STUDY OF THE NEAR FIELD GENERATED BY A POWER ULTRASONIC TRANSDUCER

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Resumen
En los últimos tiempos, los procesos asistidos por ultrasonidos de potencia (UdP) se han convertido en un atractivo campo para las industrias debido a su sostenibilidad (bajo consumo energético, bajo poder contaminante...). Estos procesos están basados en la explotación adecuada de los efectos no lineales asociados a la propagación de ondas de amplitud finita capaces de mejorar los procesos de transferencia de masa como el secado de alimentos.

El objetivo de este trabajo es el análisis del campo acústico generado por un transductor ultrasónico de potencia con radiador de placa circular escalonada, y confinado en una cámara de secado, cuyos resultados se han obtenido mediante la aplicación de métodos numéricos. También se presentan los resultados obtenidos tras realizar un estudio paramétrico para la posición de la muestra, con el objeto de optimizar la eficacia del sistema.

Palabras-clave: ultrasonidos de potencia, campo acústico, energía acústica, método de los elementos finitos, transferencia de masa.

Abstract
Industrial processes assisted by high-power ultrasound (HPU) have become an attractive field for industries because of its sustainability (low energy consumption, non-pollutant processes). These processes are based on the proper exploitation of the non-linear effects associated to finite-amplitude-wave propagation that are able to enhance mass transfer processes in food dehydration.

The main objective of this work is the analysis of the acoustic field, generated by a high power ultrasonic transducer with circular radiator confined in a drying chamber, and obtained by numerical methods; as well as the parametric study of the sample location inside the chamber, in order to optimize the system efficiency.

Keywords: high power ultrasounds, acoustic field, acoustic energy, finite element method, mass transfer processes.

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1 Introduction

Industrial processes assisted by high power ultrasound (HPU) have become a new, green and efficient technology with a high potential in its implementation. Previous researches like [1, 2] show that these HPU technologies provide a good performance in processes like particle agglomeration, ultrasonic cleaning or defoaming, among others. In the particular case of food dehydration, it has been proved by [3] that HPU provides a faster and more economic performance, improving also the quality of the final product.

Anyway, the process to achieve a good final solution is not easy. In order to produce changes in the internal structure of the food samples, it is necessary to generate an ultrasonic field with high amplitude by a high power ultrasonic transducer. Because of the special requirements for the whole system, the transducers have to be driven to its desired resonance frequency and with a high power level, thing that can produce a nonlinear behaviour in the transducer, with effects like hysteretic response, frequency shifts and drops, or modal interactions, saturation, among others [4, 5].

In [6] a complete analysis considering a high power transducer with cylindrical radiator is shown, considering design issues, the study of the acoustic field generated inside the transducer radiator and the influence of HPU in food drying kinetics.

The aim of this work can be divided into two parts, first of all, the study of the acoustic field generated by a circular plate transducer in a cylindrical drying chamber. The second objective of this work is to study how a potato sample dissipates the acoustic energy depending on its physical characteristics and the acoustic field previously determined.

2 Transducer design

In order to perform the study of the acoustic field, it is necessary to model a high power ultrasonic transducer using finite element methods and taking previous works as a basis to define the characteristics of plate transducers, the materials for each part and piezoelectricity concepts [6-8].

