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Investigation of Geometric Effect on the Ultrasonic Processing of Liquids

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INVESTIGATION OF GEOMETRIC EFFECT ON THE
ULTRASONIC PROCESSING OF LIQUIDS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfilment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Pavan Pasumarthi
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Accepted by:
Dr. Hongseok Choi, Committee Chair
Dr. Joshua Summers,
Dr. Rodrigo Martinez-Duarte
ABSTRACT

Ultrasonic processing of liquids is used in many engineering fields, from sonochemistry to material processing. Acoustic cavitation and acoustic streaming are the two key phenomena responsible for the ultrasonic processing applications. Both of them are non-linear effects of ultrasonic wave propagation in liquids and are extremely hard to characterize either analytically or experimentally. This meant that there is limited knowledge about the interactions between the various parameters that affect the extent of the acoustic cavitation and streaming generated during the ultrasonic processing of liquids. In the current study, it was hypothesized that the geometric configuration of the ultrasonic processing equipment has an effect on the resultant acoustic pressure field, which in turn affects the acoustic cavitation and the acoustic streaming flow.

Numerical modeling serves as a powerful tool to overcome the practical difficulties involved in experiments. Over the years, various finite element models have been developed to resolve the acoustic pressure field inside the ultrasonic processing cell. The majority of them have used a linear modeling of the Helmholtz equation with infinitely hard ultrasonic processing cell boundaries. In the current study, a non-linear numerical model was developed to resolve the acoustic pressure inside the ultrasonic processing cell. The viscous dissipation loss during the ultrasonic wave propagation is taken into account by replacing the general liquid material properties with complex material properties in the Helmholtz equation. The model developed was then validated with experimental results. An error analysis revealed that the simulation results show a mean error of about 33 %, with a maximum error of 78 % and a minimum error of 5 % in comparison with the experimental results. Following this, a method was introduced for the quantification of the acoustic cavitation zone size from the numerical modeling results of acoustic pressure field in the ultrasonic processing cell.
The acoustic cavitation zone size was used as the response variable and analysis of variance (ANOVA) was used to study the effect of different geometric parameters and identify their significance. A full factorial design with 27 orthogonal arrays was formed with three geometric parameters, diameter ratio to the probe diameter, immersion depth ratio to the probe diameter, and the liquid volume as three factors. Three levels of each factor, namely high, low and mid-point values were chosen based on a literature review. The values for the diameter ratio to the probe diameter are 1.25, 3.0, and 2.25 respectively. Similarly, 0.25, 3.0, and 1.625 for immersion depth ratio to the probe diameter and 20 ml, 200 ml, and 125 ml for volume. Based on the ANOVA results, it was determined that the ultrasonic processing cell diameter is the most significant of all the geometric parameters considered in this study. Parametric analyses involving these parameters was then conducted. The results show the variation of cavitation zone size with the change in the significant geometric parameters. In addition, the geometric configuration offering the largest acoustic cavitation zone size for a volume of 57 ml in the considered parameter range was determined.

Acoustic streaming is a second order non-linear effect of ultrasonic propagation and can be obtained using the acoustic pressure field values a in every time interval. The model with Navier-Stokes equations coupled to the non-linear transient acoustic wave equation will anticipate the acoustic streaming flow inside the ultrasonic processing cell. The acoustic streaming field model is then applied to the geometric configuration with parameters that give the largest cavitation zone size. It was found that a probe immersion depth of 2.54 cm would produce the maximum acoustic cavitation zone and a relatively uniform acoustic streaming flow in the ultrasonic processing cell with a diameter of 3.59 cm for processing 57 ml of liquid.

The experimental verification of the current study is performed for manufacturing metal matrix nanocomposites (MMNCs) using ultrasonic processing of the master nanocomposite with
carbon nanofibers with appropriately selected processing parameters, the area of pores in the nanocomposite was significantly decreased by 46.5% and a deviation of the hardness was also decreased by 46.0% due to further dispersion and distribution of the carbon nanofibers. The significance of this study lies in the formation of an understanding of non-linear acoustic phenomena in liquids and the development of a proper process design methodology for ultrasonic processing of liquids.
ACKNOWLEDGEMENTS

It is essential that I recognize a few of the many people who have contributed directly and indirectly in the completion of my research work. Firstly, I would like to thank my advisor Dr. Hongseok Choi for invaluable support for the last two years by offering guidance and the resources needed to complete this work. His patience and meticulousness has inspired me to become a better engineer and more importantly a better person.

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TABLE OF CONTENTS

ABSTRACT ................................................................................................................................. ii

ACKNOWLEDGEMENTS ........................................................................................................ v

LIST OF FIGURES ................................................................................................................... vii

LIST OF FIGURES (continued) ............................................................................................... ix

LIST OF FIGURES (continued) .............................................................................................. x

LIST OF TABLES ..................................................................................................................... xi

1. INTRODUCTION .................................................................................................................. 1

   1.1 Background ...................................................................................................................... 1

   1.2 Motivation and objectives .............................................................................................. 6

   1.3 Outline of the thesis ........................................................................................................ 11

2. NUMERICAL MODELING I: ACOUSTIC PRESSURE FIELD ............................................. 12

   2.1 Literature review ............................................................................................................ 12

   2.2 Constitutive Relations .................................................................................................... 15

   2.3 Modeling geometry ......................................................................................................... 16

   2.4 Boundary Conditions .................................................................................................... 18

   2.5 Study on the effect of boundary conditions .................................................................. 19

   2.6 Discretization ............................................................................................................... 20

   2.7 Modeling Parameters ..................................................................................................... 23

   2.8 Results and validation .................................................................................................... 24

   2.9 Characterization of cavitation zone .............................................................................. 26

3. DESIGN OF EXPERIMENTS FOR GEOMETRIC PARAMETER ...................................... 30
3.1 Analysis of Variance .......................................................... 30
3.2 Parametric Analysis............................................................ 34

4. NUMERICAL MODELING II: ACOUSTIC STREAMING .............. 45
   4.1 Literature Review ............................................................ 45
   4.2 Modeling ..................................................................... 46
   4.3 Modeling Parameters ...................................................... 47
   4.4 Results ..................................................................... 48
   4.5 Experimental Verification ............................................... 57

5. CONCLUSIONS AND FUTURE WORKS ................................... 63
   5.1 Conclusions .................................................................. 63
   5.2 Future work .................................................................. 64

6. REFERENCES ....................................................................... 65

7. APPENDIX I ....................................................................... 71
   7.1 ANOVA Data points ...................................................... 71
   7.2 Minitab Output .............................................................. 72
LIST OF FIGURES

