = *Immaginary component of the relative permettivity of the material* [–]

The resulting parameters (ε_{mix}', ε_{mix}'') of the material "mix" can be obtained by using a weighted mean of the complex representation of dielectric permittivity of the two substances that compose the mixture:

$$\varepsilon_{mix}' = \varepsilon_{TPA}' \cdot \%_{TPA} + \varepsilon_{H2O}' \cdot \%_{H2O} \quad \text{(Eq 9)}$$

$$\varepsilon_{mix}'' = \varepsilon_{TPA}'' \cdot \%_{TPA} + \varepsilon_{H2O}'' \cdot \%_{H2O} \quad \text{(Eq 10)}$$

Where:

- $\%_{TPA}$ = *Percentage of TPA* [–]
- $\%_{H2O}$ = *Percentage of* H_2O [–]

Finally, the theoretical polar representation (magnitude, angle) of the mixture can be expressed as:

$$|\varepsilon_{r\,mix}| = |\varepsilon_{mix}' + \varepsilon_{mix}'| \quad \text{(Eq 11)}$$

$$\arg(\varepsilon_{r\,mix}) = \delta_{mix} = arctan\left(\frac{\varepsilon_{mix}''}{\varepsilon_{mix}'}\right) \quad \text{(Eq 12)}$$

The behaviour of the dielectric proprieties of the mixture as a function of the water content is represented in Figure 3.

Once the mathematical model of the mixture has been obtained, through a linear regression for ε_r and a polynomial regression of the third order for tan(δ), it is possible to define how the dielectric parameters of the mixture will vary by knowing only the characteristics of the substances of which it is composed (Eq 14 – Eq 15).

$$\tan(\delta)_{mix} = -2\cdot10^{-7}\cdot R^3 + 2\cdot10^{-5}\cdot R^2 - 6\cdot10^{-4}\cdot R + 0.1351 \quad \text{(Eq 14)}$$
$$\rightarrow Acc^2 = 0.9902$$

$$\varepsilon_{r\,mix}(R) = -0.7407\cdot R + 75.797$$
$$\rightarrow Acc^2 = 1 \quad \text{(Eq 15)}$$
$$R = \frac{Vol_{TPA}}{Vol_{H2O}}[\%]$$

Where:

- $\tan(\delta)_{mix}$ = *Dielectric loss factor of the comosed mixture* [–]
- Acc^2 = *Accuracy of the mathematical regression* [–]
- R = *Volumetric concentration of TPA in* H_2O [%]
- Vol_{TPA} = *Volume of TPA* [L]
- Vol_{H2O} = *Volume of* H_2O [L]

Mathematical model validation at different concentrations

The dielectric characterization was performed firstly by preparing some samples of tap water and TPA (Sigma Aldrich - TPA 185361-500G – 98%) at different concentrations starting from 0% to 100% (different concentrations starting form 0% and working up in increments of 10% until reaching 100% TPA in the water) of TPA into water and secondly by measuring

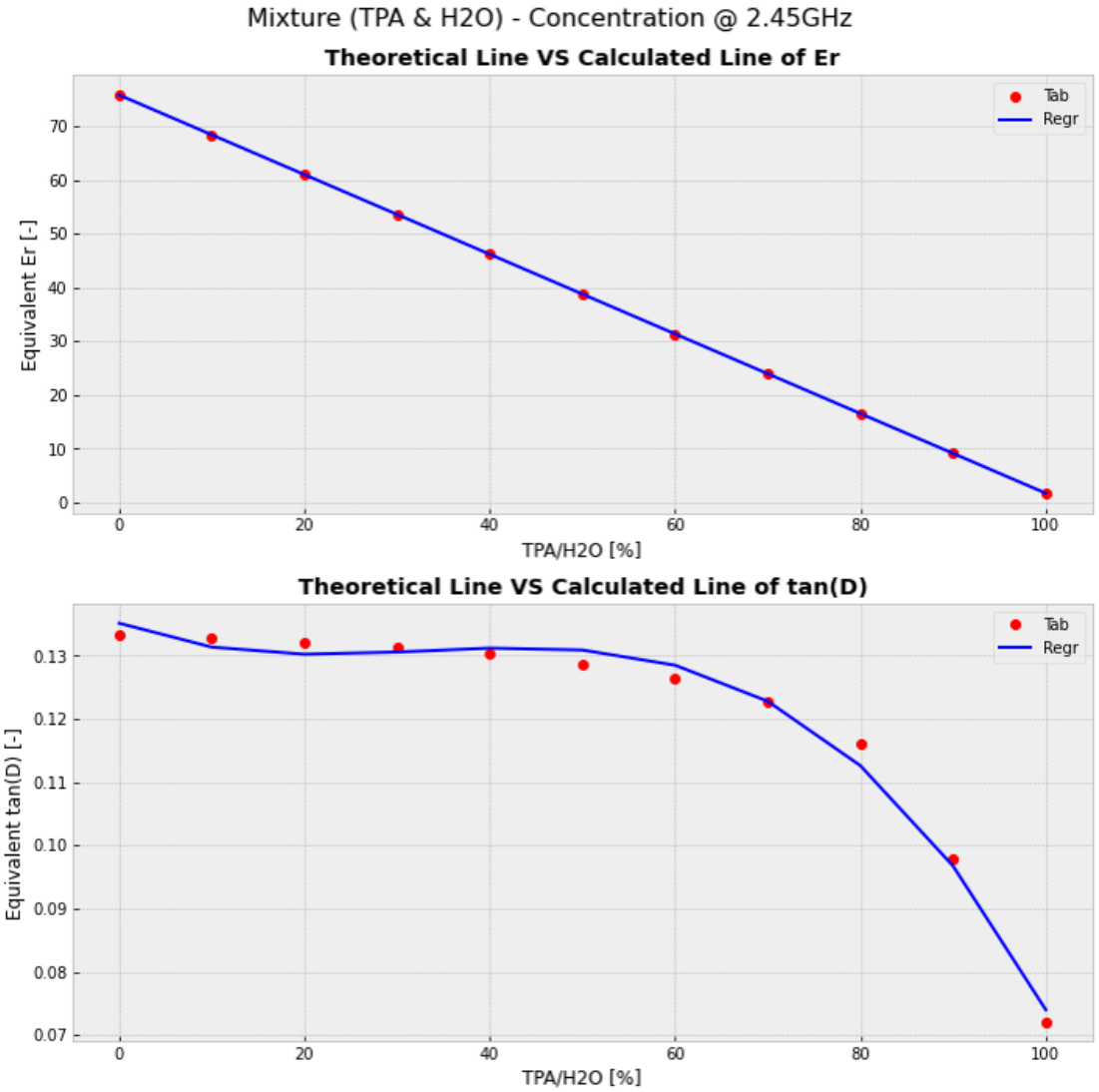

Figure 3. Theoretical permittivity curve of the mixture. Upper: Dielectric behaviour in function of terephtalic acid (TPA) concentration. Lower: Loss tangent behaviour in in function of TPA concentration.

its dielectric properties with the Agilent's 85070E Dielectric Probe Kit and the N5230A vector analyser (Figure 4).

The TPA is a powdered substance that is not soluble in water, therefore it tends to drop and sediment on the bottom side of the test tube. Given this phenomenon and since the dryer will continuously mix the chemical substance during the drying process, the mixtures have been measured after stirring them with a vortex machine (Fisherbrand – F202A0176FI). This measurement process should guarantee a better material homogeneity during the tests with the described setup afore.

Comparing the data measured with the mathematical model (Figure 5) it is possible to note a good correspondence. The mathematical model is therefore able to approximate the dielectric characteristics of the mixture at various concentrations of H_2O and TPA.

Mathematical model validation at different temperatures

By further characterizing the two substances composing the mixture at various temperatures to which the reactor will be subjected, it is possible to model their properties as a function of concentration and temperature. Therefore, previous procedure was repeated throughout the temperature range between 30 ° C and 100 ° C, in increments of 20 ° C (Figure 6). The previous samples were preheated and maintained at the desired temperature (30°C, 50°C, 70°C, 90°C) through a water bath with controlled temperature. The hypothesized model can then be introduced in the EM simulation model (Ansys Electromagnetics version R2020 – R2) to model the final reactor. As previously stated, an alternative freely available Finite Element Method electromagnetic simulator is Elmer FEM.

By knowing the variation in dielectric properties of the mixture as a function of temperature of the two main constituent substances, it was possible to model the mixture's behaviour so that it can be used in the electromagnetic simulator (in our case the study of the preheating process only contemplated a simulation at 4 different temperatures, therefore a precise regression curve was not necessary). Obviously, for simulations with many intermediate temperatures it would be possible to repeat a linear regression for the loss factor and a third order polynomial regression for the dielectric constant (Figure 7).

The graph in Figure 6 was obtained through polynomial regression of the measured data. Due to the miscibility and the potential for error in the data, a compensation was applied to eliminate measurements affected by an error greater than 10%. This correction was necessary because limited data were available and therefore, they could not be discarded. When the percentage of water in the mixture is dominant, the curve behaves as the water (mix 0%), as the percentage of TPA increases, the mixture tends to follow the temperature behaviour of the acid alone (mix 100%).

