

**AN INCLINED STEPPED PLATE TRANSDUCER
FOR ULTRASONIC APPLICATIONS**
NGHIÊN CỨU THIẾT BỊ CHUYỂN ĐỔI SÓNG SIÊU ÂM DẠNG TẦM BẬC
ĐỐC CHO CÁC ỨNG DỤNG CÔNG NGHIỆP

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ABSTRACT

A desire of ultrasonic devices with large working surfaces for industrial applications has drawn considerable attention from researchers. Many extensive radiators have been proposed and developed for various applications in the last few decades. However the design methodology for those devices is still a troublesome process and only works with some traditional profiles. In this research, an effective design method of a new i-stepped plate ultrasonic transducer is developed by using a genetic algorithm optimization scheme and finite element analyses. A possible application of food dehydration to dry heat sensitive materials and high-quality dry products has been recommended. Prototypes of the transducer are fabricated by a numerical control machining process. The effect of the ultrasonic field generated by the proposed design is investigated via a drying experiment of carrots.

Keywords: *i-stepped plate, high-intensity ultrasonic, transducers, extensive radiators, genetic algorithm.*

TÓM TẮT

Nhu cầu sử dụng các thiết bị phát sóng siêu âm có bề mặt phát sóng lớn dùng trong các ứng dụng quy mô công nghiệp đang thu hút rất nhiều sự quan tâm của các nhà nghiên cứu. Đã có rất nhiều thiết kế của các tấm phát xạ mở rộng được đề xuất cho nhiều loại ứng dụng khác nhau trong những thập kỷ vừa qua. Tuy nhiên quy trình thiết kế cho những thiết bị này vẫn còn khá phức tạp và hầu như chỉ tập trung vào các biên dạng truyền thống. Bài báo này đề xuất phương pháp thiết kế cho một thiết bị phát sóng siêu âm dạng tấm bậc dốc sử dụng thuật toán tối ưu hóa di truyền kết hợp phương pháp phân tích phần tử hữu hạn. Một ứng dụng cụ thể cho thiết bị dùng để sấy các loại thực phẩm khô có giá trị cao và tương đối nhạy cảm với nhiệt độ cũng đã được đề xuất. Mô hình thử nghiệm của thiết bị được chế tạo bằng máy gia công điều khiển số. Cuối cùng hiệu quả làm việc của thiết bị phát sóng siêu âm được thử nghiệm cho ứng dụng sấy carot.

Từ khóa: *Tấm bậc dốc, siêu âm năng lượng cao, thiết bị chuyển đổi sóng âm, tấm phát xạ mở rộng, thuật toán di truyền.*

1. INTRODUCTION

The increasing need for high displacement amplification and simple ultrasonic transducer in various industrial applications has drawn considerable

attention from researchers recently. These applications include the atomizers [1], welding devices [2], wire bonding [3], ultrasonic motor [4], food preparation [5] and so on. A traditional structure of an

ultrasonic transducer consists of three main parts, the back metal block, the piezoelectric elements and the horn. The horn acts as a mechanical amplifier where stepped horn is believed to possess the highest displacement amplification among classic profiles.

Scholars are working endlessly to find new horn profile with higher displacement amplification for their specific applications. Wang et al [6] presented a Bezier-profile horn which is a compensation between high displacement magnification of a stepped horn and low stress distribution of a Catenoidal horn. Iula et al. [7] proposed an ultrasonic horn vibrating in flexural mode instead of extensional mode. Its displacement amplification is about 50% higher than that of the stepped horn.

In some industrial applications such as food dehydration, one may expect for devices with large ultrasonic field beside the high vibration amplitude. Power ultrasonic transducers with extensive radiators have been developed by Gallego-Juarez and his group for many years [8]. The concept of combining a stepped horn vibrated in the extensional mode and an extensive plate resonated in its flexural mode helps them successfully solve the task given by industry. Stepped profile plates are the common design for their transducers. However, the high stress occurring near the abruptly changing section of this profile requires the usage of high strength metal alloys for the fabrication.

In this research, we developed a new inclined stepped profile plate or i-stepped plate for short which could reduce stress concentration. The optimal design of a high-intensity ultrasonic transducer with extensive radiator for food dehydration application is found by computational

modeling and optimization procedure. Prototypes of the transducer are fabricated by a numerical control machining process. The effect of the ultrasonic field generated by the proposed design is investigated via a drying experiment of carrots.