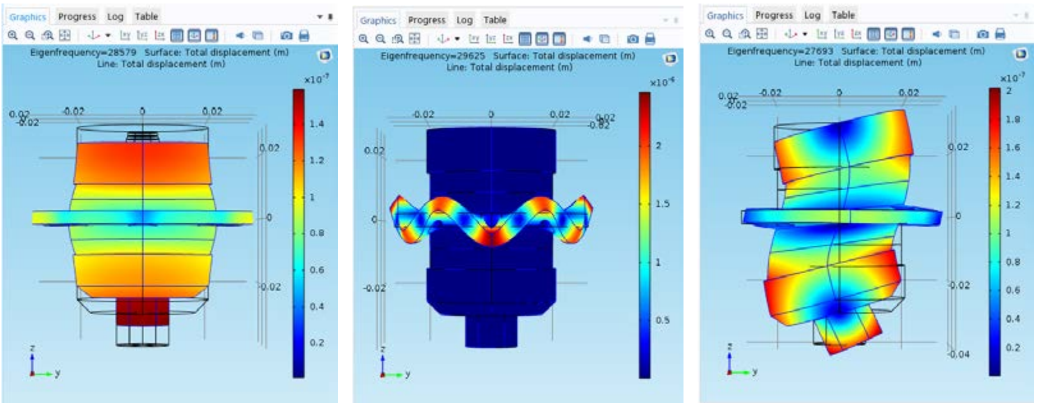
A detail design of the transducer has been taken, analysing the vibration modes of each part (Langevin-type transducer, horn and circular plate), in order to achieve a system with the proper vibration mode at the desired frequency (in this case, around 25 kHz).

2.1 Langevin type transducer and mechanical amplifier

First of all, a Langevin type transducer has been designed, applying equation (1) shown in [9] to get mass and backing mass dimensions for an axial mode of the sandwich transducer.

$$\tan\left(\frac{\omega l_c}{c_c}\right)\tan\left(\frac{\omega l_i}{c_i}\right) = \frac{\rho_c c_c A_c}{\rho_i c_i A_i}, \tag{1}$$

ω is the angular frequency, l_c, c_c, ρ_c y A_c are length, sound speed, density and area of the ceramics, respectively; and l_i, c_i, ρ_i y A_i are length, sound speed, density and area of the mass and backing mass. In the figure 1, the axial mode and other close modes are shown:



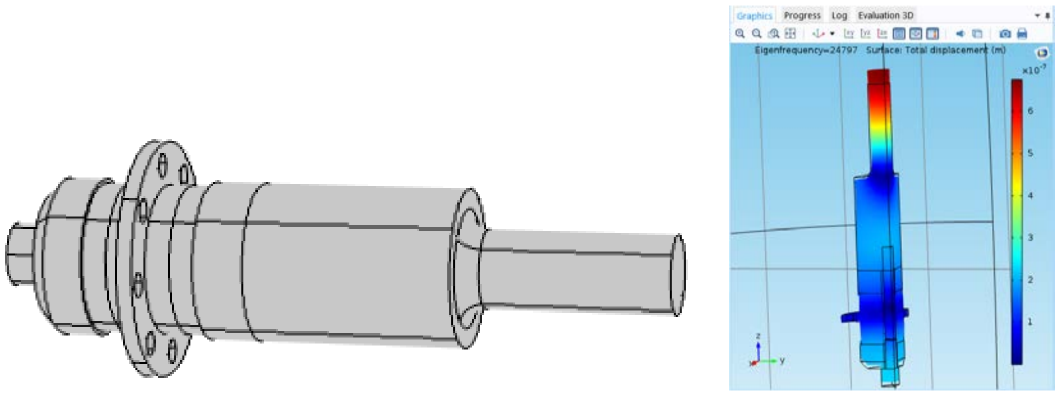
a) b) c)

Figure 1 – Different vibration modes of the Langevin type transducer. a) Axial mode (25879 Hz). b) Flexural mode in the flange (29625 Hz). c) Torsional mode (27693 Hz).