Comparison

The characterization of the substances that compose the mixture through these mathematical models allowed to obtain an excellent approximation of the dielectric constants without the need of a complete characterization for each concentration, therefore avoiding time-consuming problems and inaccuracies due measurement or handling errors. The same model could also be used for the approximation of the dielectric characteristics of the mixture at any temperature by knowing only the dielectric parameters of the substances at some specific temperatures. With the regression formulas it is possible to

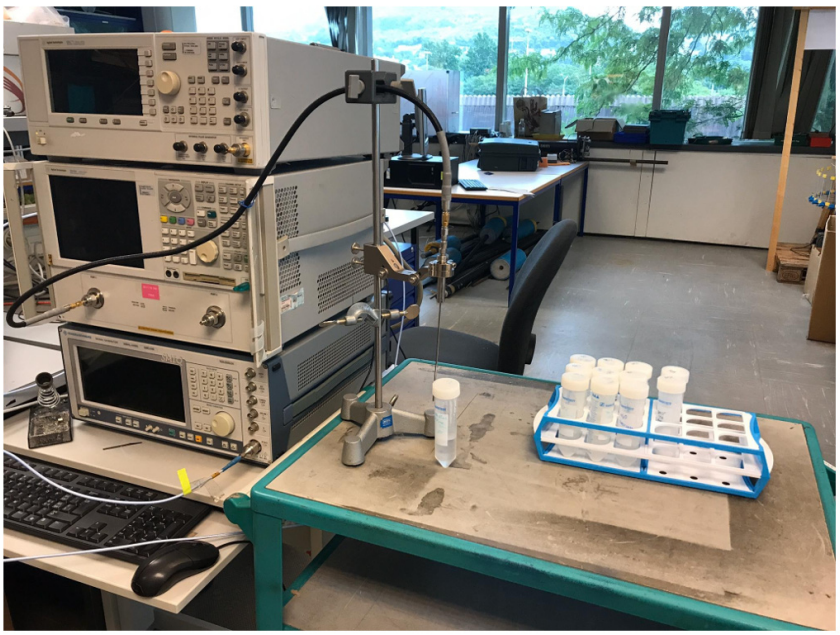

Figure 4. Dielectric proprieties - measurement setup.

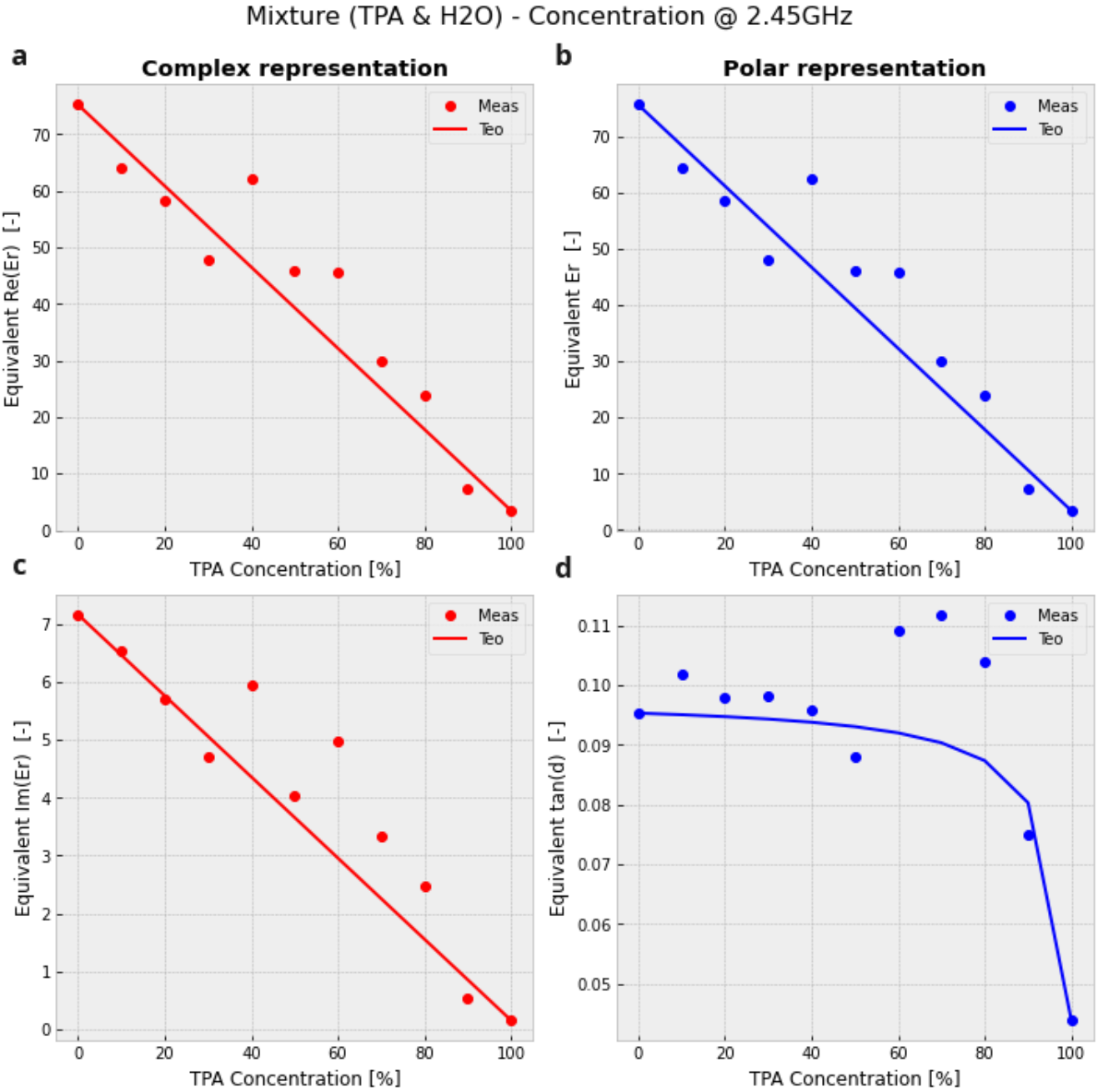

Figure 5. Mixture behaviour @30°C and 2.45 GHz. Figure 5**a** (top left): Real part of the equivalent dielectric proprieties of the mixture in function of TPA concentration. Figure 5**b** (top right): Imaginary part of the equivalent dielectric proprieties of the mixture in function of terephtalic acid (TPA) concentration. Figure 5**c** (bottom left): Equivalent dielectric proprieties of the mixture in function of TPA concentration. Figure 5**d** (bottom right): Loss tangent of the equivalent dielectric proprieties of the mixture in function of TPA concentration.

calculate the variation of dielectric properties in function of the temperature and TPA concentration and finally obtain the dielectric constants at a given temperature and concentration.

This modelling approach speeds up the characterization of a mixture, but primarily it permitted the implementation of a fully parametrizable EM model for the simulator which in

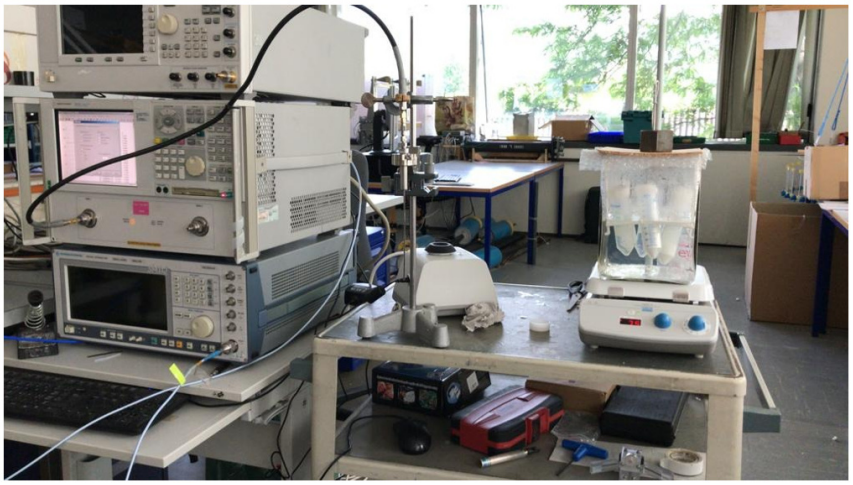

Figure 6. Measurement setup at different temperatures.

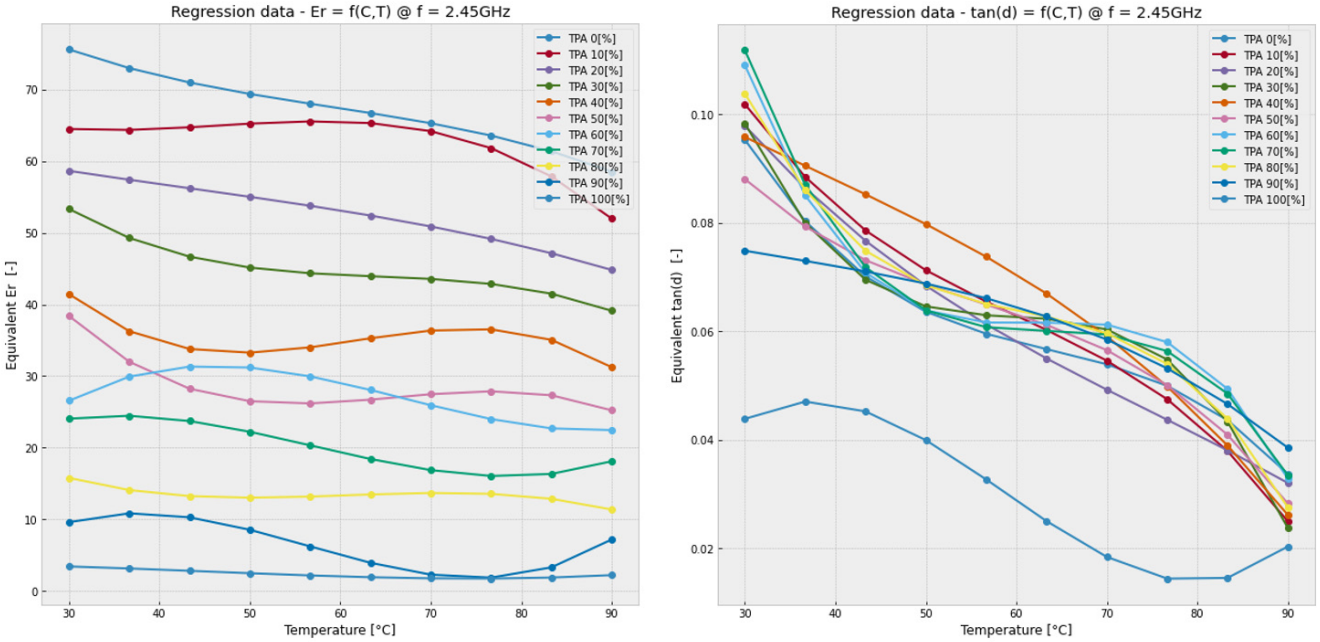

Figure 7. Mixture behaviour at different temperatures. Left: Equivalent dielectric constant in function of temperature and terephtalic acid (TPA) concentration; right: Equivalent loss tangent constant in function of temperature and TPA concentration.

turn was of great support for the study of the substance under the effect of microwaves and to simulate phenomena such as evaporation and heating.