Figure 1.1: Propagation of an ultrasonic wave ................................................................. 1
Figure 1.2: Evolution of a cavitation bubble. ................................................................. 4
Figure 1.3: Attenuation of the acoustic pressure .............................................................. 4
Figure 1.4: Acoustic cavitation based solidification processing for the dispersion and distribution of nanomaterials in a molten metal ................................................................. 6
Figure 1.5: Classification of processing parameters ........................................................ 7
Figure 2.1: Classification of numerical models for ultrasonic processing .................... 12
Figure 2.2: Axisymmetric geometric model ................................................................. 17
Figure 2.3: Boundary conditions for the inside wall of the surface are a) Hard boundaries b) Partially reflective boundaries ................................................................. 20
Figure 2.4: Unstructured meshing of the liquid domain .................................................. 21
Figure 2.5: Acoustic pressure fields for a) hard boundaries and b) partially reflective boundaries. ........................................................................................................ 22
Figure 2.6: Final model boundary conditions ................................................................. 23
Figure 2.7 Unstructured meshing of the liquid domain and the cell wall domain ............ 24
Figure 2.8 Acoustic pressure field calculated from numerical modeling ...................... 25
Figure 2.9: Validation of numerical model with experimental results from [35] .......... 26
Figure 2.10: Quantification of cavitation zone, for an example geometric configuration . 29
Figure 3.1: Further classifications of the geometric parameters ...................................... 31
Figure 3.2: ANOVA results from Minitab ..................................................................... 34
Figure 3.3: Equivalent diameter of the cavitation zone with varying the diameter ratio . 36
Figure 3.4 Reflections involved in ultrasonic wave propagation .................................. 36
Figure 3.5: Constructive interference ............................................................................. 37
LIST OF FIGURES (continued)

Figure 3.6: Destructive interference. ................................................................. 38
Figure 3.7: Divergence of an ultrasonic wave. ......................................................... 39
Figure 3.8: Cavitation zone size variations. ............................................................. 40
Figure 3.9: Equivalent diameter of the cavitation zone with varying immersion depth ratio. .... 42
Figure 3.10 Cavitation zone when Volume $= 57$ ml and $D/D_p=2.80$, $d/D_p=0.25$. ........ 43
Figure 3.11 Cavitation zone when Volume $= 57$ ml and $D/D_p=2.80$, $d/D_p=2.25$. ........ 43
Figure: 4.1 Acoustic streaming flow evolution A at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s. ................................................................................................................................. 49
Figure 4.2: Acoustic streaming, streamlines A at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s. ................................................................................................................................. 50
Figure 4.3: Acoustic streaming in water ....................................................................... 52
Figure 4.4: Acoustic streaming evolution in B at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s ................................................................................................................................. 53
Figure 4.5: Acoustic streaming, streamlines B at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s ................................................................................................................................. 54
Figure 4.6: Acoustic streaming evolution in C at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s ................................................................................................................................. 55
Figure 4.7: Acoustic streaming, streamlines C at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s ................................................................................................................................. 56
Figure 4.8: SiC micro particles and Carbon nanofibers. ................................................. 57
Figure 4.9: Ultrasonic system. ..................................................................................... 58
Figure 4.10: Schematic of the experimental setup. ......................................................... 59
Figure 4.11: Experimental setup ................................................................................ 60
LIST OF FIGURES (continued)

Figure 4.12: Disk mold for sample preparation .............................................................. 60
Figure 4.13: Samples produced during the experiment .................................................. 62
Figure 7.1 PARETO chart .......................................................................................... 73
LIST OF TABLES

Table 1.1: The three major experimental techniques available to characterize cavitation. .......... 9

Table 2.1: Studies concerning with the geometric effects of ultrasonic processing of liquids..... 14

Table 2.2: Parameters for the numerical model................................................................. 23

Table 2.3: Equivalent quantities for configuration in Figure 2.10. ...................................... 29

Table 3.1: 3 Factors and 3 levels selected for ANOVA. .................................................. 33

Table 3.2: Geometric parameter and immersion depth selected for total volume of 57 ml. ...... 44

Table 4.1: Geometric configurations selected for acoustic streaming modeling.................. 48

Table 4.2: Hardness data measured...................................................................................... 61

Table 4.3: Surface pore area measurements......................................................................... 61

Table 6.1: Data used for ANOVA. ....................................................................................... 71
1. INTRODUCTION

1.1 Background

Ultrasound is a sound wave with a frequency above 20 kHz, which is the upper limit of the audible frequency for humans. When sound propagates, the particles of the medium vibrate in the direction parallel to the wave motion. This process generates variation in pressure, known as the acoustic pressure. Figure 1.1 shows the representation of longitudinal ultrasonic wave propagation in a fluid and the corresponding acoustic pressure wave representation. There are two stages in an acoustic cycle, namely compression and rarefaction. The positive acoustic pressure is attributed to the compression, during which the fluid particles are packed closely. The negative acoustic pressure represents the rarefaction stage during which the fluid particles are loosely packed.

![Figure 1.1: Propagation of an ultrasonic wave.](image)
Ultrasound can broadly be classified into two fields based on the applications for which it is used: power ultrasound and diagnostic ultrasound [1]. Power ultrasound applications use ultrasound sources that operate in the frequency range of 20 kHz to 2 MHz. It is used in applications like sonochemistry, ultrasonic cleaning, ultrasonic machining, ultrasonic material processing and ultrasonic food processing. Diagnostic ultrasound operates in the frequency range of 2 MHz to 100 MHz. It is mainly employed in fields such as non-destructive testing, SONAR or sonography.

Ultrasonic processing of liquids comes under the classification of power ultrasound. Non-linear effects like acoustic cavitation and acoustic streaming accompany the propagation of an ultrasonic wave in liquids. These phenomena help in achieving several engineering goals across many fields. For instance, in the field of chemistry, mixing different chemical species or improving the reaction rates can be achieved by the ultrasonic processing [2]. The area of chemistry that deals with this is known as sonochemistry. Similarly, in ultrasonic cleaning, acoustic cavitation generated during the ultrasonic processing is used to remove micro sized particulate impurities from surfaces [3]. In material science, ultrasonic liquid processing is used for grain refinement and degassing. These above described processes need effective generation of acoustic cavitation and acoustic streaming, which are more prominent in the frequency ranges of power ultrasound (20 KHz- 2 MHz).

