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Optimization of the acoustic pressure distribution inside a freeze drying chamber.

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Introduction

The use of high-intensity ultrasonic energy in food dehydration processes have shown a good performance in terms of efficiency, energy reduction and quality of the final product, allowing also a reduction in the convective drying kinetics, and at lower temperatures than conventional air dryers [1, 2]. This sustainable technology needs an airborne power ultrasonic transducer (APUT) to work in a required operational mode at a high power regime in order to generate the desired ultrasonic field inside the dehydration chamber.

The airborne power ultrasonic transducer is composed by a Langevin sandwich, a mechanical amplifier and an extensive radiator [3, 4], which provides a good impedance matching with the surrounding medium and high vibration amplitudes along its surface [5].

Initial studies on the effects of applying power ultrasound in food dehydration processes showed higher efficiency with the samples in direct contact with the transducer radiator, than the experiments where the transducer was emitting in air [1], but temperature increases in the contact surfaces between the radiator and the food samples provoke the caramelization of the sugar of the samples, making this procedure unsuitable for this process.

The efforts were then focused on the generation of a high intensity ultrasonic field capable accelerating the dehydration kinetics of the food samples.

The design of the extensive radiator determines the pressure distribution in the near field generated by the transducer [5-7]. The cylindrical radiator generates an ultrasonic field in the cavity whose main characteristics is the pressure distribution in cells with higher amplitude [8]. This configuration has been proved to be efficient in terms of enhancement of the dehydration kinetics and quality of the final product [2, 9-11]. Nevertheless, the small volume covered by the cylindrical radiator makes it unsuitable for an eventual upscaling of this technology to an industrial level.

Latest designs capable of covering wider volumes are the APU transducer with stepped-grooved circular radiator [4] and the APU transducer with flat rectangular radiator and a reflectors system [7, 12], both capable of generating a coherent ultrasonic field in the near field.

The acoustic field generated inside the dehydration chamber depends both on the generator (shape and vibration mode of the radiator); and on the propagation channel (shape, wall material and environmental conditions of the dehydration chamber).

Hence, the analysis and optimization of the acoustic field in the area of interest is essential for and efficient performance in food dehydration processes.
The aim of this work is to present the numerical analysis and optimization of the ultrasonic field generated by the APUT with stepped circular radiator inside a freeze drying cabinet, using COMSOL Multiphysics®.

Dehydration chamber

The dehydration chamber (or drier) is the place where the freeze drying process (or lyophilization at atmospheric pressure) takes place. The temperature inside the chamber has to remain under the freezing point of water, and the relative humidity as close to zero as possible. Unlike lyophilization processes, which take place in vacuum, the pressure condition established for these experiments is atmospheric pressure because the ultrasounds need a medium to propagate. Therefore, the dehydration chamber has to be able to keep the desired environmental condition. A scheme of the ultrasound-assisted low temperature drier can be observed in Fig. 1, where all the elements that take part in this kind of experiments appear.

The elements placed inside the chamber are the airborne power ultrasonic transducer and the weighing scale. The transducer needs an electric supply and the guidelines to vibrate at the required frequency with the desired amplitude. Outside the chamber lies the signal generation system, composed by a dynamic resonance frequency control unit (ultrasonic controller), to give adjustable continuous power output at the resonance frequency of the transducer by keeping the voltage (V) and current (I) signals in phase, and tracking it when this frequency shifts during operation [13, 14]. The controller operates as a finely tuned electronic signal generator that sends the excitation signal to a broad-band power amplifier and then to the transducer through an impedance matching unit to allow maximum energy transfer between the electronics and the transducer.

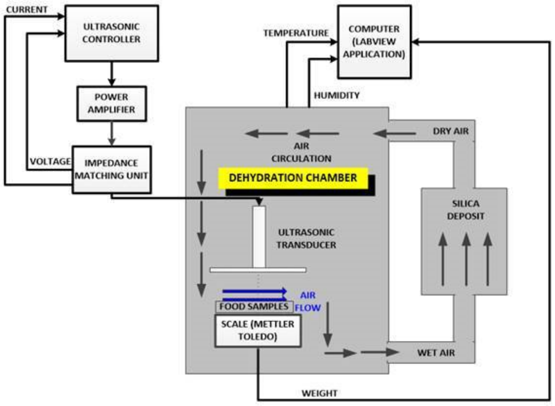


Figure 1. Scheme of the dehydration chamber.