Then, the mechanical amplifier is to be added. The horn is made of titanium and consists on a $\lambda/2$ rod with two circular sections (*S1* and *S2*), each with a $\lambda/4$ length, and diameters *D1* and *D2*. The objective of this horn is to obtain displacement amplifications, according to equation (2):

$$M = \frac{S_1}{S_2} = \left(\frac{D_1}{D_2}\right)^2 \tag{2}$$

In the figure 2 the model of the ultrasonic vibrator is shown (fig. 2.a), as well as the axial mode of the system for a frequency of 24797 Hz (fig 2.b):

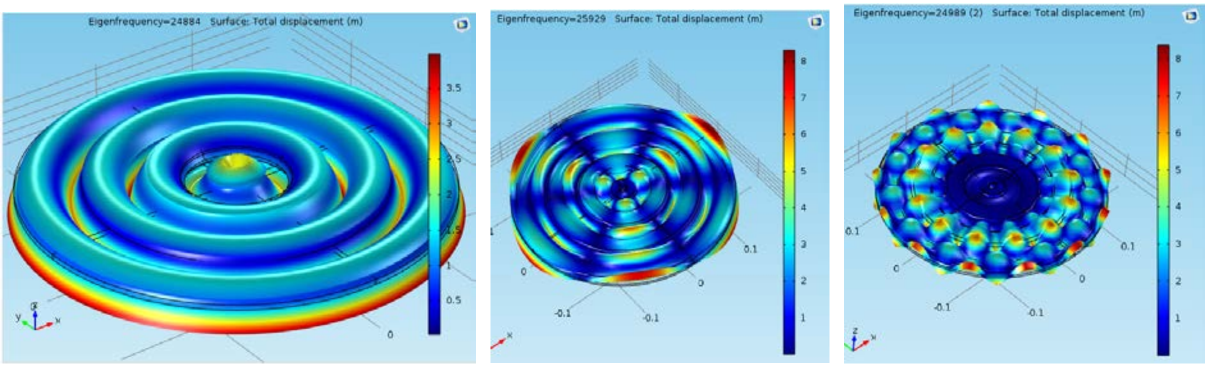


a) b)

Figure 2 – Ultrasonic vibrator with sandwich and horn. a) FEM Model. b) Axial mode (24797 Hz).

2.2 Stepped circular plate

As indicated in [7] and [10], the application of steps in the circular plate allows a highly directive coherent emitter, essential for a more efficient performance of the system. In this case, a titanium alloy stepped plate with a radius of 177,9 mm and a thickness of 11,15 mm has a resonance frequency of 24884 Hz for the 7 nodal circles mode. This frequency is near the resonance frequency for the axial vibration mode of the ultrasonic vibrator. In the figure 3 this mode is presented, as well as other close vibration modes:



a) b) c)

Figure 3 – Different vibration modes of the stepped circular plate. a) 7 nodal circles mode (24884 Hz). b) Combination of 7 nodal circles, 3 diameters and flexural modes (25929 Hz). c) Another combination with nodal circles, diameters and other shapes (24989 Hz).

2.3 Complete transducer

The next step consists in joining the ultrasonic vibrator, tuned at 24797 Hz for an axial vibration and the stepped circular plate transducer, tuned at 24884 Hz for a 7 nodal circles vibration mode. In this case, the behaviour of the whole system has been analysed with a 2D axisymmetric model. The desired mode appeared at 24928 Hz, with a maximum displacement on the top of the horn and a 7 nodal circles vibration of the plate, as is shown in figure 4.

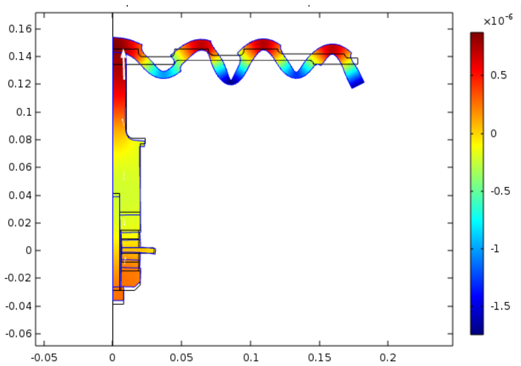


Figure 4 – Vibrational behaviour of the transducer at 24928 Hz.

Once the modal behaviour of the transducer has been analysed, the next step is the study of the generated acoustic field and the sample position.