Acoustic Cavitation: The generation of new surfaces in a liquid under the effect of ultrasonic waves can be termed as ‘acoustic cavitation’ [4]. Surfaces here mean, the walls of the cavitation bubbles in a liquid. ‘New surfaces’ can be created, either by generation of new cavitation bubbles or by the expansion of existing micro sized seeds. Generation of new cavitation bubbles by ultrasound demands the acoustic pressure to be greater than the tensile strength of the liquid [5]. The tensile strength of the liquid here is defined as the minimum tensile
stress required to rupture or cavitate the liquid. In general, this is a large value and is rather difficult to achieve. For water, it is around 120 MPa [6]. However, it has been reported that the acoustic cavitation was observed at a much lower acoustic pressure values [7]. This is caused by the existence of the micro sized bubbles in liquids known as the seed nuclei [4]. Under the presence of an ultrasonic field, the gas from the surrounding liquid fills the volume of the cavitation bubble. This occurs by a process known as rectified mass diffusion, which is the mass transfer of the dissolved gases across the wall of the cavitation bubble. During the compression cycle, the gas pressure inside the cavitation bubble is greater than the surrounding liquid pressure, this results in a mass transfer from inside the cavitation bubble to the outside. Conversely, during the rarefaction cycle the dissolved gas from the liquid is transferred into the bubble. During one complete acoustic cycle, the net flow of gas across the cavitation bubble is not zero. This is caused by the fact that the surface area of the cavitation bubble is different during the compression and rarefaction cycles. During the compression cycle, the cavitation bubble is smaller than its equilibrium size. Equilibrium size refers to the size of a cavitation bubble when the gas pressures inside and outside the cavitation bubble wall are equal (this leads to a stable cavitation bubble). During the compression cycle, there is less surface area available for the gas to be diffused. Conversely, during the rarefaction cycle the cavitation bubble is larger than its equilibrium size, which makes more surface area available for the gas to be diffused into the bubble. This net gas transfer results in an increase of size of the cavitation bubble as shown in Figure 1.2. This growth continues until the bubble reaches an unstable stage where it implodes. The implosion of a cavitation bubble produces a hotspot that is accompanied by extreme conditions like high temperature and pressure [8]. Temperatures up to 5000 K and pressures around 1000 atmospheres were reported, however, these hotspots are short lived as they have rapid cooling rates, usually above \(10^{10}\) K/s [9].
Acoustic Streaming: There is a generation of flow in a liquid during the ultrasonic processing. This is the other non-linear effect, which is caused by the attenuation of the ultrasonic wave. The attenuation of the acoustic pressure can be seen in Figure 1.3. This causes a loss of acoustic momentum, which is transferred to the fluid, resulting in a jet-like flow.
Both these phenomena are highly non-linear and are extremely difficult to characterize or measure experimentally. This creates a gap in knowledge about the interactions between different parameters involved in the ultrasonic liquid processing and how they effect the effectiveness of the process. In the current study, numerical modeling is used to investigate these effects, more specifically the effect of geometry in the effectiveness of ultrasonic processing in generating acoustic cavitation and acoustic streaming. In addition, the developed numerical model is applied to the manufacturing of metal matrix nanocomposites (MMNCs). Conventional liquid based methods have a difficulty in the dispersion of nanomaterials caused by the intense van der Waals forces of attraction between the nanomaterials and their high surface energies. However, the ultrasonic cavitation based solidification processing has proved to be successful in achieving relatively uniform dispersion and distribution of the nanomaterials in metal matrix [10]. The process uses both the acoustic cavitation and the acoustic streaming. The mechanism of the process can be seen in Figure 1.4. In the beginning of the process, there are many clusters of nanomaterials in a molten metal. The nanomaterial clusters have air pockets trapped inside them, once the acoustic pressure inside the ultrasonic processing cell (in this particular case, the crucible) exceeds the cavitation threshold pressure of the metal melt, these air micro pockets work as nucleation agents to generate acoustic cavitation bubbles. Under the subsequent acoustic cycles, these cavitation bubbles act as explained in Figure 1.2. During the implosion, the extreme conditions are generated, which disperse the nanomaterials. The other non-linear effect, acoustic streaming then distributes these dispersed nanomaterials throughout the metal matrix.
1.2 Motivation and objectives

A system for the ultrasonic processing of liquids consists of two principal components: a transducer and a vessel. The transducer produces an ultrasonic wave, which is transmitted to the liquid using a probe. The liquid is contained in the vessel that can be termed as an ‘ultrasonic processing cell’. The ultrasonic processing cell can be made of different materials depending on the application. Glass cells are used in sonochemical applications [10] and graphite or other ceramic crucibles are used for processing materials at higher temperatures [11]. The liquid can vary between anything from different chemicals to molten metals.

Various factors affect the ultrasonic processing of liquids. Appropriate design and geometric configuration of the ultrasonic processing equipment is critical for the effectiveness of ultrasonic processing. The key challenges are presented below:

- The dependence of the acoustic pressure field inside the cell on various parameters.
- These parameters can be classified into physical, geometric, and operational parameters as shown in Figure 1.5. The physical parameters are mainly the liquid properties. Geometric properties are the dimensions and positioning of the ultrasonic processing equipment. The operational parameters are the ultrasound parameters and the ambient conditions.

- The non-linearity of ultrasonic wave propagation.
- The non-linear effects like the acoustic cavitation and the acoustic streaming are complex to characterize experimentally or analytically.

- The extreme variability of time scales involved in the process.
- The acoustic cycles take place in the order of milliseconds while acoustic cavitation events (bubble growth and implosion) can sometimes take place in the order of picoseconds [9].

- The difficulty of predicting the location of cavitation bubbles.
- The bubbles are initiated by the nuclei that are dissolved in the liquid or are inside the clusters. It is not obvious where these nuclei will be located.

![Figure 1.5: Classification of processing parameters.](image)
In current practice, the processing parameters are mainly selected based on heuristic arguments or on the experience of operators. The experimental knowledge is extremely limited and highly dependent on the physical parameters like the dissolved gas content. From an experimental perspective, limited research has been attempted to characterize the cavitation activity by trying to measure the cavitation using different quantities such as cavitation intensity or degree of uniformity. Three basic techniques have been used in different forms with slight modifications. The results from the characterization using these three methods are summarized in Table 1.1. The cavitation activity has been quantified by introducing a new quantity called as the degree of uniformity [12]. In that study, hydrophones were used to measure the acoustic pressure. However, the hydrophones inside the liquid can have microscopic pockets of air trapped on their surfaces, and they will interfere with the acoustic cavitation process. Furthermore, this method is limited to be used at low temperatures (< 60 °C). High-Speed photography [13] is another widely used technique to capture the bubble structures, but it is unable to extract holistic information that can explain the mechanism of the acoustic cavitation or be able to characterize it. Other method that has been widely used is to calculate the efficiency of the cavitation reactors based on a model chemical reaction [14]. The method is based on quantifying the chemical activity that is a direct result of the acoustic cavitation. However, this only provides the information about the bulk process and cannot describe the location of the cavitation zones. Moreover, the repeatability of the process is poor because the purity of the liquid used is not taken into account.
Table 1.1: The three major experimental techniques available to characterize cavitation.

<table>
<thead>
<tr>
<th>Measurement type</th>
<th>Device</th>
<th>Ultrasonic source</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Acoustic pressure | Hydrophone | a) 36 kHz, 150 W, bath type sonochemical reactor | [12]. The difference in the degree of uniformity along the axis of the two different reactors was found out to be in the range of 10-30%.
| | | b) 20 KHz, 150 W, hexagonal flow cell | |
| Bubble structure image | High-speed camera | 230 kHz, pressure amplitude 500 kPa, bath type sonochemical reactor | [13]. Does not include any quantification. It was concluded that at over a range of higher frequencies the bubble structures shape and behaviors remain consistent.
| Chemical content after reaction | Ultraviolet (UV) spectrophotometer. (Measures the absorbance of UV spectrum at a wavelength of 355 nm) | a) 20 kHz, 240 W, and an immersion type sonochemical reactor | [14]. Cavitation yield: a) 3.53 × 10⁻⁹ g/(J/mL), b) 5.83 × 10⁻⁷ g/(J/mL), and c) 6.21 × 10⁻⁷ g/(J/mL)
| | | b) 20 kHz, 120 W, and a bath type sonochemical reactor | |
| | | c) 25kHz, 120 W, flow cell type reactor | |

On the other hand, various numerical models of the acoustic pressure field inside the sonochemical reactor have been intensively developed. Most of them simulate the acoustic pressure field in the sonochemical reactor filled with water. They are based on the linearization of the Euler equations [15], which generate the Helmholtz equation for the ultrasonic wave propagation. The linear Helmholtz equation is robust and easily solvable using finite element method (FEM). A more comprehensive discussion on the numerical model development over the years is presented in Chapter 2. Recently, attempts have been made to simulate the acoustic cavitation formation and the implosion inside the reactor [16]. It should be noted that there is an
uncertainty involved in the models caused by the time and spatial scale variations in the cavitation process. However, there have been several studies to analytically predict the acoustic cavitation distribution inside the sonochemical reactor [17-21]. They are based on the linearization of cavitisch equation, which is a widely an accepted notion that relates the cavitation bubble fraction to the corresponding acoustic pressure [22].

