Multiphysics Modeling to Assist Microwave Cavity Design for Food Processing

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Abstract: **Microwave technology has many current applications. It is very useful for food processing, including domestic cooking and warming-up and industrial heating and drying. It heats faster than conventional applications; however, in most cases result in non-uniform temperature distribution. Adequate cavity and equipment designs can reduce the impact of these heterogeneities and using multiples magnetrons is a possibility to mitigate hot and cold spots. Yet, the literature lacks methods to evaluate and compare multiple magnetrons designs. This study aimed to develop a procedure to evaluate the number and position of magnetrons connected to an application cavity using multiphysics modelling and simulation of the microwave distribution and heating of a food model. It was based on evaluating the electric field distribution into a selected working volume filled with air or a mixture of air-potato and the consequent effective power absorbed and temperature distribution into the air-potato medium. The assisted methodology with process simulation offers an insight into food temperature distribution, which would be very difficult to obtain experimentally or in any equipment design methodology. In this case study, it was found that up to 6 magnetrons are good enough when active in approximately 0.16 m3 cavity with a load that fills 10% of its volume.**

Keywords: **Design methodology, Food technology, Microwave propagation, Magnetrons, Temperature control.**

I. INTRODUCTION

The non-uniformed volumetric temperature distribution in food during application of microwave heating is a big concern [1], due to impacts food safety and quality [2-10]. Microwave intensively interact with food constituents, causing molecules realignment in the direction of the applied electromagnetic field and following its oscillations [11,12]. As a result, microwaves translate electromagnetic energy into heat. This phenomenon promotes a relatively rapid heating and internal evaporation of liquid water [13,14].

Compared to other food processing technologies, microwave presents higher thermal efficiency, shorter processing time, reduced operational costs, and improved processed food quality (such as texture and nutritional aspects) [15,16]. Although microwave heating supersedes traditional heating methods, non-uniform electric field patterns, leading to hot spot development, limit further applications of microwave technology [17]. These patterns occur due to reflection and diffraction of the direct electromagnetic waves forming standing waves and lead to local overheating [2]. The distribution of electromagnetic waves in food products changes according to dielectric properties (vary with food composition), thermal properties (conductivity, specific heat), physical properties (shape, size), microwave standing waves, the location inside the resonant cavity and oven design [6,18-20]. Regarding the design, turntables [7,21-23], modified sample compartment [18,24], stirrers [17,25], and complementary heating [26,27] are recurrent alternatives to improve microwave distribution. Also, product temperature can be further moderated by controlling magnetron duty cycle or using solid-state technology [1] and power density [28], including online feedback control [29]. However, the optimal number and position of magnetrons in cavities remains a challenge [30,31].

Earlier studies experimentally evaluated how to adapt a combination of the microwave, vacuum and rotary drum to analyze the drying process of foods or examine the feasibility of using microwave double-feed vacuum drier to dry biomaterials [32]. Gao et al. [30] and Hazervazifeh et al. [31] evaluated the influence of parameters on microwave heating performance during simulation by a multiphysics approach, coupling electromagnetic and heat transfer equations. In these cases, the simulations help to understand the phenomena involved in a drying method, to predict consequences of possible process changes, to save time and expenses to run experiments, and to verify process results in hours with intrinsic properties details [14, 27,30-33].

The use of different geometries of domestic microwave oven was analyze by other authors aiming improve electric field uniformity and increase heating. Yi et al. [20] numerically simulated and compared the electric field and temperature distribution within microwave oven with detailed realistic geometric features and an appliance with more simplifies geometry. Their results indicated significative difference of temperature pattern between models. Rajpurohit and Chhibber [19] studied the effect of two magnetrons in microwave heating efficiency, presenting different arrangements as optimal designs.

In Table I a comparison between previously published works and the present study mentioning cavity shape, number of magnetrons and sample disposition is presented. These previous studies have attempted to improve the flaws of microwave

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heating, but none have yet examined a methodology of multiport feeding position to assist microwave cavity design. In this way, the novelty is developing a method for supporting microwave oven design by evaluating the impact of the number and position of magnetrons during food processing. The total energy delivered to a working volume, the microwave distribution, and the impact on food heating were assessed using multiphysics modeling and numerical simulation. The method targeted to select the relative best configuration in terms of the electric field distribution and effective power absorbed and consequent temperature distribution into a working volume placed into the cavity.

TABLE I. COMPARISON BETWEEN PREVIOUSLY PUBLISHED WORKS AND THE PRESENT STUDY

Main achievement	**Geometric Characteristics** (Cavity Shape, number of magnetrons and sample description)	**Source**
Understand the influence of geometric feature on the electric field distribution inside a microwave oven for heating food using numerical simulations.	- Rectangular : 35 x 353 x 217 mm - 1 magnetron:: 0.4 W /2.45 GHz - Rotating glass plate for solid sample	[20]
Improved microwave industrial process efficiency by designing the geometry of a resonance cavity system and by modifying sample continuous flow orientation.	- Rectangular 450 x 450 x 1040 mm - 8 magnetrons: 2.5 kW /2.45 GHz - Viscous Fluid Sample in continuous flow 0.05 m/s	[24]
Development of an algorithm to optimize the geometry of the microwave cavity to improve heating uniformity.	- Circular: radius150 mm /Rectangular: 260 x 260 x 200 mm - 1 magnetron: 1 kW /2.45 GHz - Fixed solid sample	[34]
Stablished specific designs for industrial microwave cavities with more uniform and efficient plastic heating	- Cylindrical: radius 215 mm and height 461 mm with Hopper - 1 magnetron: 1 kW /2.45 GHz - Pellets samples	[35]
Developed a microwave cavity used with a hybrid drying process to dry coffee reducing heating costs and controlling temperature.	- Hexagonal: width 180 mm and height 365 mm - 6 magnetrons: 0.9 kW /2.45 GHz - Fixed solid sample.	[36]
Developed a method to design a multiport microwave oven for food processing.	- Cylindrical: radius 250 mm and height 800 mm - 12 magnetrons: 1 kW /2.45 GHz - Rotatory fractionated solid sample.	Present study