The environmental variables (temperature, relative humidity and air flow velocity) inside the chamber are logged in a computer application. The most adequate humidity value inside the chamber is as close to zero as possible, because the dehydration process follows the Fick’s diffusion laws, meaning that there is a transfer of the wet content from places with higher amount of water to places with smaller amount of water. If the humidity, or wet content, in the environment is zero, it is easier for the water inside the food sample to move outside.

The way to determine the evolution of the dehydration process is by weighing the food samples. The samples are composed by a solid matrix and water. The solid matrix experiences no major changes in this process, but the wet content is being transferred to the media. So, the weight of the sample decreases continuously because the wet content disappears by sublimation. A weighing scale is placed inside the chamber to weight the samples in intervals of about 15 minutes, and sends the data to the computer to be processed. The dehydration kinetics is represented as the evolution of the weight of the food samples along the operation time.

Use of COMSOL Multiphysics

The effectiveness of the application of airborne power ultrasound in freeze drying experiments depends on the amplitude of the acoustic pressure concentrated in the area where the food samples are placed.

The pressure distribution and amplitude inside the dehydration chamber depends on the design of the radiator and the dehydration chamber; and on the environmental conditions inside. Furthermore, the separation between the radiator and the food samples also determines the properties of the ultrasonic field.
As mentioned above, the ultrasonic generator is an airborne power ultrasonic transducer with a stepped-grooved circular radiator (Fig. 2), vibrating in a natural mode with seven nodal circles (7NC) at a frequency around 26 kHz (Fig. 3) [4].

The numerical characterization of the ultrasonic field generated inside the dehydration chamber has been done using COMSOL Multiphysics®, with two main objectives:

- **The determination of the most effective location of the APU transducer.** The APU transducer is hung inside the dehydration chamber, with the stepped profile of the circular radiator pointing downwards, where the food samples are placed. The distance between the samples and the radiator has been defined by a parametric study done for different values of separation between them.

-**The definition of the pressure distribution in the samples area.** This second result defines where the acoustic energy is higher, because this area is supposed to be where the freeze drying process is faster.

This simulation corresponds to a Multiphysics simulation with the Solid Mechanics interface, which defines the vibration of the circular radiator and the Pressure Acoustics interface, which obtains the pressure distribution inside the dehydration chamber.
The nature of this simulation depends utterly on the geometry of the dehydration chamber. The transducer and the food samples are placed inside the chamber,

with a separation from all the walls higher than 25 cm.

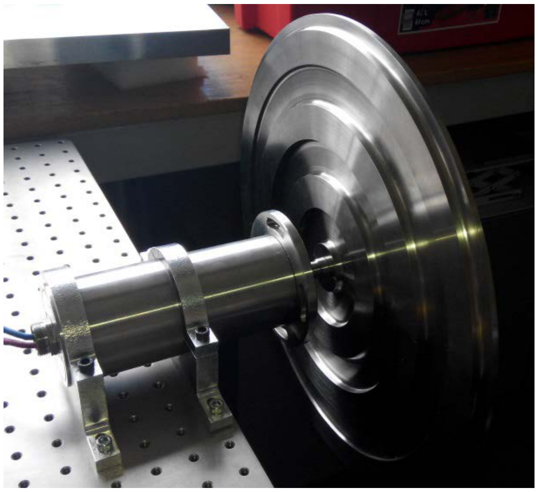


Figure 2. APUT with a stepped-grooved circular radiator.

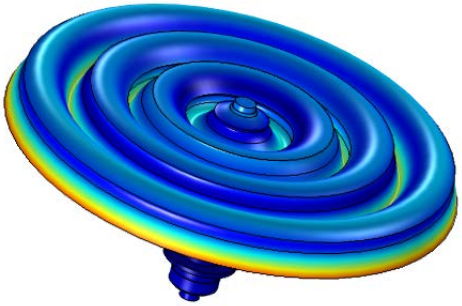


Figure 3. Operational mode with 7NC.

A 3D simulation requires much higher computational resources than a 2D axisymmetric simulation. On the other hand, the 2D axisymmetric model allows the definition of a finer mesh, associated to a more accurate result. Considering the axisymmetric nature of the APU transducer, it would be preferable this model. Considering that any reflecting surface of the cabinet is placed far away from the radiator and the food samples, the acoustical effects of the reverberation inside the cabinet can be neglected.