3 Acoustic field

As it has been mentioned before, the application of steps in the circular plate's surface provides a coherent acoustic radiation in the fluid media, generating a plane wave just like a circular piston [7]. The acoustic field generated by a circular piston has been widely studied by [11, 12] and the equations to determine the acoustic propagation or calculate the amount of radiated, dissipated or absorbed energy are used in the finite element method.

3.1 Energy dissipation in air

The fluid in which the ultrasonic propagation takes place is air and, even if it is small, there is a dissipation of energy that depends on the temperature, humidity and dynamic or bulk viscosity. Several previous researches tried to define the dissipation power in air considering it as an elastic media, as a viscous fluid or as a thermo-viscous fluid. In [11, 13-15] the dissipation considerations have been analysed, as well as the issue of the volumetric viscosity of the air.

In our study, air at 15ºC is considered as a thermo viscous fluid, meaning that energy losses are due to viscous reasons and due to heat dissipation.

3.2 Dehydrating chamber

The first draft of the chamber consists on a cylindrical structure, with the circular stepped plate transducer in the middle in order to check the acoustic focalization on both sides. The initial dimensions of the chamber are 150 λ long and a radius similar as the radius of the circular plate. In figure 5 this chamber is shown:

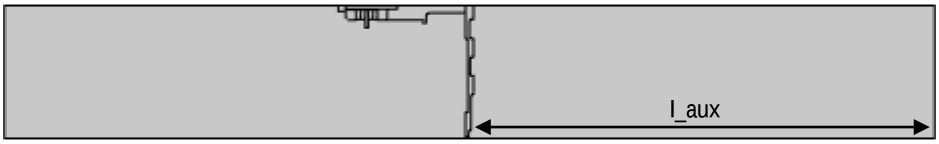
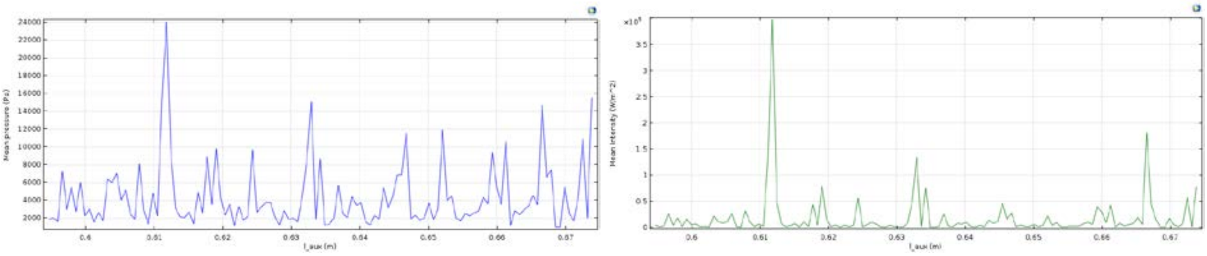


Figure 5 – First draft of the cylindrical chamber.

Anyway, a parametric study has been taken in order to determine the length that allow a maximum acoustic mean pressure and intensity. Starting with the initial value of l_aux, changes of $\lambda/20$ have been considered. The maximum value for the mean acoustic pressure and intensity has been obtained for l_aux=611.82 mm, as shown in figure 6:



a) b)

Figure 6 – Mean acoustic pressure (a) and intensity (b) for different values of l_aux.

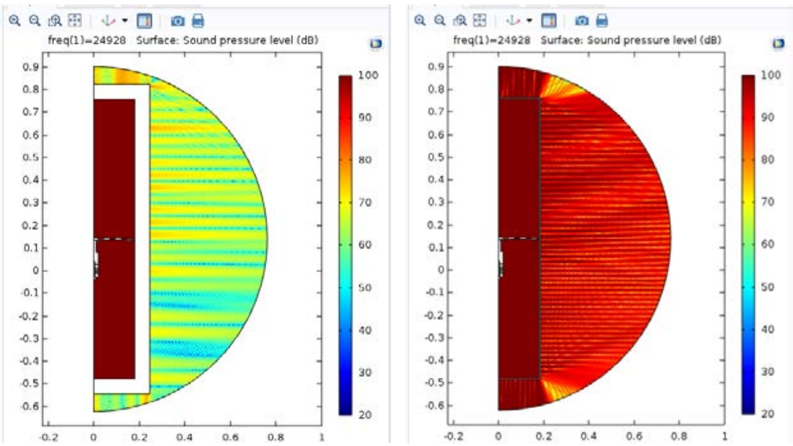
3.3 Study of the chamber wall characteristics