2. TRANSDUCER AND RADIATOR DESIGN

It is a critical challenge to generate ultrasonic energy in fluids due to the low specific acoustic impedance and high absorption of the medium [8]. Hence an extensive radiator is the key component to obtain an efficient ultrasonic transmission and to produce high pressure levels in ultrasonic dehydration application. Fig. 1 schematically shows a basic structure of an ultrasonic transducer with an extensive radiator. A Langevin transducer normally constituted by an even number of piezoelectric disks in a sandwich configuration is used to drive a solid horn. This horn which is vibrated in its extensional mode functions as a mechanical amplifier. The longitudinal vibration is successively converted to flexural vibration of an extensive radiator. In order to increase the ultrasonic field, it is suggested that the work-face area of the plate should be as large as possible. An extensive surface also helps to increase the radiation resistance in fluidic environment [9]. This is one of a key requirement to offer for a good impedance matching between the electrical input energy and the ultrasonic output work done.

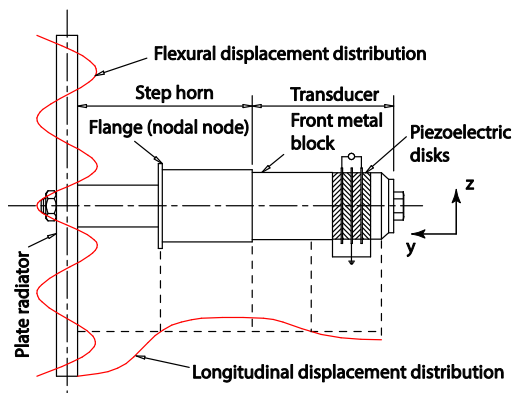


Figure 1. Schematic of a transducer with an extensive radiator.

The mechanical amplifier could be in any classical shapes such as exponential, stepped, sinusoidal, conical, catenoidal [10] or new profiles which were recently developed such as Bezier profile [6] or nonrational B-spline profile [11]. Of all designs, stepped horn provides the largest magnification amplitude and is the most popular profile used in industry due to its easy design, fabrication and modification [8]. The total length of a step horn can be calculated as following:

$$L_0 = \frac{C_t}{2f_0} = \frac{\lambda}{2} \quad (1)$$

where C_t, f_0 are the velocity of sound propagating inside the material and the vibration frequency, respectively.

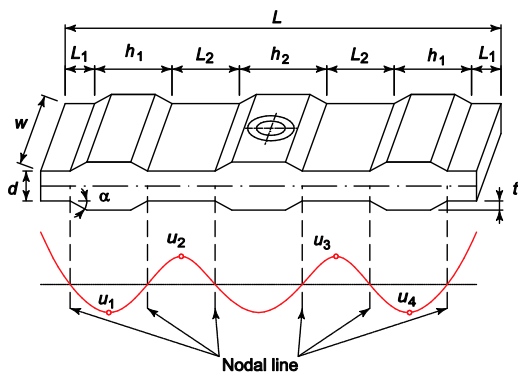


Figure 2. Schematic for the design of a stepped horn (a) and an inclined stepped plate (b)

One of the most difficult tasks is to design an extensive radiator plate which vibrates flexurally in one of its non axisymmetrical modes at the same natural frequency of the stepped horn. The design of the extensive radiator could be either a flat plate [5] or a stepped plate [9]. However an extensive flat-plate radiator showed a poor directivity pattern due to counter-phase vibrating surface elements on two sides of the nodal lines [9]. Meanwhile the high stress occurring near the abruptly changing section of the stepped-profile plate renders it unfavorable. High strength metal alloys are normally required to fabricate this type of plate. This research proposed a new *i*-stepped plate transducer design which could help release stress concentration. Fig. 2 shows the profile of the new plate which could be designed to vibrate in its flexural mode. The purpose of the step (t) on the plate is to prevent the phase cancellation when it is vibrated in its flexural modes. The thickness of the step should be half a wavelength of the sound propagating in the drying medium [12] whilst the slope angle (α) is a new parameter for the design of the plate.