Hence, a 2D axisymmetric model has been considered for this purpose (Fig. 4). The lateral boundaries of the dehydration chamber have been defined as perfectly matched layers (PML's) to simulate a free propagation in that direction (blue areas in Fig.4), while the front boundary, where the samples are placed (red line in Fig.4), is defined with a reflecting material, Polystyrene, with a specific acoustic impedance of $Z=35100$ Rayls, between the impedance of a sound hard boundary ($Z=\infty$) and of a sound soft boundary ($Z=0$). The symmetry axis is highlighted in green.

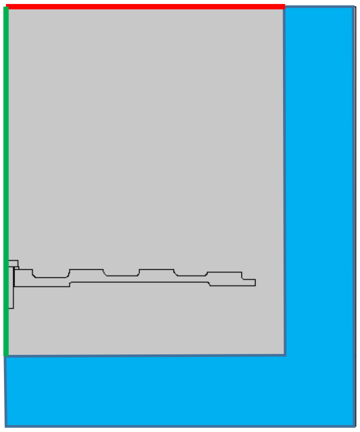


Figure 4. 2D axisymmetric representation of the model of the drying chamber and the APUT.

The APU transducer has been simulated as a stepped-grooved circular radiator excited mechanically by a rod (in this case the bolt that joins the plate with the rest of the components of the transducer. This simulation has been done with the Solid Mechanics interface, defining the geometry as a Linear Elastic Material with Free Vibration except the basis of the rod, where a prescribed displacement in z-direction has been defined. The amplitude considered of the prescribed displacement is 10 µm.

The Acoustics - Structure Boundary multiphysics interface applies in this simulation, being the edges of the bolt and the radiator the coupling interfaces between the two physics. The Multiphysics simulation consists of a mechanical vibration of the circular radiator at its operational frequency, which generates an ultrasonic field in the surrounding medium.

The next step is the definition of the mesh of this geometry. A 2D axisymmetric analysis allows a finer mesh without huge computational requirements. In this case, all the elements correspond with Quadratic Serendipity elements, whose the maximum size has been defined separately for each domain:

- **Transducer and bolt.** Free triangular elements with extremely fine size permit at least four elements in the narrowest parts of the plate.
- **Propagation medium.** The Shannon´s sampling theorem [15] comes with the idea of having at least two quadratic elements each wavelength to have a maximum error around 10%. In this case, the acoustic wave, with a frequency of about 27 kHz is propagating through air at -10ºC. According to [16], the sound speed in air at -10 ºC is 325.3 m/s. So, for a sound wave of 27 kHz, the wavelength is 12 mm, and the required maximum element size is 6 mm. In this case, in order to minimize the error, a maximum size of 3.5 mm has been chosen.
- **PML's.** The lateral and rear boundary are defined as PML's where mapped meshed are defined. In this case, more than 10 elements along the thickness of the PML have been defined to assure that the acoustic energy vanishes when incising here.

The final mesh has more than 37000 elements, with an average quality of 0.9 over 1.

The study of this simulation corresponds to a Frequency Domain study at the frequency of 27199 Hz, which is the operational frequency of the radiator.

Simulation Results

The first simulation consists on the determination of the most efficient separation between the circular radiator and the samples. A parametric analysis for different values of this separation has been carried out.

The decision of the most efficient separation between radiator and samples comes from the calculation of the acoustic pressure existent in the area where the samples are placed (highlighted in red in Fig. 4).

Integrating the acoustic pressure obtaining along this line for each simulation, we can define the most efficient configuration. The results are presented in Fig. 5. According to this, the most efficient separation between the radiator and the food samples is about 19 cm. So, this is the separation considered for the experimental determination of the acoustic field inside the dehydration chamber and for the future food dehydration experimental campaign.

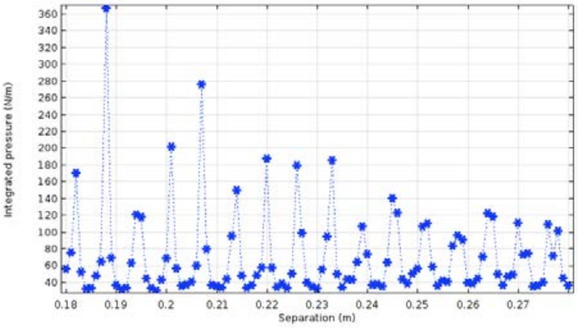


Figure 5. Integrated acoustic pressure (N/m) for each separation between radiator and samples.