II. METHODOLOGY

Geometry Cavity, magnetrons, and food load

The microwave cavity was a metallic cylinder with 0.8 (height) x 0.25 (radius) m, based on actual equipment dimensions for food processing [3]. The cylindrical structure guarantees better wave distribution in a batch system, avoiding accumulated electric charges in edges and corners [30,37]. Rectangular waveguides (45 x 72 x 35 mm) feed the cavity with microwaves from 12 connected magnetrons with 1 kW power at 2.45 GHz frequency. In food processing, the frequencies allowed in microwave heating are 915 and 2450 MHz [38].

It was used the 12 possibilities of microwave excitation to analyze different positions and the number of magnetrons. Fig. 1 shows the magnetrons placed $\pi/2$ apart, resulting in 4096 possible designs ranging from 1 to 12 active magnetrons (simple combinatory analysis without repetition). Magnetrons were named based on their location, as Front (F), Middle (M), and Back (B), and using cardinal orientation North (N), South (S), East (E), and West (W), as shown in Fig. 1. For instance, FN means Front and North position, BE means Back and East position, and so on.

The impact of each one of the 4096 magnetrons designs was based on evaluating a working volume, as in [39]. A hypothetical medium was proposed to estimate the heat generated and temperature rising due to the resulting electric field for each configuration. This medium mimicked the volumetric fraction occupied by raw potato pieces placed inside a continuously rotating drum. The drum was assumed with two internal regions: i) the working space (0.12 m external radius, 0.06 m internal radius, and 0.4 m height) composed of a mix potato-air, where the variables (electric field, effective power absorbed, and temperature) were evaluated; and ii) a concentric cylinder of air (0.06 m radius, and 0.4 m height). Rotary drums tend to push the samples to its wall; thus, the working volume was assumed hollow and presenting only air at its center. The cavity structure and the working volume are represented in Fig. 1.

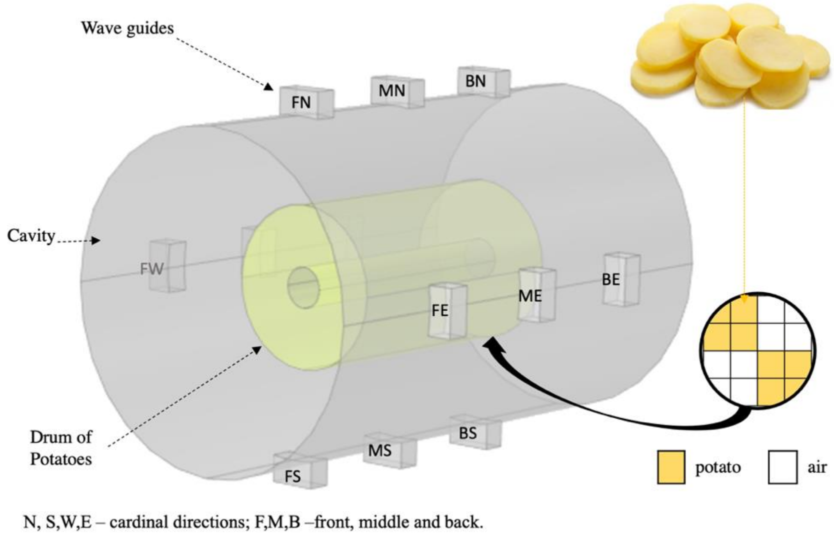

Fig. 1. Schematic of the microwave cavity with 12 magnetrons positions and in the spotlight the hollow working volume composed by air and potatoes

Electromagnetic Modelling

The electric field distribution inside the oven cavity was obtained by solving Maxwell's equations of electromagnetism, which for constant dielectric properties and without sources, can be written as (1-4) [37].

$$\nabla \times \vec{H}_s = j\omega\varepsilon_0\varepsilon_c\vec{E}_s \tag{1}$$

$$\nabla \times \vec{E}_s = -j\omega\mu_0\vec{H}_s \tag{2}$$

$$\nabla \cdot \vec{E}_s = 0 \tag{3}$$

$$\nabla \cdot \vec{H}_s = 0 \tag{4}$$

in which, j is the imaginary unit; ω is the angular frequency ($\omega = 2\pi f$, with f as the propagation frequency of microwaves); μ_0 is the permeability of free space; ε_0 is the permittivity of free space; ε_c is the complex relative permittivity ($\varepsilon_c = \varepsilon' - j\varepsilon''$, with ε' as the dielectric constant and ε'' as the loss factor); the vectors electric field ($\vec{E}$) and magnetic field ($\vec{H}$) were defined as time-harmonic functions, expressed in terms of phasor ($\vec{E}_s$, $\vec{H}_s$).