The next step consists in guessing how the chamber's walls behave regarding the acoustic absorption and reflection. On the other side, an acoustic isolation analysis has also been taken. For this purpose, several situations have been considered, 100% reflecting chamber walls, 100 % absorbing chamber walls and steel chamber walls of 5 mm and 80 mm thick, respectively. In the following chart the mean and maximum values of acoustic pressure and intensity in the chamber are shown, for the four different boundary situations:

Table 1 – Behaviour of different kind of chamber walls.

Boundary	Mean pressure (Pa)	Maximum pressure (Pa)	Mean intensity (W/m^2)	Maximum intensity (W/m^2)
100% reflecting	17955	7.77e5	1.61e5	9.38e7
Steel 80 mm	17862	7.73e5	1.59e5	9.26e7
Steel 5 mm	18113	7.82e5	1.66e5	9.65e7
100% absorbing	388.29	6415	255.06	45488

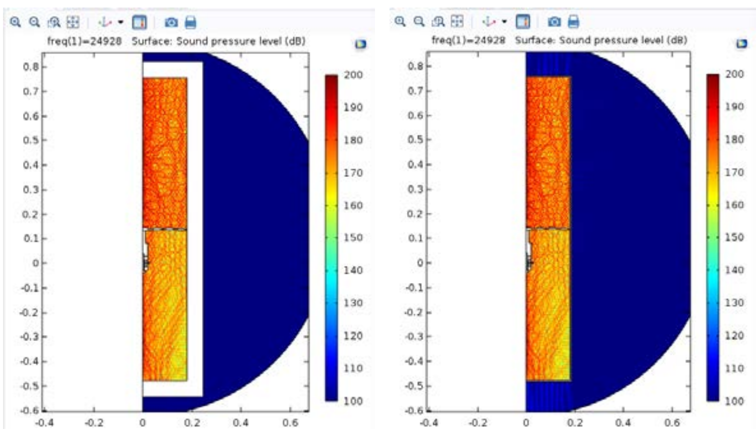
It is demonstrated that the metallic chamber walls behave basically as totally reflecting surfaces, creating a stationary field inside. On the other side, it is interesting to know if there is any energy dissipation when the acoustic waves travel through the walls and if there is an energy transmission to the exterior of the chamber. In figure 7, the acoustic field generated by the transducer vibrating at 24928 Hz and transmitted outside the chamber is shown:



a) b)

Figure 7 – Acoustic field generated outside the chamber with (a) thick or (b) thin chamber walls.

In figure 8, the generated acoustic field, at 24928 Hz, inside the chamber for the same two situations are also depicted:



a) b)

Figure 8 – Acoustic field generated inside the chamber with (a) thick or (b) thin chamber walls.

As we can guess from the previous figures, there is an energy dissipation inside the walls of the chamber, although the acoustic field in the interior of the dehydrating chamber is similar in both cases. The design with thin walled chamber is the one considered for the numerical analysis of the samples to dehydrate.

4 Samples to dry

The main objective of this analysis is the primary design of a food dehydration chamber assisted by power ultrasound. Once it has been demonstrated in figure 7 that the acoustic field is not uniform inside this chamber, it is necessary to determine what is the optimal place to locate the samples to dehydrate in order to get the most efficient drying process.