Before implementing the optimization of any design, the general dimensions of the plate should be defined. In this research, we choose the overall length (L) and width (w) of the plate. Any variation of the thickness (d) of the plate will change its mode shape frequencies. The larger the thickness is, the larger the natural frequency of the plate could be obtained. In most industrial applications using the extensive radiation plates, large surface area is always expected. However, if the surface is enlarged, thickness must be increased to maintain the working frequency. One possible solution is the usage of high mode of vibration. Therefore this thickness should be constrained in the

appropriate range. Finally, optimization parameters for the i -stepped plate include thickness (d) of the plate, width (h_i), space (L_i), and slope (α) of the step.

The profile of the i -stepped plate is found by using the same optimization procedure developed by Wang et al. [6]. The non-dominated sorting genetic algorithm [13] is applied to the optimization of the transducer profile. The algorithm is suitable for solving constrained multi-objective problems.

In the optimization process, initially, the working frequency (f), the length of the plate (L), the thickness of plate step (t) and geometry parameters of the stepped horn are specified. An assembly of the horn and an arbitrary profile of the plate is automatically built via Matlab codes. The whole structure is then input into a finite element program to run a modal analysis to find the appropriate mode shape. The objective functions of the optimization problem are

$$\text{Min } |f - f_0| \quad (2)$$

$$\text{Min } |u_1 - u_4| \quad (3)$$

$$\text{Min } |u_2 - u_3| \quad (4)$$

where f_0 is a non axisymmetrical flexural mode frequency of the i -stepped plate, u_i are the vibration amplitudes found from the displacement distribution curve in Fig. 2. Better symmetry pattern could be expected with the objective functions described in Eq. (3) and Eq. (4).

Due to the geometry complexity, the modal frequency f_0 of the ultrasonic transducer cannot be calculated analytically. Finite element analysis by a commercial software ANSYS is employed to perform the computations.

3. ANALYSES

3.1 Finite element model

In order to obtain accurate model frequency and displacement solutions for the transducer, finite element analysis are carried out. The displacements in all direction of the nodes on the circumference of the nodal flange are constrained. A voltage is applied to the piezoelectric disk for harmonic analyses of the whole structure.

In this investigation, the piezoelectric disk, front and back metal blocks of the Langevin transducer, the stepped horn and the plate radiator are assumed to be linear elastic materials. A lead zirconate titanate material (PZT-5H), mild steel (SS 41), and an aluminum alloy (AA 7075-T6) are used for the piezoelectric disk, the stepped horn, and the i -stepped plate material, respectively. Their material properties are listed in Table 1.

Table 1. Material properties

Material	Property	
AA	Young's modulus (GPa)	71.7
7075-T6	Poission's ration (μ)	0.33
[12]	Density (kg/m ³)	2810
	Velocity of sound (m/s)	5030
SS 41	Young's modulus (GPa)	210
[6]	Poission's ratio (μ)	0.3
	Density (kg/m ³)	7800
	Velocity of sound (m/s)	5188

3.2 Numerical analysis

In the genetic algorithm optimization process, the number of generation, N , is set to be 40, and the population of each generation is taken as 20. The working frequency f is set to be 20.0 kHz. In the experiments, the fabricated radiator is driven by a Langevin transducer. The available

commercial Langevin transducer is purchased from a local vendor. The working frequency of the Langevin transducer is a known and fixed parameter.

The enlargement of the radiation surface area requires the usage of a higher mode of vibration [12]. The plate can be vibrated at any flexural mode shapes. However, in order to run the design optimization, one mode shape has to be chosen. In this research, we choose mode 8 as the design mode shape. Therefore a modal analysis of each population in the optimization process is performed in order to find its 8th flexural modal frequency f_0 . The extensive radiator is designed to have this frequency equal to the working frequency of the transducer.

By using the above optimization algorithm, an optimum design of the transducer is found whose parameters are described in Table 2.