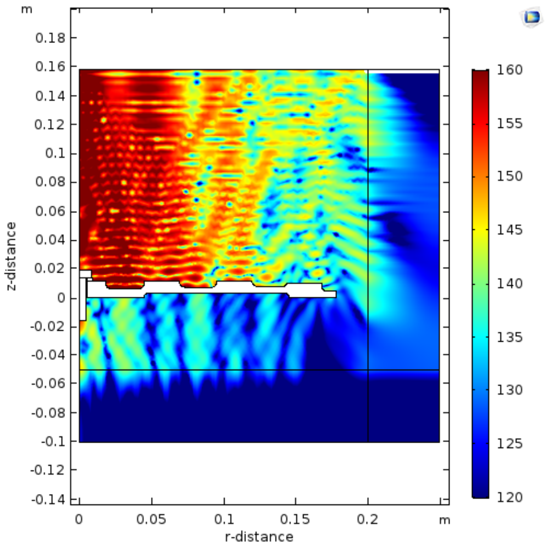


Figure 6. Ultrasonic field generated by the radiator inside the dehydration area (dB).

The ultrasonic field generated by the radiator, working at its operational frequency, inside the dehydration area is presented in Fig. 6, while the pressure distribution in the area where the samples are placed is presented in Fig. 7. The ultrasonic field obtained has a very high energy concentration, with amplitudes higher at the axis and in the central area of the basis where the samples are placed. The shape of the ultrasonic field is consequent with the observations by Beranek regarding the acoustic behavior of circular radiators following Bessel functions. The amplitude of the ultrasonic pressure obtained in this area reaches up to 160 dB in some places.

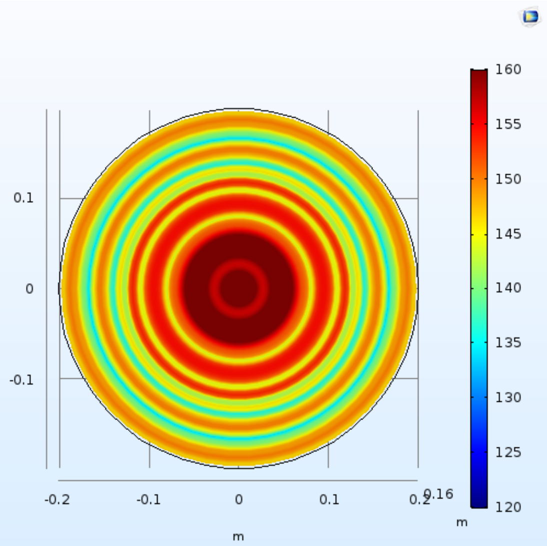


Figure 7. Pressure distribution at the basis (dB).

This numerical simulation will be validated by an experimental campaign to determine the ultrasonic field inside the dehydration cabinet, as presented in the following section.

Experimental validation

The validation of the numerical results presented in the previous section has been done by the experimental characterization of the acoustic field generated by the APU transducer with the stepped circular radiator.

The axisymmetric behavior of the transducer and the neglecting of the effects of reverberation inside the drying cabinet permit the simplification of the measurements to a plane delimited by the axis of the transducer, a radius of the radiator and the basis where the samples are placed. The experimental determination of the ultrasonic field has been done using a 1/8’’ microphone GRAS 40DP, connected to a signal adapter B&K NEXUS 2690 that supplies the polarization voltage of 200 V to the microphone, necessary for its correct performance. The NEXUS system is connected to a PC by a RS232 series port. The measurements are sent to an oscilloscope TEKTRONIX MDO3024 and then to the PC, where they are processed.

An ultrasonic controller allows the APU transducer to operate at the desired mode, even if its associated resonance frequency displaces slightly (mainly to lower frequencies). In this case, the APUT works in a mode with seven nodal circles at a frequency around 26 kHz. The electric power supplied in this experiment is 50 W.

A power amplifier supplies the required power without overloads in the excitation system. And, finally, an impedance matching unit adapts the impedance of the electric system to the impedance of the transducer, which is about 600 Ω in resonance.

The APUT is placed inside the freeze drying cabinet, where dehydration experiments are carried out.

The acoustic measurements have been done considering an axisymmetric behavior of the system, measuring the acoustic pressure in two different planes covering the area between the axis, radiator and basis. Different measurements have been done for each plane, obtaining a mean value.