EM simulation models

The EM simulations were performed to study the impact of the MW during the preheating and evaporation phase of the substance and to assess the need of a "dynamical matching adaptation" of the magnetron impedance to optimize the efficiency of the reactor. In addition, a study on the effect that the mechanical mixing process has on the absorption of MW in the mixture was conducted.

Pre-heating and evaporation model

For the "thermal" study, two models were created to study the efficiency of the reactor during:

- heating of the mixture at constant volume, until it reaches the water boiling temperature,
- evaporation of the water and the consequent decrease of the mixture's volume in the cavity.

To simulate the change in volume due to the evaporation of the water component in the mixture, the following mathematical model was elaborated (Figure 8).

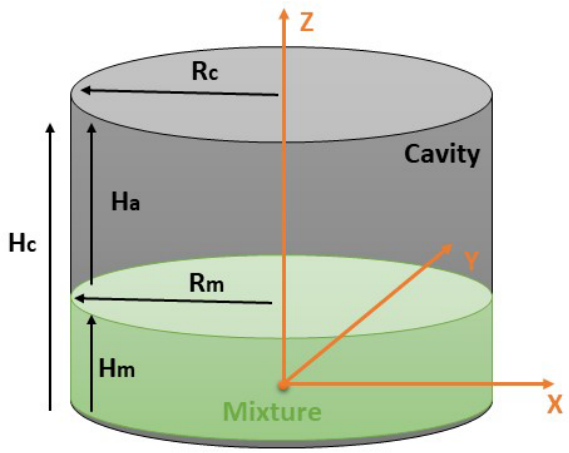

Figure 8. Thermal model. Height of the mixture (H_m), Height of the cavity (H_c), Height of the air (H_a), Radius of the mixture (R_m), Radius of the cavity/mixture (R_m).

The volume of TPA and water can be expressed as a percentage of the mix volume:

$$V_m = V_{TPA} + V_{H2O} = V_m \cdot \alpha_{TPA} + V_m \cdot \alpha_{H2O}$$

$$\alpha_{TPA} = \frac{V_{TPA}}{V_m} \qquad \text{(Eq 15)}$$

$$\alpha_{H2O} = \frac{V_{H2O}}{V_m}$$

$$V_m = A_m \cdot H_m$$

$$\rightarrow H_m = \frac{V_m}{R_m^2 \cdot \pi} \qquad \text{(Eq 16)}$$

Where:

- V_m = *Volume of the mixture inside the reactor* [L]
- V_{TPA} = *Volume of the TPA inside the reactor* [L]
- V_{H2O} = *Volume of the water inside the reactor* [L]
- α_{TPA} = *Percentage of TPA in* V_m [–]
- α_{H2O} = *Percentage of* H_2O V_m [–]
- A_m = *Reactor section* [m^2]
- H_m = *Mixture height* [m]
- R_m = *Mixture radius*

The cavity diameter will be chosen according to the maximum penetration depth according to the formulas of the previous section (Eq. 4–Eq. 5) "Microwave dryer cavity analysis". In order to relate the height of the cavity to the height of the mixture, a volumetric ratio between the mixture and the initial cavity height has been defined (the cavity is filled up with ~30% of mixture). During the pre-heating analysis, the volume of the mixture is maintained constant because the evaporation is neglectable therefore also the volume of air won't change during the process. So, the cavity height can be expressed as:

$$H_c = H_m \cdot \frac{1}{1-\alpha_{FILL}} \qquad \text{(Eq 18)}$$

$$\alpha_{FILL} = 0.3 \rightarrow H_c = H_m \cdot \sim 1.5$$

Where:

- α_{FILL} = *Percentage of the cavity filling*[–]

For the evaporation analysis the behaviour is different, the height of the mixture at the initial state (t = 0) will begin to decrease due to evaporation according to the following formula:

$$H_m(t+1) = H_m(0) - H_{H2O}(t+1) \qquad \text{(Eq 17)}$$

Where:

- $H_m(t+1)$ = *Next height of the mixture due to the water evaporation*
- $H_m(0)$ = *Initial height of the mixture*
- $H_{H2O}(t+1)$ = *Height loss due to water evaporation*

Through this parameterization it is possible to adapt the residual volume based on the presence of water in the mixture.

Geometry dimensioning: According to the manufacturing specifications provided by DEMETO partners[14], the reactor had to be as symmetrical as possible (D / H ≈ 1) and accommodate approximately 15kg of mixture. According to the theoretical calculation of the maximum penetration, the reactor had to have a height close to the maximum penetration of the MW to favour the field homogeneity and the total power absorption. Based on these criteria, initial dimensions were estimated and then refined via parametric analysis with the simulator by changing the geometrical parameters in order to reach the best power performance and a best homogeneous E-field distribution into the mixture. Table 2 compares the theoretical calculations and the simulations of the cavity size under consideration of the penetration of the MW.

Figure 9 shows the geometry used during the simulations for the optimization of the pre-heating and evaporation and

Table 2. Cavity dimensions comparison with 80% of H2O.
Manufacturing constraints provided by DEMETO partners[14].

Parameter	Manufacturing Constraint	Theoretical calculation results (99% absorption)	Simulator results
Cavity radius	~357mm	~472mm	~500mm
Cavity height	~350mm	~200mm	~178mm
Symmetry ratio	~1.02	~2.36	~2.81
Working frequency	2.45GHz	2.45GHz	2.45GHz

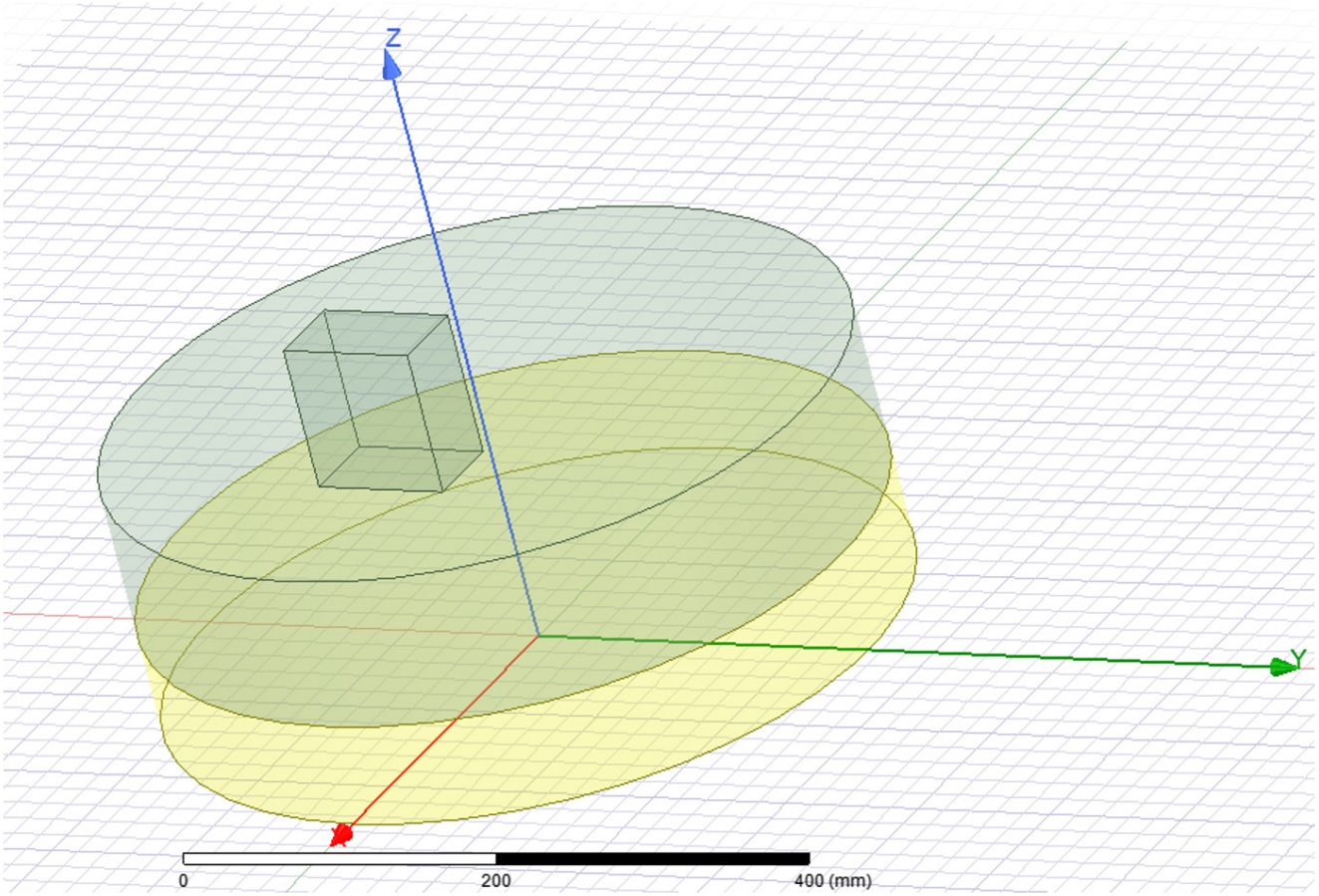

Figure 9. Ansys High Frequency Simulation Software (HFSS) – model used to optimize the dimension of the cavity according to the previous defined criteria (yellow – mixture; green – cavity air volume, green rectangle – microwave source port). All permissions granted, author's own figure.

process. Initially, the theoretical dimensions taken from Table 2 were transferred to the following model (Figure 9) and after the simulation the dimensions were adapted to optimize the pre-heating and evaporation.