It has been reported that the pressure field inside the sonochemical reactor is highly dependent on the geometric configuration of the setup [23]. This leads to the development of the following hypotheses:

- The cavitation bubble distribution is highly dependent on the geometric configuration of the ultrasonic processing cell.
- The position of the ultrasonic probe inside the ultrasonic processing cell significantly affects the cavitation distribution.
- The acoustic streaming is also influenced by the geometric configuration

In this study, the cavitation formation and implosion is characterized using the numerical model developed to resolve acoustic pressure field and the acoustic streaming field inside the ultrasonic processing cell. The numerical model is then used to investigate the dimensional effect of different geometric configurations of the ultrasonic processing cell and the position of the ultrasonic probe on both acoustic cavitation and acoustic streaming. Finally, an experimental validation is conducted to verify the developed numerical model.
1.3 Outline of the thesis

Chapter 2 presents the critical literature review of the existing numerical models. The linear Helmholtz equation has been solved using commercial FEM packages in the early stages of the model development. These linear models do not consider the complex non-linear phenomena that are an integral part of the ultrasonic wave propagation. In the last ten years, more models have been developed including those non-linear characteristics. Therefore, in Chapter 2 a non-linear numerical model was developed to resolve the acoustic pressure field and the acoustic streaming field. The effect of different boundary conditions was also investigated. The numerical model is validated using experimental results. The results obtained from the numerical model are analyzed, and the method to quantify a size of the cavitation zone is introduced.

Chapter 3 begins with the introduction of geometric parameters that will used to study the effect of ultrasonic processing cell geometry and the position of the ultrasonic probe. The significance of the parameters was identified from the analysis of variance results. The chapter ends with selection of parameters for the experimental verification of the presence of the acoustic cavitation and the acoustic streaming.

Chapter 4 discusses the numerical model used for solving the acoustic streaming flow for the geometric configuration with the parameters obtained in Chapter 4 and the discussion of the streaming results was followed by the experimental verification.

Chapter 5 presents all the conclusions of the current work and the outline of future works.
2. NUMERICAL MODELING I: ACOUSTIC PRESSURE FIELD

2.1 Literature review

Several numerical models to predict the acoustic pressure field inside the ultrasonic processing cell have been developed over the years. The earliest and simplest models were based on the linear acoustic pressure equations. Over time, with better computational resources available, the non-linearities have been considered. One of the principle reasons for the non-linearity is the attenuation of the ultrasonic wave. Different modes of attenuation are present like the viscous, thermal and bubble attenuations. Considering each and all of the acoustic attenuations different models have been developed. These can be classified as shown in Figure 2.1: Classification of numerical models for ultrasonic processing.

![Classification of numerical models for ultrasonic processing.](image)

The pressure field inside a 20 kHz sonochemical reactor was resolved and was used to characterize the sonochemical reactor [24]. The simulation results were verified with aluminum foil experiments, in which a sheet of aluminum foil is place at the bottom of the sonochemical reactor. Due to the presence of acoustic cavitation, the aluminum foils experience pitting. In [24]
the simulation areas where the magnitude of the acoustic pressure is high corresponded to the areas on the aluminum foil with the most pitting damage. Although, the simulation and the experiment were successfully conducted, it remains unreliable. From the comparison, it has been concluded that the cavitation zone is concentrated immediately below the tip surface of the probe and that the cavitation formation and implosion dramatically decreases from the tip surface along the axis of the probe. This is also consistent with the theoretical knowledge that the ultrasonic wave attenuates rapidly as it propagates away from the source. A 20 kHz sonochemical reactor has been optimized by modeling a three-dimensional simulation of the acoustic pressure field [25]. This is a linear model with boundary conditions assumed infinitely hard. Several different geometries of the sonochemical reactor have been simulated to study the effect of geometry on the pressure field. It was found that the pressure field inside the sonochemical reactor is heavily dependent on the geometry of the reactor. The methodology presented however, ignores the constant volume conundrum. Simply changing any one of the cell radius or liquid level or the immersion depth will change the volume of the sample, rendering any comparison made later of little use. The effect of using multiple converters on the acoustic pressure field has also been simulated [26]. The optimal distance between two converters has been identified to obtain a more pronounced acoustic pressure field from the constructive interference between the two converters. This work provides more insight into the interference patterns inside a sonochemical reactor during the ultrasonic processing, which is rarely discussed in the literature. However, the study correlates the maximum pressure amplitude to the effectiveness of ultrasonic processing. While, this was an acceptable approximation, it is not entirely accurate. The maximum pressure amplitude is being measured at a predetermined point and it’s relation to the acoustic cavitation process was not discussed. The temperature and pressure profiles of various solvents at different levels of ultrasonic power have been simulated by combining COMSOL Multiphysics’
(COMSOL, USA) acoustic and heat transfer modules. It was found that the changes in the property of the liquids based on the temperature influence the acoustic pressure field. [27] The specific application of the sonochemical reactor in this study is to extract the solvent, epigallocatechin gallate. The rate of the process is enhanced with acoustic cavitation and the operating temperature. The extent of cavitation is characterized by measuring the range of the acoustic pressure for a given input power and by measuring the temperature range due to ultrasonic attenuation. Moreover, the ultrasonic pressure field in a 24 kHz sonochemical reactor has been simulated and investigated the geometric effects to optimize the ultrasonic reactor [28].