4.1 Porous materials

The drying kinetics depends on how the food sample absorbs the acoustic energy that goes through its structure. In order to determine this absorbing power it is necessary to know the porosity, flow resistance and density of the sample. In [11, 12] the acoustic absorption effect in porous solid is developed, considering energy dissipation. Also the problematic due to the porosity is stated. If the sample's porosity is high, the energy absorption is low, but if the porosity is low, the sample's impedance will be high compared to air's and most of the energy will be reflected in the sample's boundaries.

In [16] the basic concepts for density, porosity, diffusivity, thermal conductivity, permeability, etc..., applied in a model for the study of mass and heat transfer in porous media (food) and the equations for the density (real and apparent) and flow resistance depending on the sample humidity are shown.

Sound propagation in a porous material is influenced by the flow resistance, that is itself function of the porosity and permeability of that material. Considering a simple harmonic motion in the interior of a porous material, the concepts of effective density ρ_e and effective sound speed c_e can be defined in equations (3) and (4), respectively, according to [12]:

$$\rho_e = \rho_p \left(1 + \frac{i\phi}{\rho_p\,\omega}\right) \tag{3}$$

$$c_e = c_p \left(1 + \frac{i\phi}{\rho_p\omega}\right)^{-\frac{1}{2}}, \quad c_p = \sqrt{\frac{1}{\rho_p \kappa_p \Omega}} = \frac{c}{\sqrt{\Omega}} \tag{4}$$

where ρ_p and c are the density and the sound speed in the fluid, ϕ is the flow resistance, ω is the angular frequency, κ_p is the effective compressibility of the fluid and Ω is the porosity of the sample. The porous material adds an imaginary component to the effective density and sound speed of the fluid that travels through it, that determine the dissipative power of the sample.

On the other side, it is also important to consider the sample's impedance because it may produce changes in the surrounding acoustic field and affect the drying kinetics. In [11] the impedance in the surface of each of the sample's pores is defined according to equation (5):

$$Z = \frac{\rho c}{\pi a^2} M'(1-i); \qquad M' = \frac{2}{a}\sqrt{\frac{\mu}{\gamma\rho\omega}} \tag{5}$$

where a is pore's radius, πa^2 is its surface, μ is the viscosity and γ is the adiabatic coefficient. That implies that the porous material adds a losses component related to viscosity and thermal conductivity.

Depending on the relation between the sample's and fluid's impedance, the sample will absorb or reflect a different amount of energy.

As a conclusion, in order to model the effect of placing a porous solid in the chamber, is necessary to know the material's impedance to know how the energy is absorbed by the sample; as well as the effective density and sound speed to determine the energetic behaviour of the material to be dried.

4.2 Definition of the sample

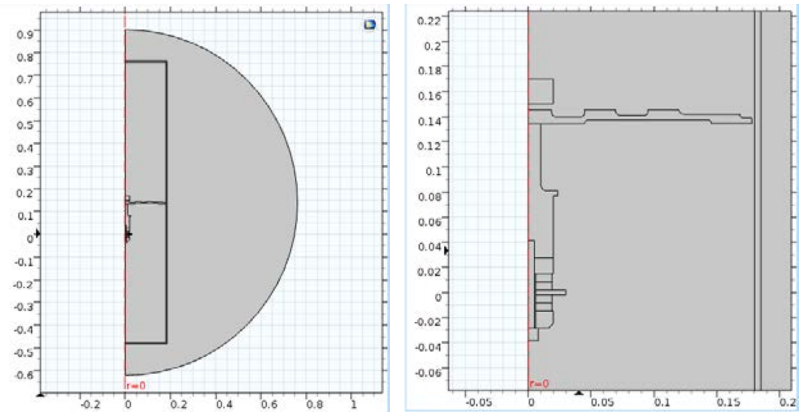
It has been considered a sample of potato for the numerical analysis of the acoustic energy absorption inside the chamber. In order to determine the density and sound speed in the sample, for the desired resonance frequency (24928 Hz) and according to equations (3) and (4), the parameters shown in Table 2 have been taken into account [17, 18]:

Table 2 – Physical parameters of the potato sample.