Mechanical blender model

The mechanical effect of mixing (agitator effect) was simulated by creating a model that is able to vary the surface[19] (based on a specific shape of the blade and its speed) of the mixture to study its impact on the power efficiency and humidity distribution. To simulate the change in surface due to the blades' shape and velocity, the following mathematical model was created (Figure 10).

In particular, due to the motion of the mixer blades the mixture tends to form waves which tends to increase the total surface to be dried while always maintaining a constant volume.

To model the waves, three concentric toroidal geometries were used:

- Two toroids extending into the positive direction of the z-axis ("up"), to represent the wave peaks
- One toroid extending into the negative direction of the z-axis ("down"), to represent the wave trough

If the speed of the blades or its width is larger, the mixture tends to squeeze on the edges of the cavity.

This change in position of the mixture (squeezing on walls and generation of waves on surface) probably gets worse the power efficiency and the humidity distribution, because the distribution of the mixture along the circumference will change the eletric-field (E-field) distribution (the position of maximums and minimums of the E-field will change). Since the E-field variation is related to the power absorbed into the dielectric, this consequently reduces the power efficiency of the microwave source. However, only an EM simulation can confirm this assumption.

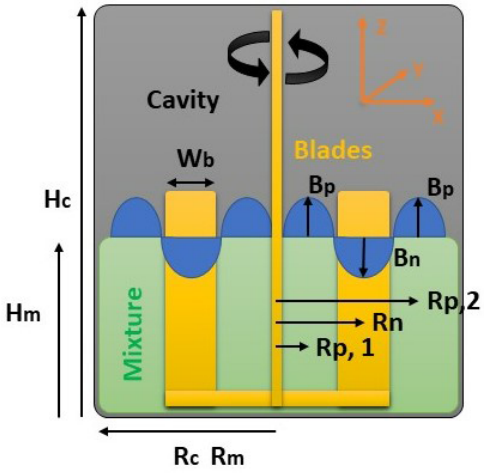

Figure 10. Blender model – Yellow cross section of the blades – Blue are the cross section of the two toroid generated by the displacement of blades. The symbols on Figure 10 are defined as: H_c = Cavity height, H_m = Mixture height, R_c = R_m = Cavity and Mixture radius, W_b = Blades width, $R_{p,1}$ = Internal pile radius, $R_{p,2}$ = External pile radius, R_n = Blades radius, $B_{p,1}$ = Internal pile height, $B_{p,2}$ = External pile height, B_n = Dig height.

The volumes of the toroid are:

$$V_{up} = V_{up,1} + V_{up,2} = 2\pi^2 \cdot B_{p,1}^2 \cdot R_i + 2\pi^2 \cdot B_{p,2}^2 \cdot R_e$$
$$B_{p,1} = B_{p,2} = B_p \quad \text{(Eq 20)}$$
$$\rightarrow V_{up} = 2\pi^2 \cdot B_p^2 \cdot (R_i + R_e)$$

$$V_{down} = 2\pi^2 \cdot B_n^2 \cdot R_n \quad \text{(Eq 21)}$$

In order to maintain the same volume of the mixture the toroidal geometry must respect the following condition.

$$V_{down} = V_{up} \quad \text{(Eq 22)}$$

Which can be translated into the following relationship between B_n and B_p:

$$2\pi^2 \cdot B_n^2 \cdot R_m = 2\pi^2 \cdot B_p^2 \cdot (R_i + R_e)$$
$$\rightarrow B_n = B_p \cdot \sqrt{\frac{R_i + R_e}{R_m}} \quad \text{(Eq 23)}$$

Results

Reactor efficiency - preheating phase

The model can emulate the effect of the pre-heating of the mixture until the evaporation occurs.

Figure 11 shows the simulation of the power efficiency during the pre-heating phase of the ANF as a function of the mixture dielectric characteristics and temperature change according to the regression curve that has been previously calculated. The relative variation of the equivalent dielectric constant of the mixture is carried out according to the previously explained mathematical model based on laboratory measurements (Figure 11).

Since the initial concentration of water in the mixture can change according to the production parameters and the efficiency of the preceding process, a simulation of the pre-heating of the mixture was designed for each concentration (0% to 100% of the volumetric ratio between the H_2O and the mixture). The obtained simulation results (Figure 12) of the V_{Loss} (Volume loss inside the mixture) were imported into Python (see *Extended data*[20]. Every *Underlying data*[20] are directly elaborated by the dedicated Python code. Python code for data processing was provided. The Python code is present inside the measurement folder together with measurements, "XX_YYYp_mix.prn").

They Python code was used to obtain the variation of the reactor efficiency as a function of the temperature and of the H_2O concentration.

It can be observed that heating with microwave is a very efficient approach, especially when the initial water content is greater than 50%, which is very often the case.

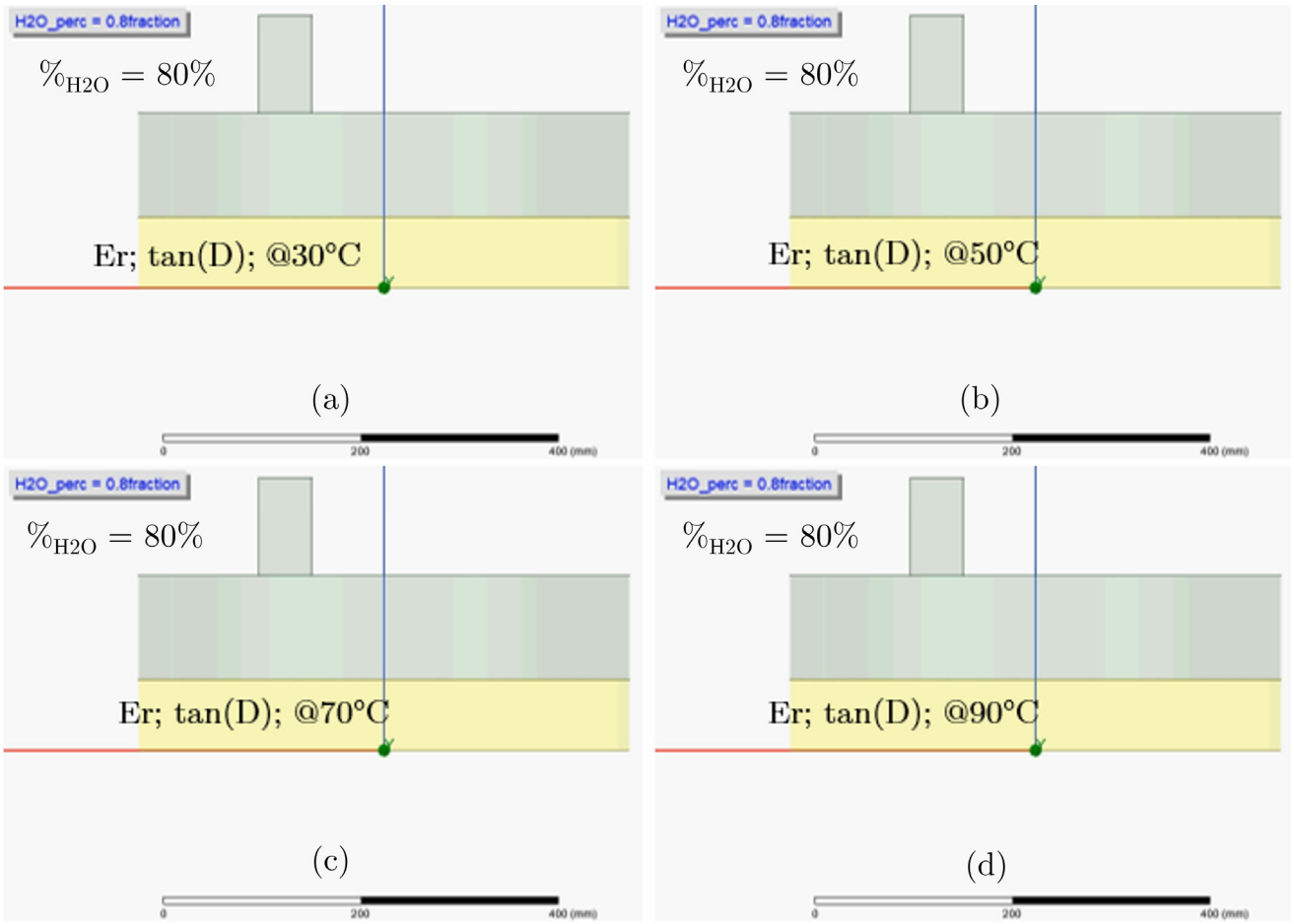

Figure 11. Ansys - 3D High Frequency Electromagnetic Simulation Software (HFSS) – pre-heating effect model from 30°C to 90°C with the mixture composed by 80% of water. Mixture with dielectric constant proprieties calculated at 30°C (**a**), 50°C (**b**), 70°C (**c**), 90°C (**d**). All permissions granted, author's own figure.