More about the study is summarized in Table 2.1

<table>
<thead>
<tr>
<th>Parameters studied</th>
<th>Ultrasonic source</th>
<th>Considered outcomes</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometric parameters: Horn position, liquid level, and cell radius.</td>
<td>20 kHz, 100 W, immersion type reactor</td>
<td>Ultrasonic intensity along the axis</td>
<td>[25] The optimum values found are: Cell radius = 45 mm, Horn position = 25 mm and liquid level = 100 mm.</td>
</tr>
<tr>
<td>Operational parameters: Effect of multiple converters</td>
<td>45 kHz, 100 W, immersion type reactors</td>
<td>Maximum pressure magnitude at the center of the two converters</td>
<td>[26] The maximum pressure amplitude is achieved when the two converters are placed apart at a distance of (3\lambda/2).</td>
</tr>
<tr>
<td>Operational parameters: Input power, Processing time, operational temperature</td>
<td>a) 28 kHz, 540 W, immersion type reactor</td>
<td>Amount of epigallocatechin gallate extracted</td>
<td>[27] A maximum amount 2.996 gms was extracted when the power is 300 W, with a processing time of 20 min at 303.12 K</td>
</tr>
<tr>
<td>Geometric parameters: Aspect ratio of the reactor, defined by (H/D)</td>
<td>24 kHz, 250 W, immersion type reactor</td>
<td>Maximum acoustic pressure magnitude.</td>
<td>[28] It was found out that an aspect ratio of 3.5 gives the maximum pressure magnitude of 0.723 MPa.</td>
</tr>
</tbody>
</table>
2.2 Constitutive Relations

Eq. 2.1 describes an acoustic pressure wave with variation in space and time.

\[ \nabla \left( \frac{1}{\rho} \nabla P \right) - \frac{1}{\rho c^2} \frac{\partial^2 P}{\partial t^2} = 0 \tag{2.1} \]

Since most ultrasonic sources emit sinusoidal waves, the pressure wave can be assumed as harmonic as shown in Eq. 2.2,

\[ P(r,t) = p(r) \cdot e^{i\omega t} \tag{2.2} \]

where \( \omega \) is the angular frequency of the ultrasonic wave and is given by \( \omega = 2\pi f \), \( f \) being the frequency in Hz, and \( r \) describes the position in the Cartesian coordinate system \((x, y, z)\).

Substituting Eq. 2.2 in Eq. 2.1 we get the linear homogenous wave equation (Eq. 2.3) which is only dependent on the spatial variable, \( r \). Although the above linear model describes the geometric attenuation due to multiple reelections and wave dispersion, it ignores the attenuation due to the liquid properties. In order to describe the damping properties of a medium, the complex ultrasonic speed, \( c_c \) and the complex density, \( \rho_c \) of the medium are defined as follows [29]:

\[ \nabla \left( \frac{1}{\rho} \nabla P \right) - \frac{\omega^2}{\rho_c c_c^2} \frac{\partial^2 P}{\partial t^2} = 0 \tag{2.3} \]

\[ c_c = c \left( 1 + i\omega \frac{4\mu}{3 \rho_c^2} + \mu_b \frac{2}{\rho c^2} \right)^{0.5} \tag{2.4} \]

And,

\[ \rho_c = \rho \left( \frac{c}{c_c} \right)^2 \tag{2.5} \]

Here, \( \mu \) is the dynamic viscosity and \( \mu_b \) is the bulk viscosity of the medium, \( c_c \) is the complex ultrasonic speed, \( \omega \) is the angular frequency. Numerical models accounting for the viscous losses have been also developed it is observed that the viscous losses are dependent on
the volume of the liquid being processed [30]. The viscous dissipation of the ultrasonic wave increases with the increase in the distance of path the ultrasonic wave has to traverse, so larger volumes experience more losses. The effect of different reactor sizes [31] on the acoustic pressure field has also been studied using a similar model. The basic numerical models have been developed to resolve the ultrasonic field propagation in an ultrasonic processing cell used in the purification of magnesium alloy melt [32, 33]. The ultrasonic wave loses its energy as it propagates primarily because of its viscosity. Although most studies used water as the samples, the same models can be extended to other samples with different viscosities, like molten metals.

In this study we the ultrasonic processing in water instead of molten metal. Liquid properties that are relevant for the acoustic propagation are of comparable magnitude in water and molten aluminum. For example, the kinematic viscosity of water at room temperature (293 K) and that of molten aluminum at 973 K have comparable magnitudes, \( \eta_{\text{water}} = 0.5 \times \eta_{\text{Al}} \) [34]. Simulating the pressure field inside water will save the experimental costs involved in measuring the properties of molten aluminum. It should also be noted that the thermal effects of the ultrasonic processing, which can influence the viscosity of the sample, could be safely neglected because the temperature rise induced in the process is small enough compared to the processing temperature.

### 2.3 Modeling geometry

An axisymmetric geometric section of the ultrasonic processing cell was modeled. It can be seen in Figure 2.2. The ultrasonic probe was immersed into the liquid up to a height, \( d \). The cell geometry is given by diameter \( D \) and height \( H \). \( \Delta H \) is the rise in the fluid level caused by the immersion of the probe whose diameter is \( D_p \). The thickness of the cell, \( t \) is 0.3 cm, which is a standard thickness of a laboratory borosilicate glass beaker. The values of the geometric...
parameters are taken from the experimental results published in [35]. The ultrasonic probe surface is modeled as a boundary condition, because solving the structural mechanics of the probe will require additional computational resources. The pressure amplitude at the probe surface can be given by [36]:

\[ P_a = \sqrt{2I\rho c} \quad (2.8) \]

Here \( P_a \) is the pressure amplitude of the ultrasonic probe, and \( I \) is the intensity of the power input into sample given by,

\[ I = I_0 \times \eta \quad (2.9) \]

where \( \eta \) is the factor of conversion of the ultrasonic probe assumed to be around 0.85 [36], \( I_0 \) is the intensity of power input into the ultrasonic probe, \( \rho \) is the density, and \( c \) is the speed of ultrasonic wave in water.

![Figure 2.2: Axisymmetric geometric model.](image)
2.4 Boundary Conditions

Three different types of boundaries are defined based on the behavior of the ultrasonic wave when it meets a wall:

1) Soft boundary: The ultrasonic wave experiences a reflection with no phase change. The current cell has no soft boundaries.

2) Hard boundary: A hard boundary reverses the polarity of the ultrasonic wave. It changes the phase of the wave by 180°. The side surface of the ultrasonic probe are modeled as rigid walls. Mathematically it can be represented using the following equation

\[
\frac{\partial P}{\partial n} = 0
\]  

(2.10)
where \( n \) is the plane normal to the boundary.

3) Partially reflecting boundary: Both hard and soft boundaries are idealized cases. In practice, almost all the boundaries are ‘partially reflecting boundaries’ also known as ‘discontinuous boundaries’. The discontinuity is in the impedance across the media. As the ultrasonic wave propagates across the boundary between different media, it realizes a change in the impedance. Impedance of a medium is the material property that dictates the propagation characteristics of the ultrasonic wave. It is given by:

\[
Z = \rho \times c
\]  

(2.11)
where ‘\( \rho \)’ is the density of medium and ‘\( c \)’ is the ultrasonic speed in the medium. This affects the propagation characteristics of the ultrasonic wave. One way to quantify the impedance mismatch is to calculate the reflection coefficient at the interface, given by the following expression:

\[
R_{ce} = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2
\]  

(2.12)
, where $Z_1$ and $Z_2$ are the impedances of the first medium and the second medium respectively.

The effect of different types of boundaries has been investigated over the years. Several researches [29] have resolved the linear Helmholtz equation in sonochemical reactors assuming infinitely hard boundaries. Simulations considering the vibrations of the container walls when calculating the pressure field inside an ultrasonic bath have also been performed [37]. It was found that the effect of the boundary vibrations is quite prominent in large ultrasonic baths. However in smaller sonochemical reactors, the effect of vibrations of the boundaries can be neglected this is because the horn-type converters that are generally used in the sonochemical reactors only generate intense vibrations close to the horn surface and the intensity of the wave dissipates quickly.