It was used three boundary conditions to solve the electromagnetic model: a) The walls of the waveguide and cavity are assumed to be a perfect electrical conductor. Therefore, tangential components of the electric field on these walls is zero, implying in $\vec{n} \times \vec{E}_s = 0$; b) The drum wall is assumed to be electromagnetically transparent, i.e., continuity boundary was used between air and drum, implying in $\vec{n} \times \left(\vec{E}_{s,air} - \vec{E}_{s,working\ volume}\right) = 0$; and c) At the excitation port, electromagnetic energy was supplied through a rectangular TE_{10} mode waveguide at constant power (P_{in} = 1 kW) and 2450 MHz.

The local volumetric power absorbed by the medium in the working volume (Q_{MW}) was obtained using the Poynting's theorem, as in (5):

$$Q_{MW} = \frac{1}{2}\,\omega\varepsilon_0\varepsilon''(\vec{E}.E^*) \tag{5}$$

Local complex relative permittivity in the working volume was estimated using the equation of Landau, Lifhitz and Looyenga [14], which ponders the local volumetric fraction of potatoes (v) (6), where pot subscribes to potato and air to air proprieties.

$$\varepsilon_c^{1/3} = v(\varepsilon'_{pot} - j\varepsilon''_{pot})^{\frac{1}{3}} + (1-v)(\varepsilon'_{air} - j\varepsilon''_{air})^{\frac{1}{3}} \tag{6}$$

Heat Transfer Modelling

The main goal when describing heat transfer is to correlate how the resulting electric field distribution impacts the temperature distribution, correlating microwave power into the working volume for food processing purposes. The temperature distribution into the working volume was obtained by the energy equation (7), which includes conduction heat transfer and volumetric heat source (Q_{MW}):

$$(\rho c_p)_{ef}\frac{\partial T}{\partial t} = \nabla(k_{ef}\nabla T) + Q_{MW} \tag{7}$$

in which ρ, c_p, and k, are the density, specific heat capacity, and thermal conductivity.

The initial condition assumed the entire working volume at a uniform temperature, T_0. As boundary conditions, the working volume was assumed adiabatic, i.e., at the working volume frontiers with the air, $\vec{n} \cdot \vec{\nabla} T = 0$. Here, due to the relatively short period of analysis, the convective heat transfer from the working volume to the surrounding air does not impact significatively on the temperature distribution (data not shown).

Effective thermal properties of the working volume were balanced by the volume fraction of each phase (air and potato), as presented in (8) and (9):

$$(\rho c_p)_{ef} = v\rho_{pot}c_{p,pot} + (1-v)\rho_{air}c_{p,air} \tag{8}$$

$$(k)_{ef} = vk_{potato} + (1-v)k_{air} \tag{9}$$

Potatoes thermal properties were estimated based on [40], assuming a porous medium composed of water, solid, and air. It was assumed constant thermal and electrical properties, and possible ablation effects are neglected. Table II shows the values and source of the physical properties and process conditions used for solving the model.

Numerical Solution

The mathematical model was solved by finite element method using the software COMSOL Multiphysics®. It was used the RF Module with Frequency Domain interface and FGMRES iterative solver (Flexible Generalized Minimal Residual) for solving the electromagnetic equations (1-4). The energy equation (7) was solved using Heat Transfer Module with Heat Transfer in Solids interface and GMRES multigrid solver. The electromagnetic field in the cavity was solved in steady state, and then the heat transfer was used to solve the energy balance in transient state.

Tetrahedral mesh elements with second-order interpolation function were used for the discretization of the computational domain. A mesh sensitivity analysis was performed comparing the numerical solution using elements from 0.023 to 0.23 cm, resulting in 1,217,259 to 387,901 elements in the whole model, respectively. The mesh with a lower number of elements was considered good enough to solve the system since it presented less than 1% of error compared to more refined mesh, while the solution was three-time faster. The average temperature of the working volume was the variable calculated to compare the meshes in this case. In earlier studies regarding just the electric field in the air, the mesh was also evaluated comparing the average electric field and using the element quality tool from COMSOL.

The analysis of different designs in COMSOL totaling 4096 simulations was performed with the functions *if + end if* and with the parametric sweep tool. The *if + end if* functions enable to randomize geometry, i.e., the calculation domain was modified, generating a new design for each simulation.

TABLE II. PARAMETERS USED IN THE SIMULATION FOR MICROWAVE CAVITY DESIGN WITH HOLLOW WORKING VOLUME (DRUM) OF AIR AND POTATOES.

Parameter	Value	Unit	Source
Dielectric Constant,			
Potato, ε'_{potato}	39.545	-	Eq.6
Air, ε'_{air}	1	-	[27]
Dielectric loss, ε''			
Potato, ε''_{potato}	6.413	-	[27]
Air, ε''_{air}	0	-	[41]
Volumetric heat capacity			
Potato, $\rho_{potato} c_{p,potato}$	$2.9x10^6$	J/m³K	[27]
Air, $\rho_{air} c_{p,air}$	1191	J/m³K	[27]
Thermal conductivity			
Potato, k_{potato}	0.440	W/m K	[27]
Air, k_{air}	0.026	W/m K	[41]
Input Power in each magnetron, P_{in}	1000	W	Assumed
Microwave frequency, f	2450	MHz	[38]
Initial temperature at the working volume, T_0	20	ºC	Assumed
Potato Volumetric fraction in the work volume, v	0.3	-	Assumed

Design Evaluation

The design evaluation was performed in three successive levels, as presented in Fig. 2. First, the electric field distribution was analyzed into the empty cavity, i.e., the working volume is air only. All magnetron (active port) position possibilities in the oven cavity full filled with air were evaluated, aiming to identify the higher average values and low standard deviation of the resulting electric field. Thus, it was evaluated the electric field distribution in the microwave cavity simulating the working volume as a mix of potatoes and air.