Generally, combining the heat generated through MW (see the HF component in Figure 1) with that which is delivered traditionally through thermal conduction from electrical resistors applied to the reactor walls, allows for drastic reduction in the drying time, and more importantly obtains a better heat distribution; this in turn will lead to a better homogeneity of the end product.

Reactor efficiency – evaporation phase

Based on the mathematical EM model described in the previous sections (see the section "Pre-heating and evaporation model"), a simulation for analysis of the microwave energy distribution has been set up in Ansys HFSS (Ansys Electromagnetics version R2020 – R2). An alternative freely available Finite Element Method (FEM) electromagnetic simulator is Elmer FEM. The simulated model is able to demonstrate the effect of evaporation of water once the process has reached its nominal operating temperature (in our simulation we used the 90°C because the dielectric proprieties at 100°C were not available). Figure 13 shows the simulation of the power efficiency and humidity distribution as a function of the mixture's volume change due to the evaporation of the water. In addition to the geometric variation due to the evaporation of water,

the simulation is also able to calculate the relative variation of the equivalent dielectric constant of the mixture by using the mathematical model previously explained.

The simulation result (Figure 14) shows how the absorption of the MW inside the mixture varies in function of the water content. This plot approximates the behaviour of evaporation over time (the time to pass from one concentration to another is unknown but it is not needed for this simulation; see blue line in plot), which in this simulation is discretized with the variation of the height of the mixture as a function of the concentration. The efficiency of the reactor never drops below 80% and averages around 90%; a dynamic matching adaptation of the impedance (between the cavity and the microwave source) is therefore not necessary for this phase of the process.

The variation of the electric field inside the cavity is shown in Figure 15. The field intensity increases with decreasing amounts of water. By decreasing the amount of water, the electric

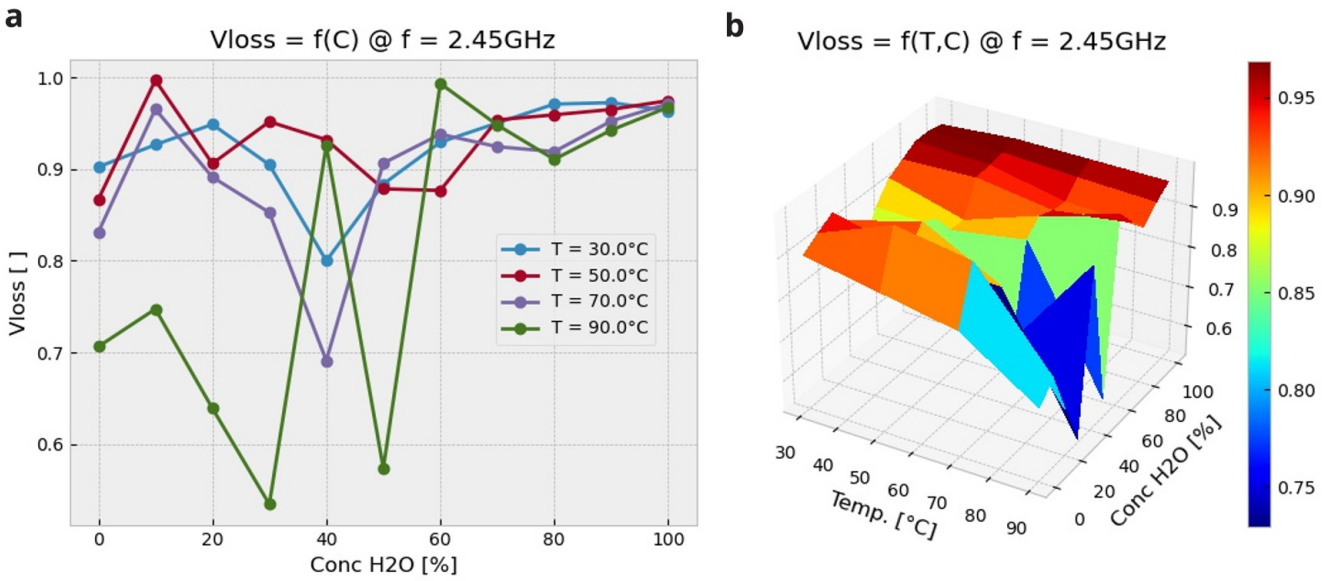

Figure 12. Preheating effect results as a function of Temperature (T) and %H2O. (**a**): V_{loss} versus water volume concentration and temperature (2D representation); (**b**): V_{loss} versus water volume concentration and temperature (3D representation). All permissions granted, author's own figure.

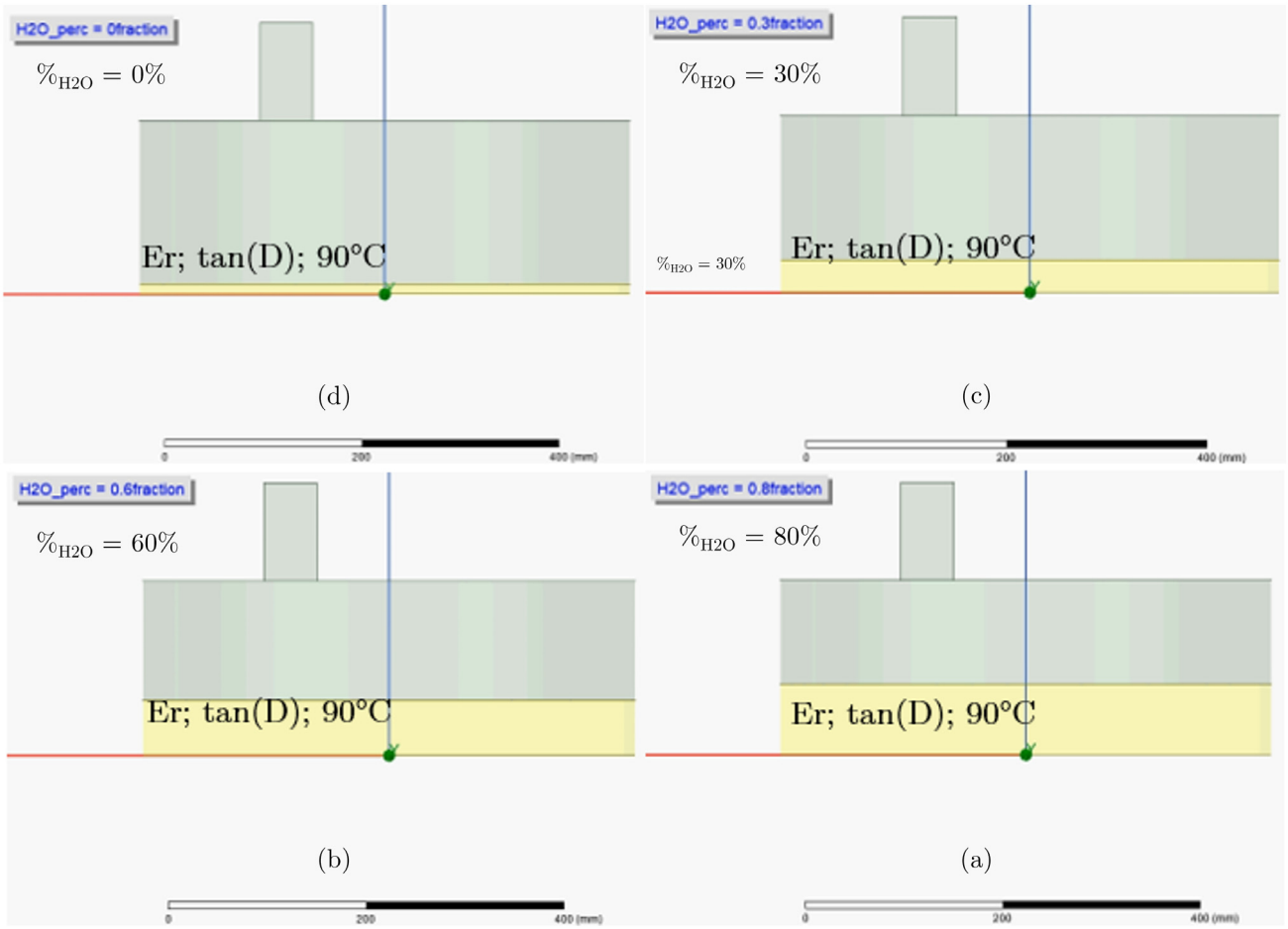

Figure 13. Ansys - 3D High Frequency Electromagnetic Simulation Software HFSS - Evaporation effect (starting from a = "wet" to d = "dry"), model at boiling temperature ~100°C. Mixture volume calculated for 80% of water (**a**), 60% of water (**b**), 30% of water (**c**), 0% of water (**d**). All permissions granted, author's own figure.

