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Investigation of Corner Radius Effect in a Piezoelectric Ultrasonic Microcontainer to Improve Nanoemulsion Stability

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ABSTRACT: Utilizing ultrasonic waves for nanoemulsion preparation is one of the most important research topics related to the pharmaceutical, food, mechanical and chemical engineering industries. The number and arrangement of the piezoelectric ceramics, the frequency of their excitation and the fillet radius of container's internal edges are effective parameters in the design and optimization of an ultrasonic bath which cause either resonance or cancelation of the waves. In this paper, using COMSOL Multiphysics software, the simulations of the edge fillet radius effect in four different piezoelectric ceramics layouts of an ultrasonic microcontainer were performed in 36 possible configurations. In this way, the edge fillet radii and excitation frequencies of piezoelectric ceramics are simulated in zero, 2.5 and 5 mm, and 20, 200 and 300 kHz respectively. It has been shown that although sharp edges elimination leads to improve acoustic energy density at all frequencies, however, arrangements which have more piezoelectric ceramics or lower frequencies are affected more. Experimental works were performed to prepare nanoemulsions in two modes of ultrasonic bath: with and without filleted edges. While approving the simulation outputs, the experimental results showed that the use of ultrasonic bath with filleted edges increased the stability of the nanoemulsion.

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1- Introduction

The use of high-frequency waves in engineering applications has been reported since the beginning of the 20th century [1]. Nowadays, ultrasonic irradiation has become one of the most widely used methods in different fields such as imaging and damage investigation [2-4], heat transfer [5-6], machining and metal forming [7-9], particle removal and cleaning [10-13], as well as the industries related to oil and gas [14], medicine and pharmaceuticals [15-16], and food and dairy [17].

Fabricating materials and preparing emulsions with nano-size dispersed phase (nanoemulsions) in Ultrasonic Bath (UB) have been used by a large number of researchers [18]. In addition to the shape and dimensions, quantity and arrangement layout of piezoelectric ceramics (PZTs), and the stimulation frequency play an important role in the performance of UB. On the other hand, increasing the possibility of occurring acoustic cavitation, as one of the criteria of UB performance, depends on the local acoustic pressure values and the uniformity of its distribution. In this regard, PZTs arrangement is considered as one of the most important criteria in the UB design, which has been conducted until now [19]. The present study aimed to evaluate the effect of edge fillet radius on the distribution of acoustic pressure and the acoustic energy density in order to improve the efficiency of nanoemulsion preparation in a micro container, through simulation and experimental investigations.

2- Methodology

In this study, the simulations are conducted by using COMSOL Multiphysics, finite element software, as well as its frequency domain acoustic pressure module (acpr). The simulated UB is designed as a cube with 8000 mm3 volume, which is surrounded by six hard type walls, without any free surface. In this research, 36 simulation states have been considered, through which across different frequencies (20, 200, and 300 kHz), four arrangements have been used (see Fig. 1). Evaluation of each arrangement has been done with filleted edges of zero, 2.5, and 5 mm.

3- Results and Discussion

The most appropriate design for a UB can be determined by comparing the volumetric average of the acoustic energy densities (Eq. 1) in different mode, which represents the amount of acoustic energy released in a cubic meter volume. Table 1 represents the acoustic energy density in 36 states.

$$\overline{E} = \frac{1}{V_0}\int_{V_0}\frac{1}{2}\left(\frac{P^2}{\rho c^2}\right)dV \qquad (1)$$

Consequently, at three simulated frequencies, an increase in edge fillet radius results in increasing the acoustic energy

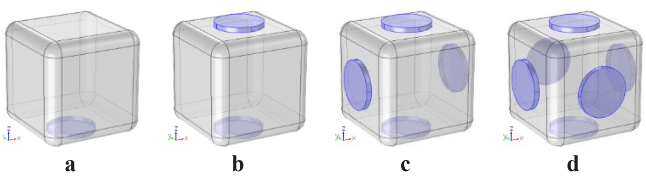

Fig. 1. Four layouts piezoelectric transducers arrangement

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Table 1. The acoustic energy density of 36-states (Pa)