In this level, only designs with 6 magnetrons or less are evaluated (2047 designs) due to the results from previous level 1, based on the electric field average. After these simulations, the designs with a lower *CV* and higher efficiency, representing 10% of better results, were chosen for level 3 evaluation.

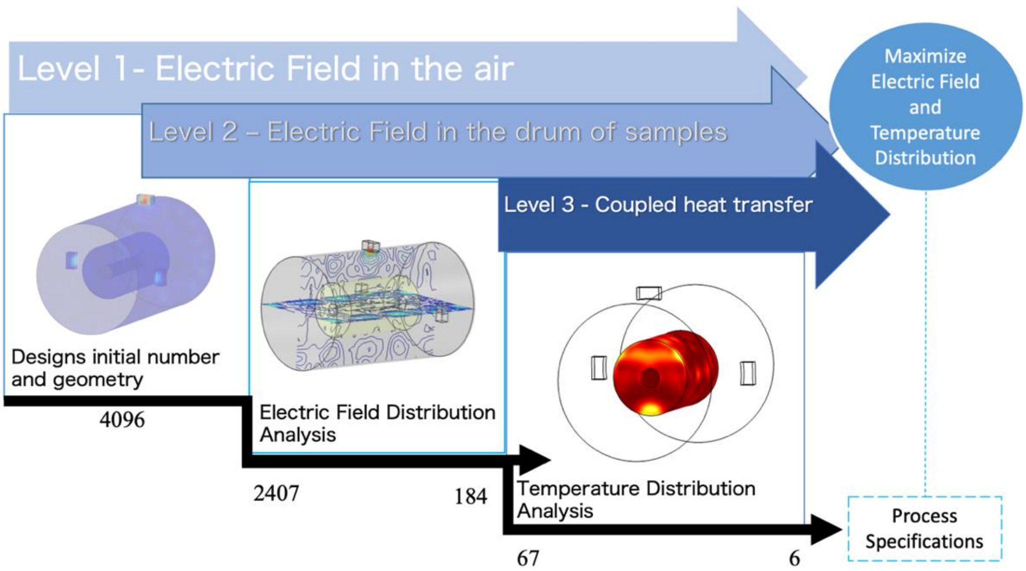

Fig. 2. Schematic of the design evaluation for a multiport microwave cavity based on successive levels: electric field in the air (level 1), electric field in the hollow drum of potatoes and air (level 2), and heat transfer in the hollow drum of potatoes and air (level 3).

After excluding the symmetric designs, level 3 evaluated the electric field and temperature distribution into the potatoes-air mixture. In this last step of the proposed method, the temperature distribution in the working volume was computed during 30 s of heating by microwave. In this analysis, the temperature at any point of the working volume did not exceed the saturation temperature of water at 1 atm (100 ºC), ensuring no phase change and presence of vapour. At last, one design for each number of ports with the lowest CV was selected, forming a new group of 6 simulations.

For all levels, it was evaluated the average ($\bar{X}$), standard deviation (SD), efficiency (Ef) and coefficients of variation (CV) of the targeting variables, electric field or temperature, estimated according to (10-13):

$$\bar{X} = \frac{\sum_{i=1}^{n} X_i}{n} \quad (10)$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n}} \quad (11)$$

$$Ef = \frac{P_{abs}}{P_{in}} \quad (12)$$

$$CV = \frac{SD}{\bar{X}} \quad (13)$$

in which $\bar{X}$ and SD are the volumetric average of each specific variable in the working volume and the respective standard deviation value estimated from every element in the mesh (X_i). The power absorbed (P_{abs}) was then estimated as the average power density dissipation in the working volume. In this case, the difference of energy stored in the working volume and ohmic losses were estimated for each finite element. The efficiency (Ef) was calculated as the ratio between the power absorbed (P_{abs}) and the total inlet power (P_{in}).

In addition, since one may be more interested in the temperature extremes than an equally weighted standard deviation, it was also used the range of temperatures as an identifier of temperature non-uniformity [43].

III. RESULTS AND DISCUSSION

Level 1 - Electric Field in the Air

The first level evaluated all magnetron positions using the electric field result to evaluate the uniformity in distribution. In Fig. 3, the plot $\bar{X}$ versus SD of the electric field for each design shows SD values increasing as the average electric field intensity increases, i.e., as higher the resultant energy in the cavity, the bigger the deviation of its distribution.