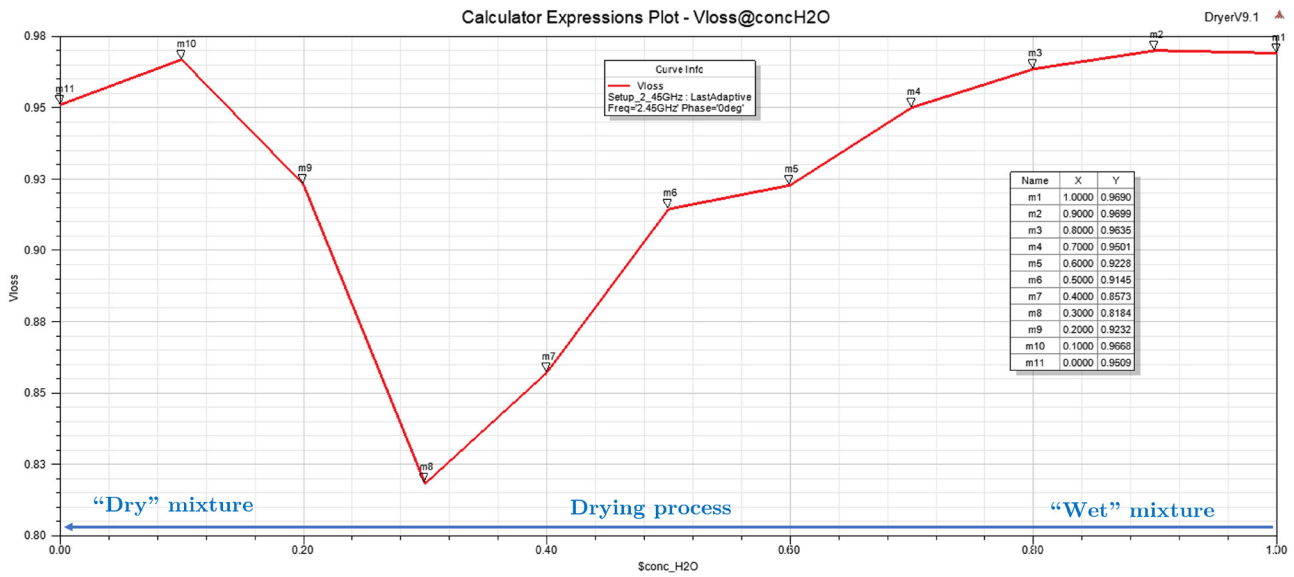

Figure 14. Ansys - 3D High Frequency Electromagnetic Simulation Software HFSS - Total absorption power (volume loss, V_{Loss}) versus the mixture's water content at the boiling temperature (~100°C).

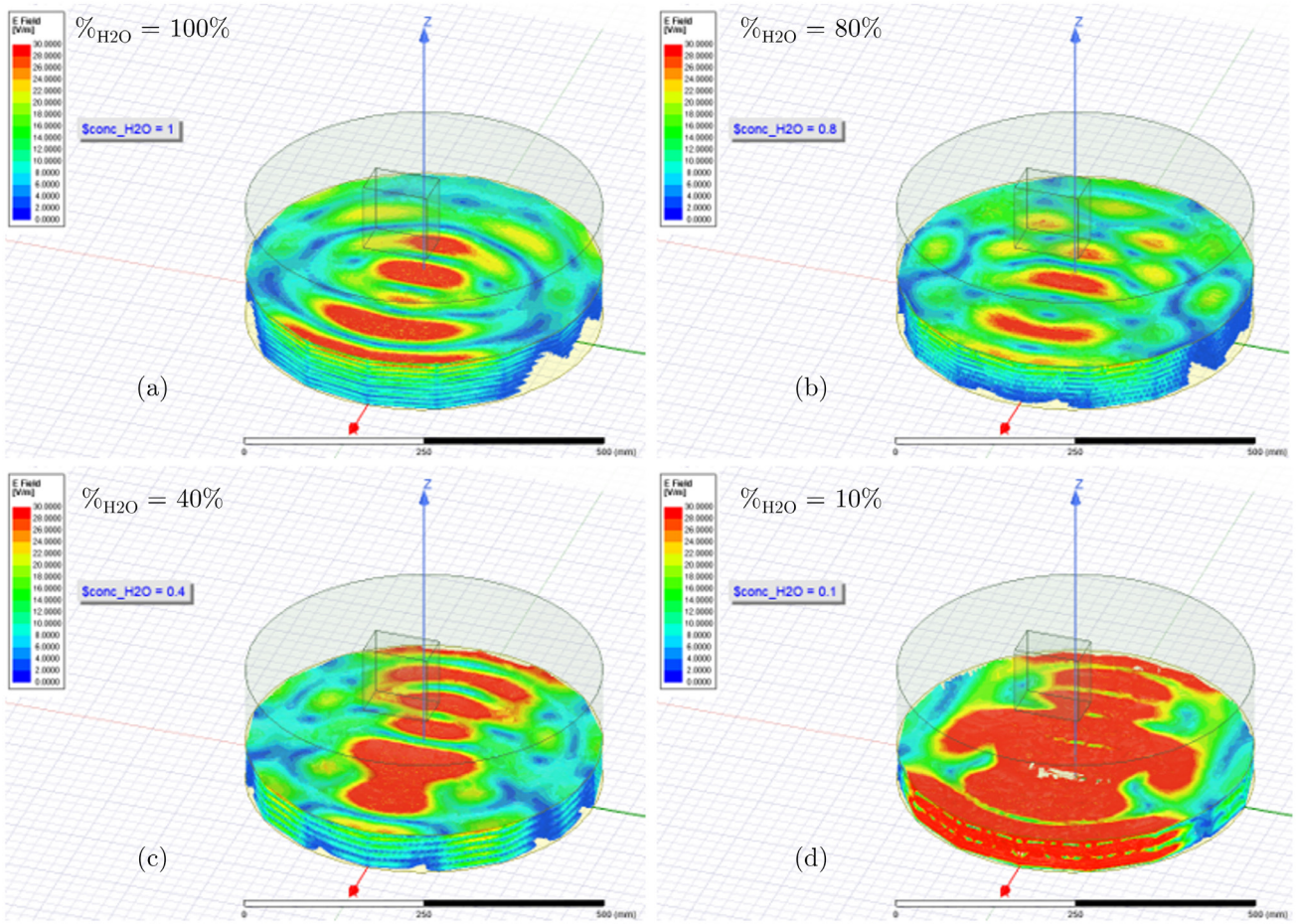

Figure 15. Ansys - 3D High Frequency Electromagnetic Simulation Software HFSS - E-Field intensity for 100% H2O (**a**), 80% H2O (**b**), 40% H2O (**c**) and 10% H2O (**d**). All permissions granted, author's own figure.

field is more and more homogeneous and allows the TPA to dry homogeneously.

Reactor efficiency – mechanical blender

Based on the mathematical EM model (see section "*Mechanical blender model"*) described in the previous sections, a simulation for analysis the power efficiency and the humidity distribution inside the mixture has been set up in Ansys HFSS (Ansys Electromagnetics version R2020 – R2). An alternative freely available Finite Element Method (FEM) electromagnetic simulator is Elmer FEM. The model is able to demonstrate the effect of blades geometry/velocity[1] on the power efficiency and humidity distribution of the mixture (this model will only take into account the displacement of the blades without considering the influence due to the metallic blades). Figure 16 shows the simulation of the blender movement as a function of the blades effect. The three toroids explained in section "Mechanical blender model" allow to model the volume displaced by the blades and consequently the influence on the total absorption in the mixture.

In general, the use of the blades to improve the efficiency of the reactor (in terms of microwave absorption) seems of limited interest, due to the low influence on efficiency (in Figure 17, the Y axis varies from 0.97% to 0.93%). In addition, the size of the blades for this study is too complicated and depends on too many factors that cannot be taken accurately into account in the simulation model. Therefore, in this application, the mixing blades will be used only for thermal homogeneity reasons. And to prevent possible reductions in the efficiency of the reactor that have not been modelled, the blades should mix the substance very gently by minimizing their size and speed.

[1] In this simulation it is assumed that a large blade creates the same displacement as a smaller blade, but which rotates at a higher speed.