Table 2. Optimum designed parameters

Parameters	Value (mm)	Parameters	Value (mm)
L	260.00	h_1	46.15
w	125.00	h_2	52.00
d	17.82	L_1	17.55
t	5.44	L_2	40.30

The stepped profile helps to improve the performance compared to a flat surface. Harmonic analysis of a flat-profile plate and *i*-stepped plate with the same dimensions, mode shape and external vibration input is undertaken. Their distributions of displacement are shown in Fig. 3. The added mass to the surface of the plate improves its displacement significantly. However, the present of steps also raises a challenge for the design of the extensive radiator due to maximum concentrated stress. High fatigue

resistance material is a common requirement for the fabrication of such transducer. Instead of using a sharp step, an inclined step in this design help to smooth the stress distribution therefore less expensive materials can be used for the fabrication.

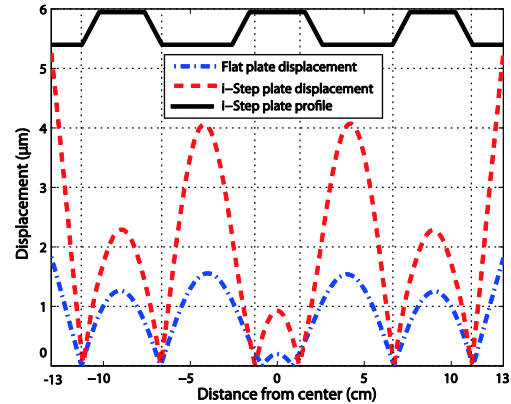


Figure 3. Displacement distribution of flat plate and *i*-stepped plate

The complexity of the structure and its operation in a high power ultrasonic system inherit highly nonlinear vibration characteristics. Modal interaction [14] and combination resonance [6] are the common problems that may cause failure to the operation of the transducer. In order to characterize the performance of the transducer, any mode combinations or modal interactions are carefully considered to implement the design modifications.

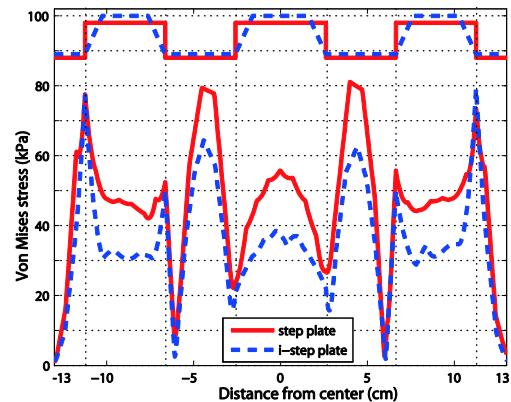


Figure 4. Stress distribution of the stepped plate and the *i*-stepped plate transducer

Under high frequency working condition, failure due to concentrated stress is always a considerable concern. Von-Mises stress analysis with stepped and i-stepped profiles characterizes the stress reduction effect of the new design. Fig. 4 shows that the

i-stepped plate has lower stress distribution in comparison to the stepped plate vibrating with the same frequency. Three-dimensional finite element models are also built for these transducers (Fig. 5). The same results are also observed.