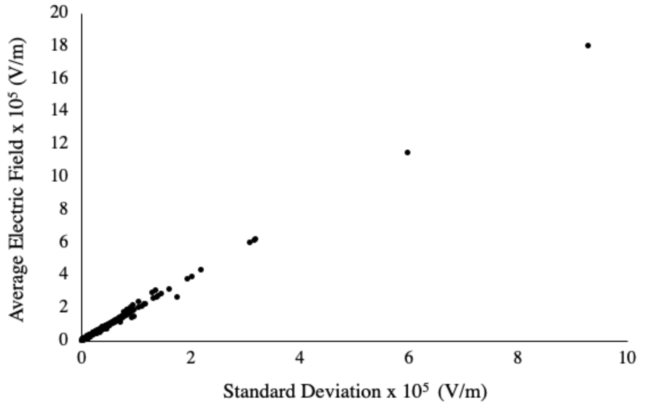

Fig. 3. Average versus standard deviation of the electric field intensity distribution in the air for each of the 4096 possible designs evaluated

The power provided to the cavity increase as the number of magnetrons increase, but the resultant energy in the system (average electric field) not necessarily is higher, as shown in Fig. 4. The maximum value of the average electric field was 18 x 10^5 V/m when using 7 magnetrons, leading to the maximum standard deviation value observed. Most design configurations presented average electric field values between 1 and 4 x 10^5 V/m with SD from 0.1 to 2 x 10^5 V/m, representing 20% of the maximum values obtained. Fig. 4 shows the average electric field intensity by the number of active ports. The higher the number of active ports (i.e., energy amount provided to the cavity), the higher the average electric field intensity until 6 ports. Then, when increasing the number of active ports, the average electric field is reduced.

It is a consequence of constructive and destructive wave interactions, resulting from the position of the magnetrons in the cross-section of the drum. Thus, aiming to find the best configuration for the proposed working volume, it is not recommended to use more than 6 active ports since more energy will be wasted, considering the power necessary to turn on the magnetrons and energy losses inside the cavity.

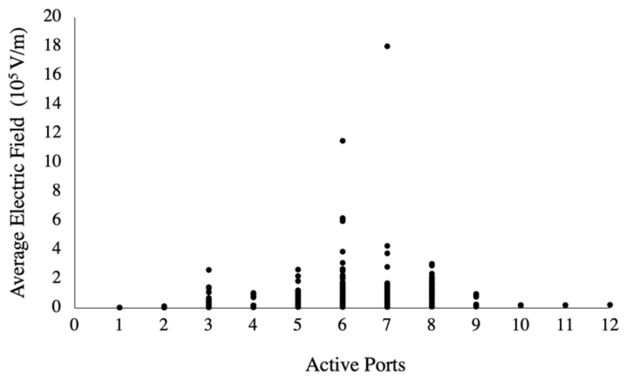

Fig. 4. Average electric field intensity versus the number of active ports (magnetron turned on) for the electric field distribution in the air for each of the 4096 possible designs.

Another indicator of the effective distribution of energy is the coefficient of variation (CV). Low CV values show that the relative standard deviation is small for a certain average value, something that is desirable [42]. If the average electric field is high and the standard deviation low, it is possible to find the uniformity aimed and the most effective configuration. Fig. 5 shows the CV plot as a function of the average electric field in the working volume of air.

In Fig. 5, a group can be observed for CV values lower than 45%, and, in Fig. 6, another group for 2, 4 and 6 active ports (red boxes). Regard to maximizing the electric field distribution, it is desired that the designs present low CV, resulting in more uniform energy distribution in the working volume. Attention is necessary, though; a low CV can also represent a situation where the design of the oven is enabling wave destructive phenomena (low average electric field and low standard deviation). Even if interesting design groups could be found at this level, it is chief to keep analyzing the 2407 designs with 6 or fewer magnetrons since they counted just the air in the working volume.

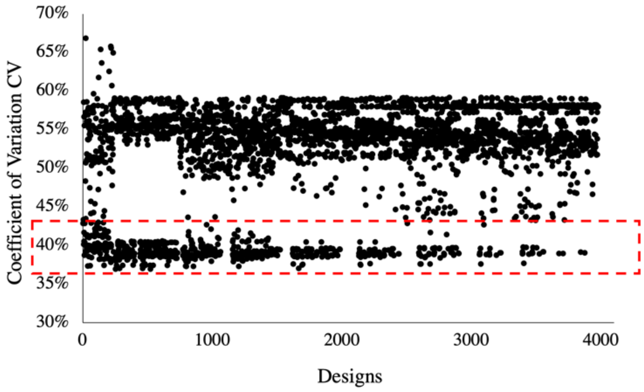

Fig. 5. CV of the electric field intensity for each possible design in the working volume (drum) with air in detail CV values group lower than 45%.

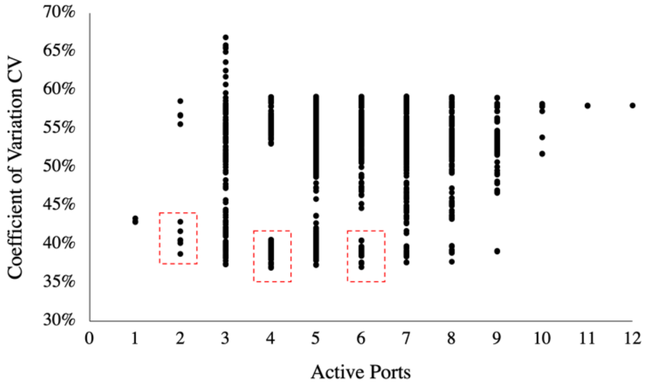

Fig. 6. CV of the electric field intensity versus the number of active ports (turned on magnetron) in the working volume (drum) with air for each 4096 designs. In detail CV values group lower than 45%.