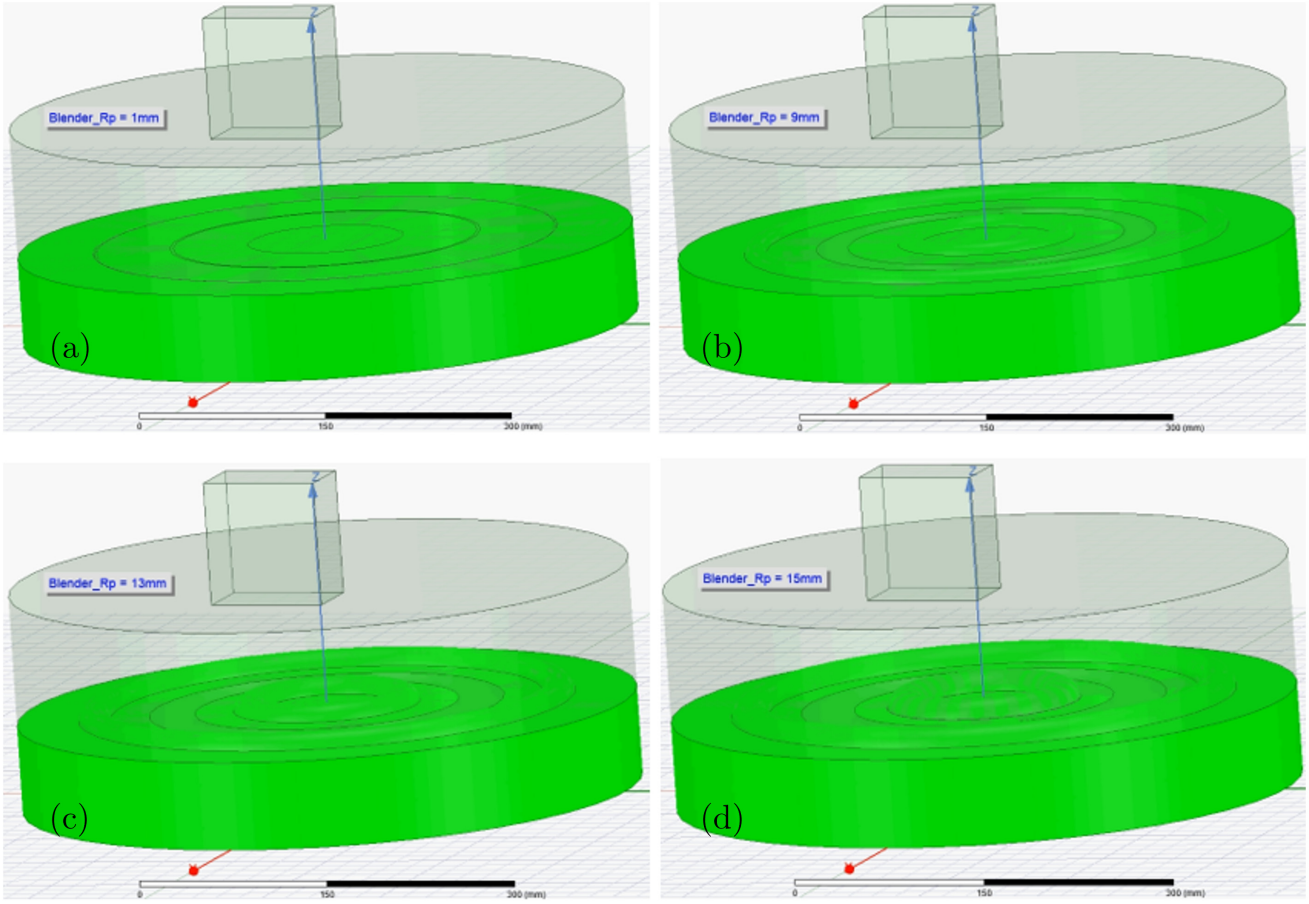

Figure 16. Ansys - 3D High Frequency Electromagnetic Simulation Software HFSS - Blender effect model. Displacement (wave peak and wave trough) generated with different blade width/velocity: (**a**) 1mm, (**b**) 9mm, (**c**) 13mm and (**d**) 15mm. All permissions granted, author's own figure.

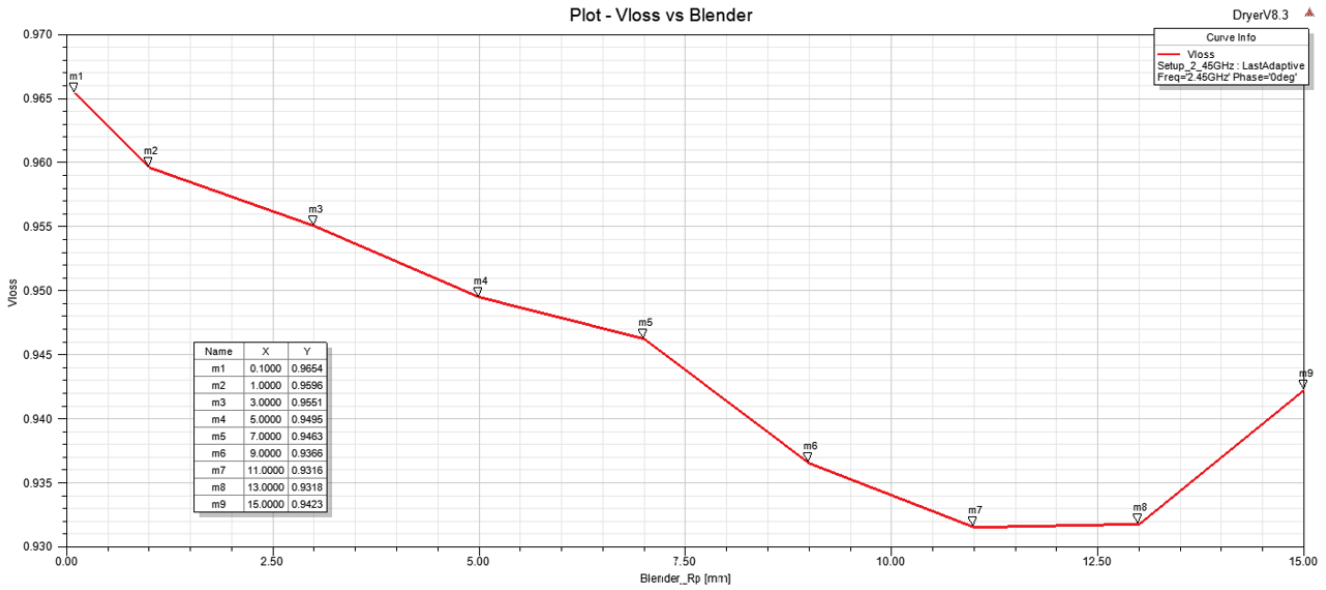

Figure 17. Ansys - 3D High Frequency Electromagnetic Simulation Software HFSS - Total power absorption (volume loss, V_{Loss}) versus blade geometry/velocity. All permissions granted, author's own figure.

Conclusions

The careful modelling of certain aspects (normally not available in electromagnetic field simulators) such as the variable geometries, the mixing effect, the heating, the evaporation, as well as the dielectric proprieties characterization process has proven to be a critical, but indispensable step to be undertaken in order to obtain acceptable simulation results.

Through the study, analysis and characterization of "mixture substances" it has been possible to create mathematical models for an excellent estimation of the dielectric variations in temperature and concentration. These parametrizable models replicate the thermal properties of the whole mixture and require a minimum of tuning effort, typically consisting of a few measures or a priori knowledge of the mixture composition.

The combination of real measurements of the components of the mixture with the mathematical modelling of the dielectric material properties based on concentration and temperature, allowed for optimization of an industrial reactor (ANF) by decreasing the drying times, improving efficiency, and obtaining a better drying homogeneity, without needing costly dynamic impedance matching adaptations into the microwave circuit.

Ethics and consent

Ethical approval and consent were not required.

Data availability

Underlying data

Zenodo: SebaSchuetz/DEMETO_Dryer: DEMETO - Dryer – Repository. https://doi.org/10.5281/zenodo.7694803[20].

This project contains the following underlying data:

- Permittivity measurements. Each file is named as "XX_YYYp_mix.prn" (similar to CSV format), where XX is the temperature at which it was measured and YYY is the percentage concentration of the mixture.
- VLOSS results provided by the ANSYS HFSS simulation. Each file is named as "Vloss-@Temp-ConcH2O-XXXp.tab" (similar to CSV format), where XXX is the percentage concentration of the mixture simulated at different temperature (30°C – 50°C – 70°C – 90°C).
- Ansys model files:
  - Dryer V1 - Resonant Mode: resonant cavity analysis
  - Dryer V8.3 - Blender effect: blender effect analysis
  - Dryer V9 - Evaporation emulator High Temp - Second set data -0p to 100p: Evaporation effect analysis
  - Dryer V10 - Preheating effect - second set data 0p to 100p: Pre-heating effect analysis

Extended data

Analysis code available from: https://github.com/SebaSchuetz/DEMETO_Dryer

Archived analysis code at time of publication: https://doi.org/10.5281/zenodo.7694803[20].

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgements

The authors wish to acknowledge Matthieu Jaccard who contributed to the writing of this manuscript.

References

1. Ramopoulos V, Link G, Soldatov S, *et al.*: **Industrial scale microwave applicator for high temperature alkaline hydrolysis of PET.** *Int J Microw Wirel Technol.* no. S1759078718000727, 2018; **10**(5): 709–716.
Publisher Full Text
2. promasengineers: **promasengineers.** [Accessed 03 02 2023].
Reference Source
3. DDP System: **www.ddpsinc.com.** [Accessed 03 02 2023].
Reference Source
4. microwaves101: **Introduction to S parameters.** [Accessed 30 01 2023].
Reference Source
5. De Dietrich Process Systems: **https://www.ddpsinc.com/.** November 2014; [Accessed June 2020].
Reference Source
6. Wikipedia: **Cavity magnetron.** [Accessed 30 01 2023].
Reference Source
7. Praveen Kumar AV, Burt G: **Hybrid Electromagnetic Modes - Structures and Characteristics.** *IEEE Xplore.* IEEE Applied Electromagnetics Conference (AEMC), 2017; 1–3.
Publisher Full Text
8. Saeed K, Shafique MF, Byrne MB, *et al.*: **Planar Microwave Sensors for Complex, Permittivity Characterization of Materials and Their Applications.** *IntechOpen.* 2012.
Publisher Full Text
9. Sebastian MT: **CHAPTER TWO - MEASUREMENT OF MICROWAVE DIELECTRIC PROPERTIES AND FACTORS AFFECTING THEM.** Elsevier Science, In: *Dielectric Materials for Wireless Communication.* 2008; 11–47.
Publisher Full Text
10. Nowak D: **The Impact of Microwave Penetration Depth on the Process of Heating the Moulding Sand with Sodium Silicate, Archive of Engineering.** *Archives of Foundry Engineering (AFE).* no. ISSN (1897-3310), 2017; **17**(4): 115–118.
Publisher Full Text
11. Peng Z, Hwang JY, Mouris J, *et al.*: **Microwave Penetration Depth in Materials with Non-zero Magnetic Susceptibility.** *ISIJ International.* 2010; **50**(11): 1590–1596.
Publisher Full Text
12. Micro Denshi Co: **https://en.microdenshi.com/microwave/.** 2020; [Accessed June 2020].
Reference Source
13. Sabbagh MEL: **Electromagnetic-Thermal Analysis Study Based on HFSS-ANSYS Link.** *EECS Tech Rep - Syracuse University.* 2011.
Reference Source
14. DEMETO: **DEMETO - Chemical Recycling Revolution.** [Accessed 03 02 2023].
Reference Source
15. ScienceDirect: **Dielectric Constant.** *ScienceDirect.* vol. From: Cell Physiology Source Book (Fourth Edition), 2023.
Reference Source
16. Singh SP: **An Analysis of Dielectric Parameters and Penetration Depth of Tomato Sauces.** *J Food Process Technol.* 2018; 1–4.
Publisher Full Text
17. Wikipedia: **ISM radio band.** Wikipedia, 2021.
Reference Source
18. Lewis MJ: **Physical Properties of Foods and Food Processing Systems.** Cambridge England: University of Reading, UK, 1990; 480.
Reference Source
19. Xiao M: **Thesis - Modelling of conductor surface roughness effect.** University of Illinois, Urbana, Illinois, 2014.
Reference Source
20. Rotolino93: **SebaSchuetz/DEMETO_Dryer: DEMETO - Dryer - Repository.** *Zenodo*. [Dataset], 2023.
http://www.doi.org/10.5281/zenodo.7694803

Open Peer Review

Current Peer Review Status: ✗ ✗ ?