### 2.5 Study on the effect of boundary conditions

In order to study the effect of the boundary conditions on the acoustic pressure field, an analysis with two different boundary condition configurations was performed. Figure 2.3 shows two boundary conditions. In Figure 2.3 a, the inside walls are considered to be infinitely hard, and the top boundary is considered as soft boundary. In Figure 2.3 b, both the inside wall and the top surface are considered to be partially reflecting. It should be noted that the surface of the ultrasonic probe remains as infinitely hard in both cases. The impedance mismatch between water and the titanium ultrasonic probe is excessively high, hence the majority of the ultrasonic waves reflect back, and a little passes through the interface.
In finite element modeling of acoustic pressure field, the node length ($h_i$) should satisfy the following condition [38],

$$
\left( \frac{\Delta h_i}{\lambda} \right) \ll 1
$$

Side length $\Delta h_i$, here is the size of the longest side of the triangular mesh element and $\lambda$ is the wavelength of the ultrasonic wave. The longest side length in this study is 0.0128 cm. This satisfies the condition shown in the above expression. In order to capture the effects closer to the probe surface, an unstructured mesh is utilized. In addition, it is known that the cavitation zone is often concentrated in the region immediately below the probe tip surface [36]. The region closer to the probe tip surface has much finer meshes than ones in other areas of the domain do, as shown in Figure 2.4. The triangular mesh elements are used in order to achieve smoother transition between the two regions. In region 1, the smallest element size is 0.0002 cm, whereas in the region 2 it is 0.00752 cm. The total number of elements including region 1 and 2 is 3334.
The relatively finer mesh size around the probe tip surface is applied to the circular area with a diameter of about ‘$\lambda/10$’.

Figure 2.4: Unstructured meshing of the liquid domain.

Figure 2.5 a and b show the respective acoustic pressure fields. It can be observed that the boundary conditions have an impact on the resultant acoustic pressure field. In Figure 2.5 a, at the boundary the ultrasonic wave is completely reflected back. In Figure 2.5 b, the glass wall has higher acoustic impedance compared to water, so majority of the ultrasonic wave is reflected back but a portion of them is transmitted through the glass wall. Comparing these two, Figure 2.5 a has higher-pressure zones at the wall, this is because of the interference between the partial reflection and the incident wave. In Figure 2.5 b, the transmitted waves travel to reach the subsequent boundary, which is the interface between glass and air.
All the interfaces involved in the setup can be seen in Figure 2.6. The transmitted ultrasonic waves once again undergo partial reflection. They are leaving the glass wall (higher acoustic impedance) and entering air (lower acoustic impedance), so the majority of the waves are transmitted through the interface while a minor portion is reflected back. The reflected waves come back into water and interact with the incident ultrasonic waves. Therefore, it is imperative that the walls of the ultrasonic processing cell are properly modeled. Figure 2.6 shows all the appropriate boundary conditions, and the resultant acoustic pressure field is shown in section 2.8.
2.7 Modeling Parameters

As explained in the previous chapter, an FEM model for calculating the acoustic pressure field inside the ultrasonic processing cell has been developed. The geometric and operational parameters are obtained from [35] and can be seen in Figure 2.6.

Table 2.2. The ultrasonic processing cell was made of borosilicate glass, a standard thickness of 3 mm, with a diameter of 13.5 cm and the liquid level was 17 cm. The probe was positioned at a 2 cm below the water surface. An ultrasonic source of 20,000 Hz and a power of 36 W were used. The model was solved using the commercial FEM package, COMSOL Multiphysics 5.1 (COMSOL, USA).

<table>
<thead>
<tr>
<th>Table 2.2: Parameters for the numerical model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>D, cm</td>
</tr>
</tbody>
</table>

Figure 2.6: Final model boundary conditions.
Meshing is done based on the previous discussion. The additional glass thickness is also meshed similar to the liquid domain adjacent to it. It can be seen in Figure 2.7. The wall thickness of 0.3 cm is very small compared to the wavelength of the ultrasonic wave, so the relatively coarser mesh used in the wall thickness would capture the acoustic pressure wave.

![Figure 2.7 Unstructured meshing of the liquid domain and the cell wall domain.](image)

2.8 Results and validation
The model is solved using COMSOL Multiphysics 5.1 (COMSOL, USA) on a Dell workstation with 4.0 GB RAM and 3.22 GHz processor. The acoustic pressure field calculation took about 600 seconds. Figure 2.8 shows the acoustic pressure field inside the ultrasonic processing cell. The acoustic pressure magnitude is the highest at the probe tip surface, which means most of the acoustic intensity is concentrated near the probe tip surface and after that, it attenuates quickly.

![Figure 2.8 Acoustic pressure field calculated from numerical modeling.](image)

The experimental measurements of the acoustic pressure along the axis of a sonochemical reactor were conducted using hydrophones. The measurements start at a distance of 1 cm from the probe tip surface and continue at 14 different points with the last measurement taken at 14 cm. Figure 2.9 shows the comparison between the acoustic pressure variations along the axis calculated numerically to experimental measurements. The solid line represents the experimental measurements and the dashed line shows the numerical calculations. An error analysis reveals
that the mean error is about 33 %, with a maximum error of 78 % at a point 2 cm away from the probe and a minimum error of 5.8 % at a point 4.5 cm away from the probe surface. It can be observed that the difference between the numerical results and the experimental measurements is larger when the measurement is close to the probe tip surface and the bottom surface of the ultrasonic processing cell. This would be caused by the fact that when the hydrophone is close to the probe tip surface or the bottom surface of the ultrasonic processing cell the interference caused by the existence of the hydrophones would be constructive. The difference would be proportional to the distance between the hydrophone and the probe tip surface and the ultrasonic processing cell bottom surface.

![Graph](image.png)

**Figure 2.9**: Validation of numerical model with experimental results from [35].

### 2.9 Characterization of cavitation zone

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26
While the acoustic pressure field is a useful result, there is no directly available information about the acoustic cavitation formation and implosion inside the ultrasonic processing cell. It is known that the cavitation only takes place at locations where the acoustic pressure is above the threshold pressure. In this study, the acoustic cavitation area is used to quantify the acoustic cavitation formation and implosion inside the ultrasonic processing cell.