Level 2 - Electric Field in the Drum with Potatoes

Following the results from level 1, only designs with 6 magnetrons or less are evaluated (2047 designs), since those with a bigger number of magnetrons tend to a low electric field distribution and high values of CV. In Fig. 7, the design of each number of ports active was analyzed separately. When considering only one active port, it was directly identified the maximum electric field average distribution since just one of the designs fits the criteria. In the designs with 2 and 3 active ports, it was found designs that respect the objective proposed in the methodology, maximize the electric field distribution.

For more than 4 active ports, it was not observed a group of designs that presented a high average electric field and low SD. The coefficient of variation (Fig. 8) and efficiency (Fig. 9) estimation helped in this analysis.

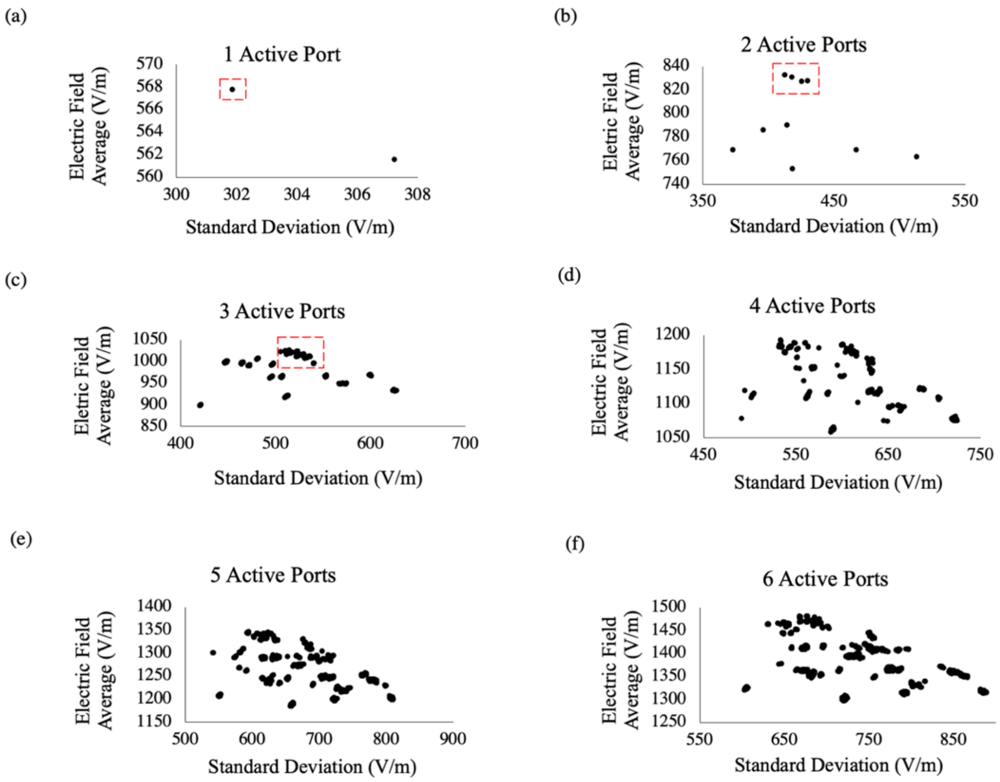

Fig. 7. Average versus standard deviation of the electric field intensity in the working volume (drum) of potato and air for (a) 1 active port; (b) 2 active ports; (c) 3 active port; (d) 4 active ports; (e) 5 active port; (f) 6 active ports. In detail the groups with maximum electric field average distribution.

A good design should present a low CV (showing uniform wave distribution) and high efficiency, i.e., most energy is available in the working volume. The designs with CV lower than 53% and efficiency higher than 97%, representing the 10% best designs, were chosen to further analysis. These values were chosen to fit the criteria of a maximum electric field in the working volume with low spatial variability, i.e., maximum electric field distribution. The method defined a new group of simulations composed of 187 different designs, and after identifying the symmetries, it remained with 67 different designs to proceed to the next level.

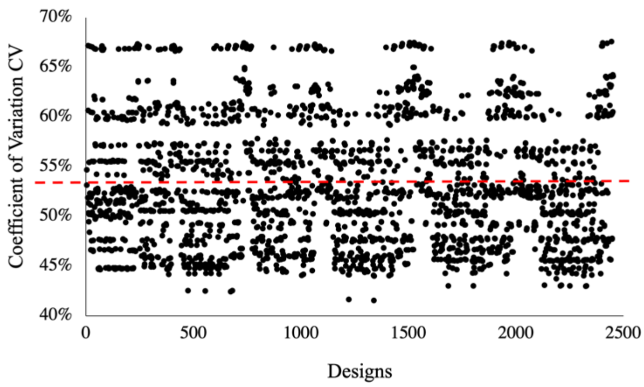

Fig. 8. CV of electric field distribution for every 2407 designs in the working volume (drum) of potato and air. The red line limits the arrangements with CV lower than 53%

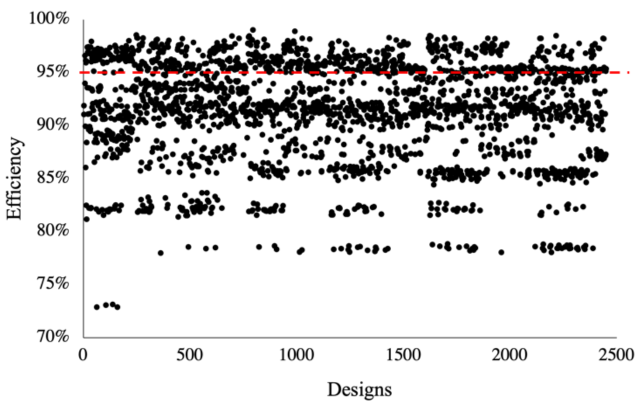

Fig. 9. Efficiency of power absorption of the 2407 designs in the working volume (drum) of potato and air. The red line limits the arrangements with more than 97% efficiency.