Version 1

Reviewer Report 02 August 2023

https://doi.org/10.21956/openreseurope.16778.r33431

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?

Venkatesh Meda
University of Saskatchewan, Saskatoon, Saskatchewan, Canada

The article needs a very thorough proof reading.

Heat and mass transfer, kinetics and process flow diagram are missing completely (basics will be required) as they relate to the drying speed, mixing efficiency, homogeneity of microwaves inside the cavity, and resonance shift.

Link to the moisture content (humidity) is presented however need to elaborate the effect on drying, initial content and desired end ratios.

Process safety aspects need to be included as temperature and pressure, both, will increase during the reaction. Simulation results are acceptable. Error analyses data is a suggested new information that may be useful for readers.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Need revisions as suggested

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 02 August 2023

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Pranjali Muley
National Energy Technology Laboratory, Morgantown, USA

The manuscript titled " A microwave cavity design and optimisation for a homogeneous and faster drying process inside an industrial Agitated Nutsche Filter" evaluates modifications to an industrial dryer by addition of microwave cavity to evaluate drying rates. The manuscript provides detailed changes to design and develops a numerical model to analyse the heating inside the newly modified dryer. However, the manuscript lacks key parameters.

1. The dielectric properties measurement details are missing. (a) What method did the authors use for measurement? (b) What kind of VNA was used? (c) How was the temperature measured and maintained during measurement? (d) What probe was used?

2. The numerical modelling details are missing: (a) What were the heat transfer and EM equations solved for? (b) what were the boundary conditions? (c) what was the meshing criteria? (d) what assumptions were made? Was convective cooling, conductive radiative cooling considered? What were the heat losses?

3. The model was not shown to be validated experimentally or via grid independence

4. There was no discussion on non-uniformity of temperature inside the cavity

5. The scale on figure 15 is unreadable. The figures seem to have been cut paste instead of exporting from Ansys

There are no experimental results showing that the heating efficiency with microwave increases.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Microwave heating, numerical modeling

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 31 May 2023

https://doi.org/10.21956/openreseurope.16778.r31263

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Ferruh Erdogdu
Department of Food Engineering, Ankara Universitesi, Ankara, Ankara, Turkey

Review of the manuscript:

A microwave cavity design and optimization for a homogeneous and faster drying process inside an industrial agitated Nutsche filter.

General:

The English of the manuscript should be revised – polished. As reported below in detail for different sections, the manuscript needs a significant re-write and a significant revision. Upon the completion of these revisions, it must be re-evaluated. The results section should also be rewritten with respect to the given comments below. In general, a mathematical system geometry optimization is expected, with respect to the abstract, but the mathematical background (use of

governing differential equations and boundary conditions) was not presented while the use of empirical equations is stated to be the mathematical models. Besides, there is no information given about the software and its background and applied approach.

Title:

- The title should be modified to replace homogeneous with `uniform` considering that the objective is to obtain temperature uniformity inside the product.

Abstract:

- DEM3TO? The introduction of this project in the abstract does not make any sense.
- The significance of ANF is not clear.
- Objectives should be stated explicitly.
- The objective is to design a microwave cavity and/or process, but this is not clear, and the background was also not stated in this purpose.
- What is the reason to introduce the microwave?
- Methods were rather weak; it is not possible to understand the applied approach.
- What is the relationship to increase the absorption of electromagnetic energy and uniformity? This gives a faster heating rate, but this does not mean that you will obtain temperature uniformity.
- That the mixture was characterized for the dielectric properties and ANF is not clear.
- What is careful modeling?
- The last part of the conclusion section is the common knowledge, not the conclusion derived from this study.
- Another important problem is: the abstract starts with recycling the PET and then jumps into the design of the microwave cavity design, but the relationship – connection is not clear at all.

Introduction:

- Homogeneous drying: in terms of what, temperature moisture content? And again `homogeneous` should be `uniform`. Humidity is also not the correct term.
- Microwaves have lower penetration depth (and this depends upon the dielectric properties). Therefore, it is not possible to expect a uniform penetration in a microwave process. The heating rate might be accelerated, but this never means that you will get a uniform heating or temperature distribution.
- Determining the S parameters is not the objective. It is the parameter that you will use for the efficiency. How will you understand whether dynamic controlling for the impedance will be needed? Explain the expectation out of the S-parameters (but not in the objectives).

- Humidity is not the correct word, and in the objective, there is no `design` mentioned. The objectives must be stated explicitly.
- It was stated that the behavior of the microwave cavity inside the ANF will be studied, but assuming that this was not yet designed, don`t the authors think that the first step should be the system design?
- Not water concentration, use `moisture content`.
- If we are talking about the drying process, boiling temperature is not the correct word.
- Numbers 3 and 4 in the summary must be the first in the summary of the study and stated in a clear way.

Microwave dryer cavity analysis:

- The permanent resonance mode background and relationship with the cavity geometry must be first explained.
- Before presenting the results of the simulations (Fig. 2), please introduce the mathematical background first. In addition, in this figure, it does not present that the resonant frequency is influenced by the resonance cavity size and material dielectric properties. Especially, the cavity size and resonance relationship must be presented in more detail and in a representative figure.
- It is a great idea to adapt the excitation frequency with respect to the changes in the dielectric properties (as a function of moisture content and temperature!), but his section must be presented and explained in more detail. How will the system decide upon this?
- All cavities allow penetration, but depending upon the features of the resonance, the efficiency will change. This section should be written in this concept.
- Eq. 1 does not show the speed reduction but the decrease of the wavelength.
- In Eq. 2, you do not need to use `2` in the square root symbol.
- Eqs. 1 to 3: the relationship and how will be applied in this study must be explained. They were nicely introduced, but the reader is not sure about how they will be used in the scope of the cavity design.
- Dielectric height is not the correct term. I am assuming that the authors are addressing the dielectric constant, but the rest of this section is about the size of the sample.
- Derivation of the Eq. 4 is not clear! And what is log2? Is this a natural algorithm? Not clear. Since the correct cavity diameter is calculated in this aspect, this section should be explained in more detail. And one more question, what is the background on choosing the cylindrical cavity? And how will the height of the cavity be determined?
- Regarding the determination of the absorbed power, it will be good to introduce the mathematical background and not the feature of the software.

Mixture dielectric properties:

- Please give more detail regarding how the TPA represents the industrial mixture.
- Table 1: based on all the background introduced by this point, it does not make any sense to use the constant dielectric properties. In the meantime, in the next section, the effect of the moisture content (not temperature?) is given. With respect to the scope of this study, dielectric properties should be a function of temperature and moisture content. Therefore, the authors clarify this section. In addition, it will be better to report the dielectric loss factor rather than the loss tangent value.
- Boiling temperature is not the correct term in the concept of drying.
- It is okay to choose 2.45 GHz, but 915 MHz is also allowed. So, the authors should explain this section in this concept.

Mathematical model design:

- The mathematical design section is all about presenting the empirical equations for the dielectric properties. One would expect the computational background in this section with all the required differential equations, boundary conditions, and system cavity geometry that is planned to be used with respect to the results of the previous sections.
- The features of the used software should also be explained. With this kind of presentation, the study is a black-box modeling where the inputs and outputs are known but not what is happening in the modeling background (inside the box).
- Besides, it is not true to address this section with the mathematical model validation with its contents.
- Given the explanation in the preparation of the TPA, with the continuous mixing, does it still become a sedimentation? If this is the case, I am not sure whether a uniform dielectric property measurement will hold!
- Figure 4 should be omitted.
- Figure 5: for the last one (fig. 5d), this empirical equation cannot be used. This is obvious. The authors should reconsider this case.

EM simulation models:

- It is clear how that cavity diameter will be determined, but as questioned above, the height is a question mark. Explanation by the volumetric ratio is not enough. And all the dimensions must be presented in Figure 8 with their calculations by citing equations 4 and 5.
- We are talking about a cavity (Figure 8). Then, the location of the magnetron (with the waveguide) should be presented.
- It is not true to address the empirical equations as `mathematical models.
- Was that assumed that the evaporation starts along the surface boundary? Then the question is how the temperature increases within the volume of the sample was controlled to prevent internal evaporation.

- According to Demeto partners? This is not a scientific explanation. please demonstrate how this D/H=1 was concluded. And by the way, this is not a definition of symmetry.
- figure 9: the location of the port should be presented precisely with its dimensions.
- Including the mechanical blender model, all the required governing equations with the boundary conditions must be presented. There is no explanation about the fluid rheological properties of the mixture and how the interphase surface issue was handled. It was stated that a mathematical model was created with respect to Figure 10, but it is not clear.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Novel thermal technologies (infrared, microwave and radio frequency processing) with computational process design and optimization

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.