Each plane has dimensions of 20x19 cm, in which a mesh has been defined, with measurement points separated 4 mm in both directions, axial (Z) and radial (R). The APUT works in the desired mode with 7 nodal circles at around 26 kHz. This implies that the acoustic wave has a wavelength higher than 13 mm. A mesh with 4 mm between measurement points guarantees at least three points each wavelength. Each measurement lasts 15 s, obtaining a linear average for the whole period in each measurement.
The measurement system is composed by a trolley that leans on the existing metallic profiles and which allow horizontal displacements. Another trolley hangs from the horizontal one, allowing vertical displacements. At the bottom of the vertical trolley, a stepper motor (McLennan 23HSX-206) is placed to allow the vertical displacement of the trolley. A horizontal arm is bolted at the bottom of the vertical trolley and the microphone is stuck at the end of this arm. The measurement system is presented in Fig. 8.

The measurement plane mentioned previously had a surface of 20x19 cm. Considering that the closest the microphone could get to the radiator was 4 cm, the effective measuring surface was 20x15 cm. This implies a mesh with almost 2000 measurement points (1989 points).

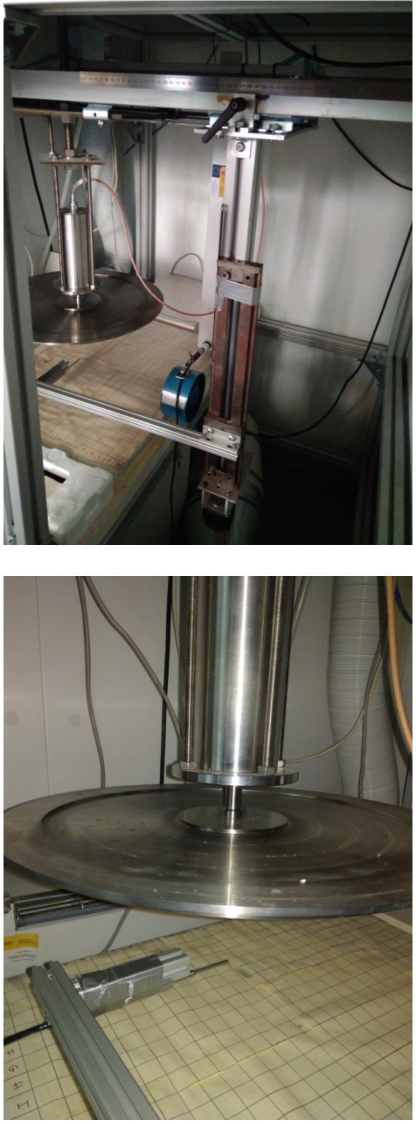
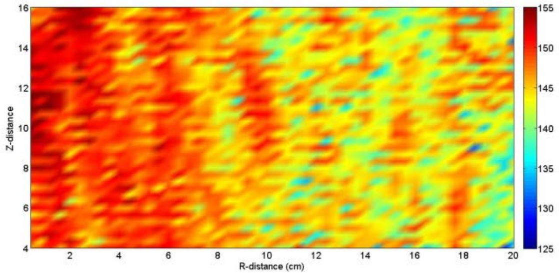


Figure 8. System for the acoustic measurements

The acoustic distribution in an axisymmetric plane, obtained experimentally for a power supply of 50 W, is presented in Fig. 9.

It can be observed how the acoustic energy is concentrated at the axis of the radiator, but with levels over 140 dB in almost the whole area. The experimental results obtained after the measurement campaign and presented in Fig. 9 validate the numerical model whose results are presented in Fig. 6, in terms of distribution of the acoustic energy.



Conclusions

The use of power ultrasounds as an aid in freeze drying has been proved to be efficient in terms of acceleration of the process.

An APU transducer with a stepped-grooved circular radiator, placed inside the dehydration chamber, generates a high-intensity ultrasonic field with the desired pressure distribution.

The analysis of the ultrasonic field generated inside the chamber has been carried out using the Solid Mechanics and Pressure Acoustic interfaces of COMSOL Multiphysics®, and validated by means of an experimental campaign.

The position of the APU transducer has been optimized at a distance of 19 cm from de samples, obtaining a sound pressure level higher than 140 dB in the whole volume of interest.

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Acknowledgements

This work has been supported by the project DPI2012-37466-C03-01 funded by the Spanish Ministry of Economy and Competitiveness.