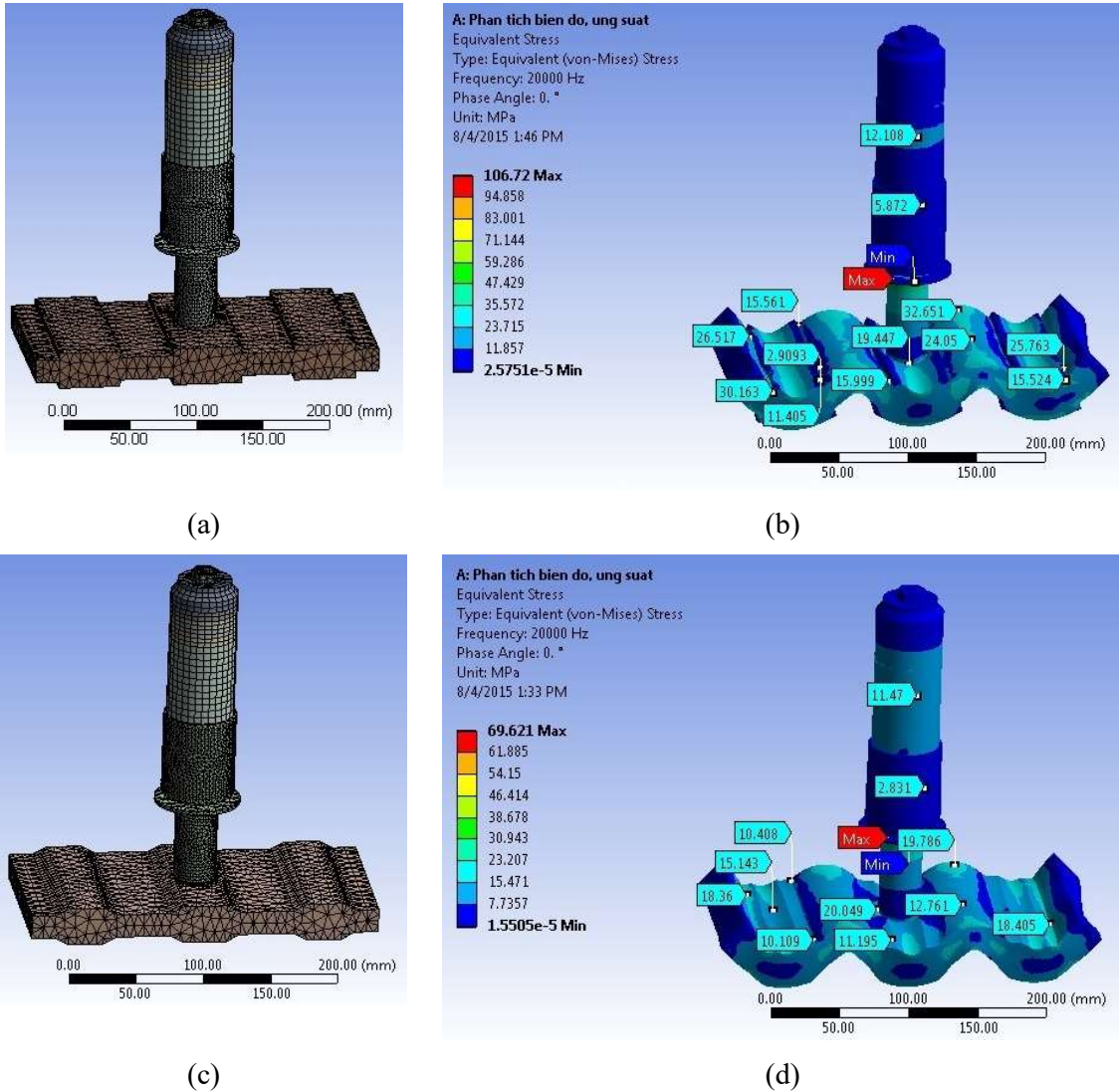


Figure 5. 3D stress simulation of the stepped plate (a,b) and the i-stepped plate transducers (c,d)