Boyle and Lehmann first reported the presence of acoustic cavitation in 1926 [39]. As described in Chapter 1, cavitation is the generation of gas-filled cavities inside a fluid. There are two types of acoustic cavitation that are reported: stable cavitation and transient cavitation [40]. The stable acoustic cavitation events usually describe the oscillation of bubbles in the ultrasonic field whose size is close to their equilibrium bubble sizes. These oscillations typically last several acoustic cycles and the cavities in general are larger in size (compared to transient cavities). The transient cavitation on the other hand involves bubbles of several different sizes oscillating volumetrically (expanding and contracting) in the ultrasonic field. The oscillations continue until the cavities reach a critical radius (resonance size) during one of the rarefaction cycles, in the subsequent compression cycle they implode. The transient cavitation is an extremely rapid phenomenon that occurs in the scales of picoseconds. Transient cavities can often expand to double their initial size until they implode. The implosion generates an array of physical phenomena, mainly a shockwave and micro-jets that are accompanied by tremendous amount of pressure (few thousand atmospheres) and temperatures (few thousand Kelvin). These extreme conditions are highly localized and are rapid (picoseconds). Cavitation occurs during the rarefaction cycle. Theoretically, when the negative pressure exceeds the threshold pressure, voids are formed in the liquid and the dissolved gas inside the liquid is diffused into the void forming a gas cavity [4]. Several authors have investigated the transient cavitation threshold value in several liquids over the years. In 1967, Blake developed an equation for calculating the cavitation
threshold by incorporating the equilibrium bubble radius into the term [4]. ‘Equilibrium bubble radius’ is the radius at which a gas bubble is stable in a given liquid in the absence of external ultrasonic field. This is in fact the radius of the seed nuclei that act as the cavitation spots [4,5].

\[
P_b = P_0 - P_v + \frac{4}{3} \times \sqrt[3]{\frac{2\sigma}{\left(P_0 + \frac{2\sigma}{R_0 - P_v}\right) \times R_0}}
\]  

(2.13)

where \(P_0\) is the ambient pressure which is 101 kPa, \(P_b\) is the cavitation threshold, \(P_v\) is the vapor pressure of water which is 3.17 kPa, \(\sigma\) is the surface tension of water, 7.04 mN/m, and \(R_o\) is the equilibrium radius of the cavitation bubbles, 5 µm [4]. All properties of the water are taken at 298 K. The cavitation threshold pressure for the acoustic cavitation is found out to be 0.8 MPa. If the ultrasonic pressure exceeds this threshold value, acoustic cavitation takes place. At ultrasonic pressure lower than the cavitation threshold pressure, no cavitation occurs.

With that value, the regions inside the ultrasonic processing cell where the acoustic pressure exceeds the threshold are identified. An example can be seen in Figure 2.10. The dark region is the acoustic cavitation zone, and the white regions have little probability of the cavitation formation since the acoustic pressure is less than the cavitation threshold pressure. It should be noted that it is challenging to exactly anticipate the location of a single cavitation bubble generation. To quantify the size of the acoustic cavitation zone, two new mathematical quantities are defined in this study as shown in Figure 2.10,
a) Equivalent Area \((A_{eq})\): The area of a circle that has same area as of the acoustic cavitation zone in a given geometric configuration. This is obtained by integrating the areas of all the mesh elements, whose nodes have acoustic pressure values in excess of the acoustic cavitation threshold pressure value.

b) Equivalent Diameter \((D_{eq})\): It is the diameter of the circle whose area is given by equivalent area \((A_{eq})\).

The equivalent diameter is used to characterize the effectiveness of a given geometric configuration during ultrasonic processing. For the configuration shown in Figure 2.10, two quantities are summarized below in Table 2.3.

<table>
<thead>
<tr>
<th></th>
<th>Equivalent Area ((A_{eq})), cm(^2)</th>
<th>Equivalent Diameter ((D_{eq})), cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.28</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Figure 2.10: Quantification of cavitation zone, for an example geometric configuration.
3. DESIGN OF EXPERIMENTS FOR GEOMETRIC PARAMETER

3.1 Analysis of Variance

As discussed in Chapter 1, there are various geometric parameters of the ultrasonic processing. The geometric configuration of the ultrasonic processing refers to the geometric parameters shown in Figure 3.1, which include the different geometric variables of the ultrasonic processing cell like its diameter \( D \), height \( H \) and volume \( V \). The geometric variables of the ultrasonic probe are its diameter \( D_p \) and its position given by the immersion depth \( d \). All these parameters can be classified into one of the two categories: direct and indirect parameters. The direct parameters affect the acoustic pressure field directly by altering the power transmitted to the liquid in the first place, whereas the indirect parameters influence on the acoustic pressure field indirectly after the power is transmitted to the liquid, by altering the interference patterns of the ultrasonic waves. Figure 3.1 shows all the geometric parameters that affect the acoustic pressure field inside the ultrasonic processing cell. Among those parameters, only the probe diameter \( D_p \) has a direct effect on the amount of input power delivered to the system. Therefore, it can be considered as the direct parameter. All the other parameters can be considered as the indirect parameters.
In this study, the dimensional effects of the indirect geometric parameters on the cavitation zone size are investigated. Therefore, the probe diameter $D_p$ is kept as a constant value of 1.27 cm. It is to be noted that the height $H$ does not represent the height of the ultrasonic processing cell, but the height of the liquid inside the ultrasonic processing cell. When the ultrasonic probe is immersed into the liquid, there is a rise in the liquid level and it changes the $H$ value. The detailed explanation for each parameter is as follows:

a) **Real height, $H$**: This is a final height of the liquid level when the ultrasonic probe is immersed into the liquid, including the height rise $\Delta H$.

$$H = H' + \Delta H$$

b) **Nominal height, $H'$**: This is a height of the liquid level before the ultrasonic probe is inserted into the liquid.

$$H' = \frac{4 \times V}{\pi \times D^2}$$

c) **Rise height, $\Delta H$**: This is the rise in the liquid level after the ultrasonic probe is immersed into the liquid.

$$\Delta H = \frac{d \times D_p^2}{D^2}$$
The nominal height, $H'$, will be determined by the selected total volume of the liquid and the ultrasonic processing cell diameter, ‘$D$’. The rise height, $\Delta H$, will be changed by the selected immersion depth of the ultrasonic probe, ‘$d$’. As a reference for the relationship between the geometric parameters and the immersion depth with respect to the ultrasonic probe diameter, two newly defined geometric parameters, $D/D_p$ and $d/D_p$ are introduced in this study. Therefore, the three parameters – diameter ratio, immersion depth ratio and liquid volume, will be the important variables to study the effect of the geometric parameters of the ultrasonic processing cell and the immersion depth of the ultrasonic probe on the acoustic pressure field and the acoustic cavitation formation and implosion.

In order to find the optimal geometric configuration and reduce the number of simulations in the parametric analysis, the analysis of variance (ANOVA) was employed. The three geometric parameters, diameter ratio, immersion depth ratio, and volume, are considered as the three factors whereas the equivalent diameter $D_{eq}$ is the response variable. The purpose of the study is to find out the geometric configuration that allows the largest value of $D_{eq}$ within the considered range of levels for each factor. The following section discusses the selection of the levels for each factor.

For a full factorial design with three factors and three levels, 27 runs need to be performed. Each factor has a high level, a low level, and a mid-point. For the diameter ratio, the lower level of 1.25 is selected considering the physical feasibility of the experimental setup. A $D/D_p$ value of 1.25 gives the ultrasonic processing cell diameter of 1.58 cm for the Ultrasonic probe with a diameter of 1.27 cm. That leaves a gap of 0.16 cm between the probe side surface and the inside walls of the ultrasonic processing cell, which is not practical. The high level is selected to be 3.0 from the literature [41]. It has been reported that the radial variation of acoustic pressure field is pronounced when the distance between the probe center and the inside walls is
less than 1.5 times the probe diameter. Over that, point there is a significant decrease of ultrasonic power intensity.