Permeability κ (m^2)	Flow viscosity μ (Pa·s)	Flow resistance ϕ (Pa s/m2)	Flow density (kg/m^3)	Adiabatic coefficient γ	Porosity Ω	Effective density (kg/m^3)	Effective sound speed (m/s)
10^{-18}	$1.8\ 10^{-5}$	$1.8\ 10^{13}$	1.21	1.4	0.020	$1.21 + i\ 1.15\ 10^{8}$	0.176 + i 0.176

4.3 Energy absorption analysis

In order to determine the optimal areas for the sample location inside the cylindrical chamber, a parametric study has been made, defining a 20x20 mm potato sample and obtaining the acoustic energy dissipation inside that sample. The parametric study consists in a displacement of the potato sample along the whole superior zone of the chamber. The acoustic properties of the sample (effective density and sound speed) are those indicated in Table 2. In figure 9, the general view of the system and a more detailed view of the initial sample position are shown:



a) b)

Figure 9 – a) Model of the system. b) Detail with the potato sample and the circular stepped plate transducer.

The dissipated energy inside the sample has been determined according to equation (5), and the result is shown in figure 10:

$$\iiint_V -\phi|U|^2 dV \tag{5}$$

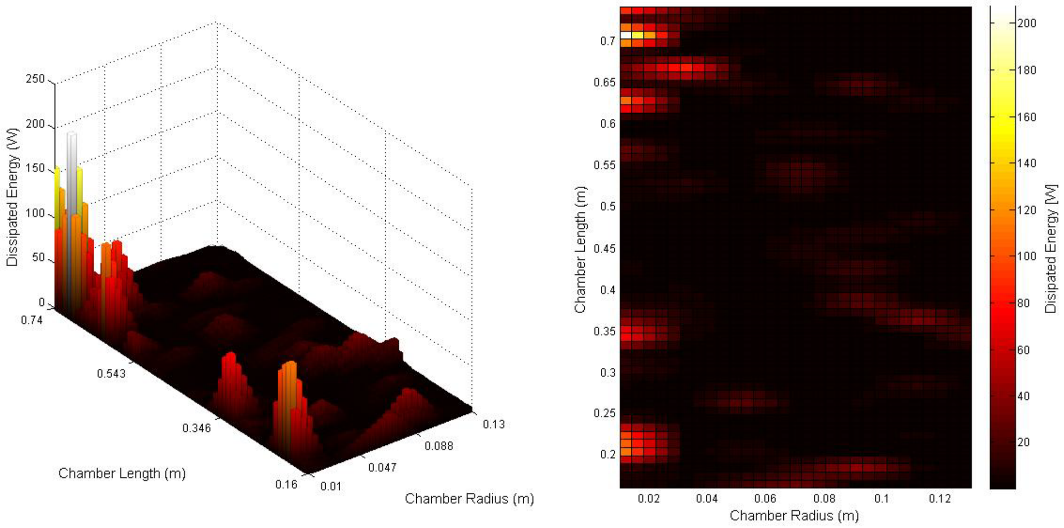


Figure 10 – Map with the dissipated energy inside the potato sample, depending on the sample's location in the drying chamber.

According to figure 9, the areas with a highest energy dissipation by the sample are located near the axis and the end wall of the chamber. In this case, a maximum energy absorption is obtained at 550 mm from the surface of the circular radiator.

5 Conclusion

A numerical study of the acoustic field generated by a high power ultrasonic transducer with circular stepped-plate radiator has been taken. This study comprises the design of each part of the transducer, the modal analysis of the whole system, the design of the optimal dimensions of the cylindrical chamber, the study of the behaviour of the chamber walls, the analysis of the acoustic field generated inside the chamber and the study of the behaviour of a food sample located inside the chamber.

Acknowledgments

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