Level 3 - Heating and Temperature of Potatoes

The average temperature and the respective CV value are presented in Fig. 10 and Fig. 11, respectively. Fig. 10 indicates that average temperature values increase as the number of ports increase, as expected when increasing the input power.

Data in Fig. 11 shows an increase of CV as the number of active ports increases, and similar values of CV and different designs configurations could be found for 4 and 5 or 5 and 6 active ports. In these specific configurations, designs with 4 active ports provided the same average electric field and variability as designs with 5 active ports, representing an economy of energy.

It is well known that microwave food processing results in hot spots [43], where a relatively higher temperature during cooking or drying may lead to a burned material. The non-uniformity in heating is particularly undesired if the difference between the cold and hot spot is so high, and unprocessed and burned regions may be found in the same product [43]. Therefore, if the port positioning for the cavity design can guarantee reduced temperature gradients (with low CV) in the product, it is correct to say that the most efficient configuration is reached. One design for each number of ports with the lowest CV was selected in this perspective, forming a new group of 6 simulations.

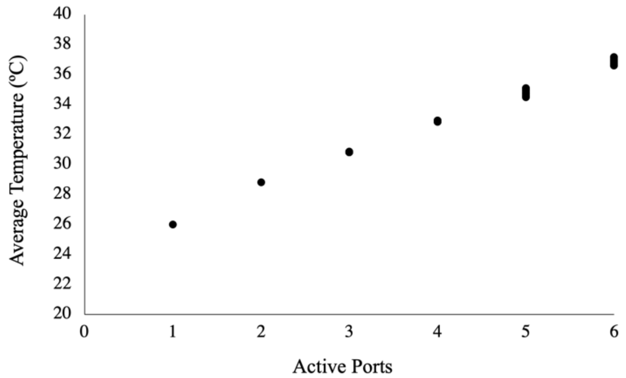

Fig. 10. Average temperature versus the number of active ports (turned on magnetrons) in the working volume (drum) of potato and air.

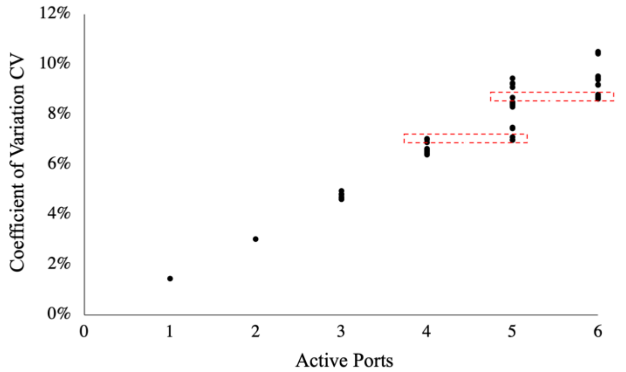

Fig. 11. CV for temperature distribution versus active ports (turned on magnetrons) in the working volume (drum) of potato and air. In detail designs with the same variability, but different number of active ports.

Fig. 12 shows the average temperature and the CV for each design with 1 (Fig. 12 a) to 6 (Fig. 12 f) active ports. It is possible to see the temperature surface distribution in the working volume and the electric field distribution in a plane in the cavity. The higher the number of turned-on magnetrons, the higher the average temperature of the working volume and the higher the energy converted into heat. The process of heating a material with electromagnetic waves is a function of the dielectric medium, which, in this case, is a mix of air and potatoes. If the load density or material properties are modified, then the variability of these systems will also change. For instance, it is possible to consider different load densities by adding more material to the volume under analysis. As the proposed method is based on numerical simulations, it provides flexibility to change some process features, such as the load, initial temperature, and power input.

Each step of the method reduced the number of possible designs, continuing to the next step with a more complex physical-based model for simulation. It is worth to highlight that a consecutive step always offers an improved model to describe the relevant physics involved than the previous step.

This approach simulates a large number of designs with a simple simulation and fewer designs with more complex simulations that were studied with more details. All selections were based on objective targets.

Cavity and waveguide measurements, cavity geometry, volume and type of load are required to use this methodology. To get realistic simulations, the knowledge of material properties is also very important. For example, a final refinement can be carried out for establishing the desired temperature for the material under study, assuring a minimal center temperature for thermal processing of a food material or more homogeneous energy distribution or a more efficient energy consumption. The proposed method with process simulation offered an insight into food temperature distribution, which would be very difficult to obtain experimentally or in any equipment design methodology that is a limiting for finding the desired design. Also, current methods do not provide a visualization of the functioning equipment design. Besides, CV and efficiency also allowed the assessment of the non-uniformity of microwave and temperature distributions. As shown in Fig. 12 it was possible to suggest relatively better option on designing a microwave cavity.