Main frequency (kHz)	Edge fillet radius (mm)	Layout			
		First	Second	Third	Fourth
20	0	6.74E+3	9.07E+3	3.81E+4	8.52E+4
	2.5	1.26E+4	2.02E+4	5.45E+4	1.01E+5
	5	7.90E+4	2.00E+5	7.72E+5	5.29E+6
200	0	7.14E+4	2.20E+5	5.86E+5	5.49E+6
	2.5	5.13E+5	1.20E+6	8.29E+6	3.84E+7
	5	3.76E+6	8.85E+6	8.40E+7	2.63E+8
300	0	1.31E+6	3.23E+6	1.43E+7	1.78E+8
	2.5	3.82E+6	6.50E+6	4.12E+7	7.96E+8
	5	1.05E+7	5.19E+7	5.20E+8	2.26E+9

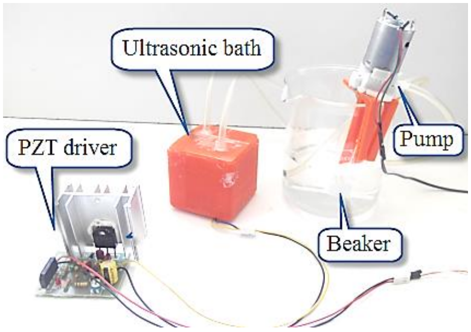

Fig. 2. Experimental setup

density. In addition, due to the wavelength effect, it appears more effective at lower frequencies. Therefore, the highest growth in the acoustic energy density is related to the fourth-layout states at 20 kHz frequency.

Experimental tests were carried out in two modes of regular ultrasonic bath and a filleted-edges ultrasonic bath. Fig. 2 demonstrates a schema of the equipment used for the experimental tests. The total volume of the solution has been 300 ml with a concentration of 5% without any stabilizer, in which only distilled water and refined olive oil have been used.

As water and oil are two insoluble fluids and since they separate off each other over time, measuring the turbidity of the nanoemulsion over time is one of the ways for investigating the extent of oil-in-water stability. One of the most common ways of investigating the effect of time is the use of centrifuge through which the gravity exerted to the object is enhanced by up to several hundred times. In this way, the samples turbidities, after each mode, were measured during 30 minutes of centrifugation (across six 5-min stages) at around 4400 rpm in order to determine the stability of oil nanodroplets. Fig. 3 and Table 2 demonstrate the results.

As can be acquired, the extent of turbidity of the nanoemulsions prepared in the filleted edge UB is larger than that of regular UB.

4- Conclusions

The present study aimed to evaluate the effect of edge fillet radius in an ultrasonic microcontainer with four arrangements of piezoelectric transducers on the distribution of acoustic pressure and acoustic energy density. By using COMSOL

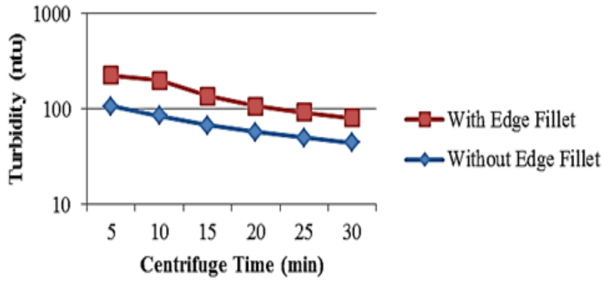

Fig. 3. Turbidity of prepared nanoemulsions in ultrasonic bath in two states (ntu)

Table 2. Turbidity of prepared nanoemulsions in ultrasonic bath in two states (ntu)

UB mode	Centrifugation time (min)					
	5	10	15	20	25	30
Regular	225	201	136	106.6	92.3	80.6
Filleted edge	107.7	84.7	67.7	57.3	49.7	44.3

Multiphysics, as finite element software, simulations are conducted by 36 states at different frequencies (20, 200 and 300 kHz), with three edge fillet radii (zero, 2.5 and 5 mm) and in four cubic microcontainer layouts. Based on the simulation results, increasing edge fillet radius leads to an increase in the acoustic energy density, as well as the level of the acoustic pressure distribution at all frequencies and layouts.

As well, the rate of increase in acoustic energy density due to an increase in edge fillet radius was negatively related to the excitation frequency . The maximum effect appeared in states had more PZTs and lower frequencies. Similarly, the results of experimental tests in two modes of with and without rounded edges also confirmed that the filleting has a positive effect on improving nanoemulsions stability.

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