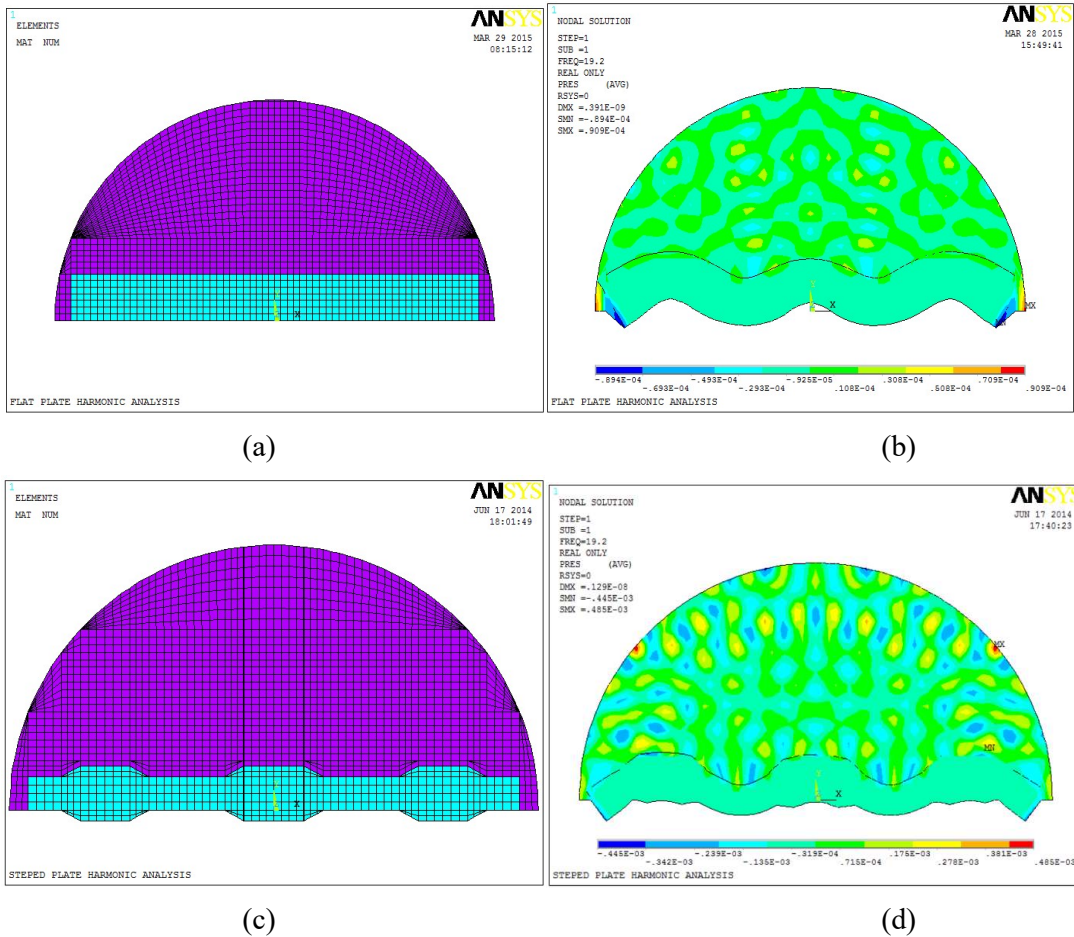


Figure 6. FEM mesh and fluid–structure analysis for flat plate and *i*-stepped plate

In ultrasonic assisted dehydration applications, pressure variation, oscillating velocity and micro-streaming affect the solid-gas interface therefore it would improve the water transfer rate from the solid surface to the air medium [15]. Coupled fluid–structure analysis is undertaken to investigate the acoustic field and scattering pressure generated by different transducer profiles. The schematic mesh of flat plate and *i*-stepped plate are shown in Fig. 6(a) and Fig. 6(c). Both plates are enveloped inside a fluid medium (air) which is constructed by a half circle of radius, $r = 140\text{mm}$, from the center of the plate. The infinite acoustic elements (FLUID129) used along the circular boundary can absorb the pressure waves. This boundary condition simulates the outgoing effects of a

domain that extends to infinity beyond the acoustic field modeled by finites elements of FLUID29. A 2D four-node structural element (Plane182) is used for the plates. The primary goal of this analysis is to model the acoustic field and hence to evaluate the variation of the air pressure above the plates. It can be seen in Fig. 6(b) and Fig. 6(d) that the *i*-stepped plate produces larger pressure variation which would be an important criterion for the dehydration of products in drying application.

4. FABRICATION AND EXPERIMENTS

In order to verify the effectiveness of the proposed transducer, prototypes of a flat plate and an *i*-stepped plate were fabricated by numerical control machining. Subsequent polishing process is undertaken to eliminate

any defects on surfaces of the radiation plates. Experiences showed that any micro crack appeared on the surface of the as-fabricated prototype would quickly propagate when it was operated. Dimensions of the prototype are based on the finite element analyses. Fig. 7 are photos of the fabricated transducers. Upon the operation of the transducer, they were tuned to the machine frequency such that it drew minimum current in the no-load condition.