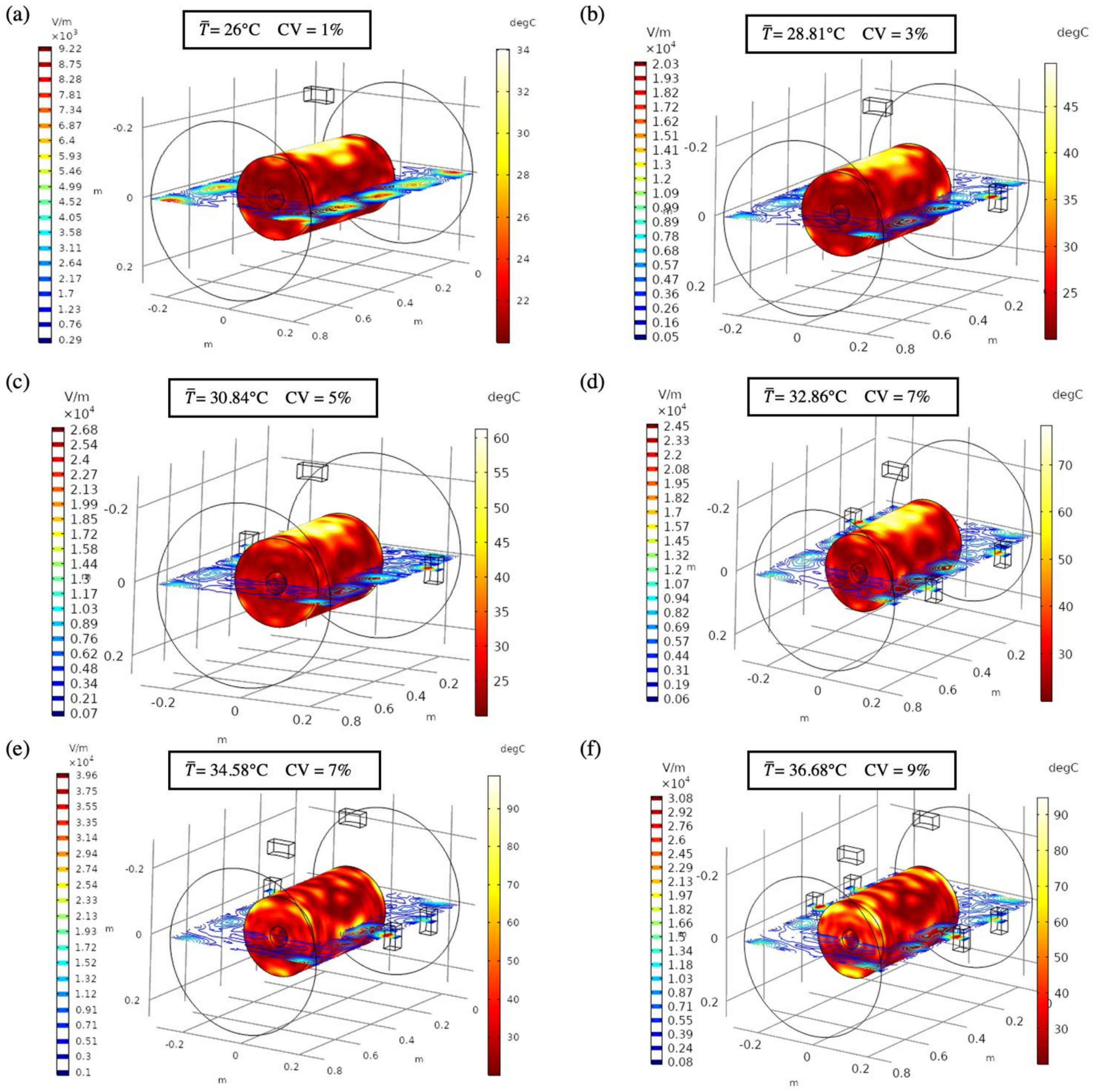

Fig. 12: Designs from (a) 1 to (f) 6 active ports (turned-on magnetrons) representing the electric field distribution in the cavity and temperature distribution in the working volume (drum) with potato and air

One of the advantages of the selected designs is a better distribution of the electric field and temperatures in the food, contributing to more uniform heating or drying, giving a superior quality to the dehydrated food. In addition, the chosen configurations can guarantee a lower energy cost if consider the energy offered to the system and the energy that heated the food. And as a disadvantage, it is important to mention that the design was chosen based on the characteristics of food that presents itself as material fractionated in small dimensions, for larger or whole foods the process would need to be reviewed. In addition, the penetration depth calculation database comes from the potato. If other foods are used, with very different properties, new simulations will be necessary.

IV. CONCLUSION

Electromagnetic wave distribution and heat transfer equation were solved to simulate the temperature distribution in a food product inside a microwave oven cavity with multiple energy sources. It was successfully implemented a stepwise strategy for designing a microwave oven cavity with several magnetrons in different positions based on mathematical modeling and simulation of the physical phenomena involved. It was obtained the best configuration based on statistical evaluation with average, standard deviation, and coefficient of variation of the variables of interest, electric field and temperature in the present case. Thus, in a cylindrical cavity with until 12 active ports, it was demonstrated that up to 6 ports led to more efficient designs than those with a largest number of ports due to a higher energy efficiency keeping homogeneous temperature distribution. This method can be applied to different types of process or cavities geometries regarding microwave technology, but the step by step presented here need to be followed. We mean that the cavity geometry needs to be defined with the process aims and specification and, just after that, use the simulations tools. In addition, the simulation model is fast and flexible to be applied in different food types, even for new products applications.

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