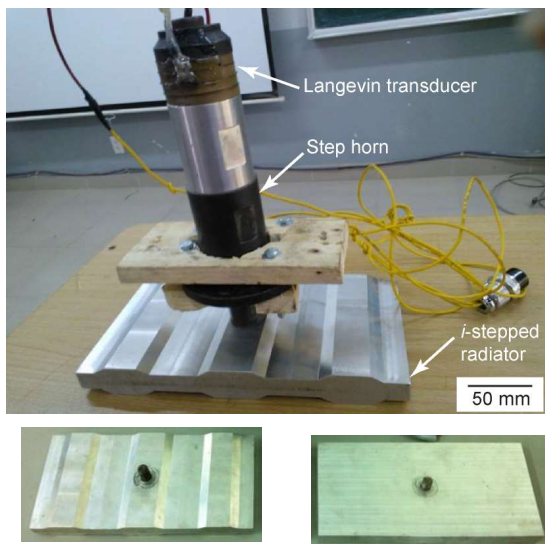


Figure 7. Fabricated prototypes

The application of air-borne ultrasonic energy for drying materials has been described in previous studied [16-18]. In a convective drier assisted by power ultrasound, the effect of hot-air flow is enhanced by using high intensity sonic and ultrasonic waves. Most recent researches focused on investigating the water transport mechanism and drying kinetics for food dehydration in order to apply this technology in large-scale industrial plants. The current study aimed to modify the stepped plate to enhance its reliability in dehydration applications. The fabricated *i*-stepped plate is assembled to a convective drying system to quantify the effect of acoustic drying.

An experimental set-up is shown in Fig. 8. The equipment consists of an aluminum *i*-stepped plate which is driven by a piezoelectrically activated vibrator (20.0 kHz). The ultrasonic transducer is clamped and mounted under a thermal insulation drying chamber. AC voltages were applied to the Langevin transducer by an ultrasonic generator that works like a nearly ideal voltage source. Electrical parameters (voltage, current, frequency, phase, power) were measured and controlled by a developed program written in LabVIEW (National Instruments, Austin, TX, USA). A controlled velocity and temperature air is blown into the chamber from a hot air generator. A digital balance (METTLER TOLEDO, RW00-1220-301) is used to weight the samples at preset times.

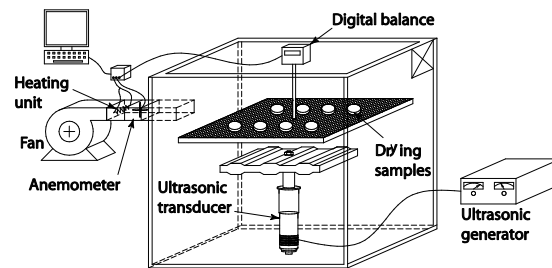


Figure 8. Experimental setup for the ultrasonic dehydration system

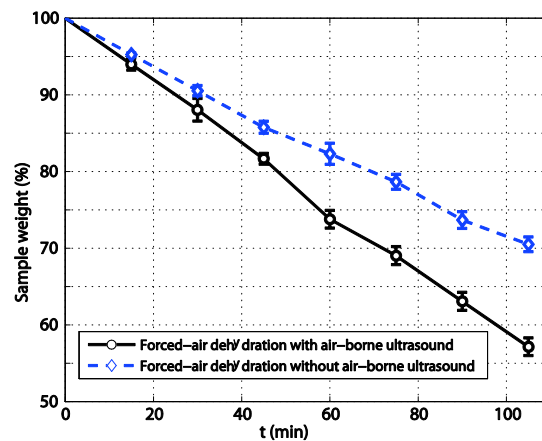


Figure 9. Experimental results of dehydration process with and without ultrasonic power.

In this experiment, carrots of cylindrical shape with the same diameter and thickness of 30 mm and 2 mm, respectively, were prepared. Each batch consists of eight slides with an initial weight of 16.8 grams. Those samples were put into a tray with a weight of 78.6 grams. The total weight of samples and tray is 95.4 grams. Drying experiments were carried out at 40⁰C and 2 m/s for the air flow temperature and velocity, respectively. Two batches of carrots were dried with and without using the ultrasonic power. Each batch was conducted at least in triplicate. Moisture content of samples was measured by weighting them at fixed intervals of 15 minutes. A summary of the results is presented in Fig. 9. The evolution of the sample weight during the drying process assisted by power ultrasound and without ultrasound confirmed the strong influence of the acoustic energy.

5. CONCLUSIONS

This research has presented an effective method for the design of a new *i*-stepped plate ultrasonic transducer. The radiator is resonated in flexural mode that is activated by an extensional vibration from a solid stepped horn. An acoustic analysis has proven that the optimum design could also provide a larger air pressure variation in the drying medium. Prototypes of the transducers have been fabricated and tested in a drying experiment to verify the effectiveness of the proposed design. With the new design of the extensive radiator the problem related to stress concentration could be reduced and less expensive metal alloys could be used for their fabrication.

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