For the immersion depth ratio, the lower level of 0.25 is selected, which gives the immersion depth of 0.32 cm. Although it is only a quarter of the probe diameter, the ultrasound probe still transmits the ultrasonic waves into the liquid. With shallower immersion depth below this point, however, the coupling of the ultrasonic waves with the liquid is expected to be poor. A higher level of 3.0 is selected based on the literature [42], which provides with a design limit for the immersion depth in the sonochemical reactor.

The lower and the higher volume limits are selected to be 50 ml and 200 ml, respectively. When the volume is 50 ml with $D/D_p$ of 3, it gives the real height of 4.45 cm, which allows a gap of only 0.64 cm between the tip surface of the ultrasonic probe and the bottom surface of the ultrasonic processing cell for the immersion depth ratio to the probe diameter of 3:1. Similarly, the higher level of volume is selected to be 200 ml. Table 3.1 shows the selected factors and levels for this study. Therefore, total 27 different geometric configurations will be solved for the response variable, $D_{eq}$, and the results are summarized in Appendix I.

| Table 3.1: 3 Factors and 3 levels selected for ANOVA. |
|-----------------|-----------------|-----------------|-----------------|
| Factor          | Low level (-1)  | Mid-point (0)   | High level (+1) |
| $D/D_p$         | 1.25            | 2.25            | 3.0             |
| $d/D_p$         | 0.25            | 1.625           | 3.0             |
| Volume, ml      | 50              | 125             | 200             |

A full factorial DOE was conducted using Minitab 17 (Minitab Inc., USA). The results from the ANOVA show a plot of standardized effects as shown in Figure 3.2. It can be clearly observed that two factors, diameter ratio and immersion depth, are more significant than the
volume. However, it should be noted that the effect of the volume can not be completely neglected because there is an evidence of its high significance from the interactions with the diameter ratio and the immersion depth.

Figure 3.2: ANOVA results from Minitab.

3.2 Parametric Analysis

From the ANOVA results, the volume of the liquid has less significance on the cavitation zone size. Therefore, the total volume of the liquid was selected as a constant value of 57 ml. A parametric analysis was conducted to identify the optimal geometric configuration that gives the maximum cavitation zone size inside the ultrasonic processing cell within the considered ranges. The parametric analysis was carried out in two steps.
a) *Step 1:* The immersion depth ratio to the probe diameter of 0.5 was selected, and the ultrasonic processing cell diameter ratio to the probe diameter is varied from 1.25:1 to 4:1 with an increment of 0.25.

b) *Step 2:* In this step, the ultrasonic processing cell diameter ratio to the probe diameter was set to a constant value obtained from the result in the previous step. The immersion depth ratio to the probe diameter, on the other hand, was changed from 0.125:1 to 4:1 with an increment of 0.125.

The ANOVA results clearly show that the ultrasonic processing cell diameter to the probe diameter ratio is more significant than the immersion depth ratio to the probe diameter. Therefore, the parametric analysis was first conducted with respect to the $D/D_p$ to find the optimal value within the considered range (from 1.25 to 4.0).

The results from the step 1 show the variation of the equivalent diameter of the cavitation zone with changing the $D/D_p$ as shown in Figure 3.3. The drastic variations in the size of the acoustic cavitation zone would be attributed to the interference of ultrasonic waves and their multiple reflections from the walls of the ultrasonic processing cell. It is to be noted that at the ultrasonic processing cell diameter ratio to the probe diameter of 2.80:1, the largest equivalent diameter is obtained as 2.15 cm.
As previously described, there are three boundaries inside the ultrasonic processing cell. The boundary between the water and air is almost non-reflective because of the low reflective coefficient. Therefore, the boundaries as shown in Figure 3.4 that directly contribute to the resultant acoustic pressure field are:

Figure 3.3: Equivalent diameter of the cavitation zone with varying the diameter ratio.

Figure 3.4 Reflections involved in ultrasonic wave propagation.
1) Reflections from the inside wall

2) Reflections from the bottom surface

3) Secondary reflections from the glass/air interface

Reflections from these three boundaries meet the incident ultrasonic wave inside the ultrasonic processing cell. The interaction of the reflections with the incident ultrasonic wave can result in one of the two outcomes.

a) *Constructive interference:* In wave physics, constructive interference occurs when two waves interact when they are in same phase [15]. The resultant wave will have an amplitude magnitude higher than both the waves. This can be seen in Figure 3.5.

![Figure 3.5: Constructive interference.](image)

b) *Destructive interference:* Any interaction that is not constructive is destructive interference [15] as shown in Figure 3.6. It occurs when waves are not in the same phase.
The phase of the reflected wave is dependent on the distance from the source. Consider a one-dimensional wave that has a wavelength $\lambda$. If the boundary is at a distance of $n\lambda/2$ then the reflected wave will be in the same phase (or $360^\circ$ phase reversal). The resultant wave will have higher amplitude. Extending, this to a two dimensional wave is complicated because the dispersion of the wave divergence makes it difficult to calculate the distance between the source and the boundary. Divergence as shown in Figure 3.7 is the degree of spherical spreading of the wave after it travels a certain distance. In the present configuration, the divergence of the ultrasonic wave also makes it difficult to calculate the exact distance between the source and the sidewall.
Considering the divergence of the wave, it is obvious that there is a difficulty involved in estimating the pressure field inside the ultrasonic processing cell. Figure 3.8 shows the variation in the values of equivalent diameters for a change in $D/D_p$ values. It can be seen that there is a high dependence of the cavitation zone size on the diameter of the ultrasonic processing cell. When the distance between the inside wall of the ultrasonic processing cell and the probe side surface is small, the effect of reflection from the inside wall is strong, which might be caused by constructive interference. The equivalent diameter becomes smaller, as the inside wall gets farther from the probe side surface. The bottom surface of the ultrasonic processing cell is also expected to have a similar effect, although, the result shows that the equivalent diameter is higher when the bottom surface is at a much farther distance. Moreover, the equivalent diameter value falls down even though the bottom surface is at a closer distance from the ultrasonic probe. The equivalent diameter is consistent at a certain level until it suddenly starts decreasing starting from $D/D_p = 1.65:1$ until $2.0:1$, with an exception at $1.80:1$ where it increases again. Figure 3.8 shows the drastic change in cavitation zone size with a change in diameter ratio to the probe diameter from.
1.65:1 to 2.0:1 with an increment of 0.05. As the $D/D_p$ increases, the distance between the inside walls and the probe side surface keeps increasing and at $D/D_p= 2.0$, the constructive interference ceases resulting in smaller a cavitation zone size. The following conclusion can be drawn:

The effect of reflection from the inside wall is more dominant than the effect of reflection from the bottom surface.

![Figure 3.8: Cavitation zone size variations.](image)

In order to better understand the above conclusion, it is necessary to consider the diffraction of the ultrasonic wave. Diffraction is defined as phenomenon that results in the reduction of the intensity due to the spreading of the wave front. The diffraction can be physically modeled by identifying the near-field and the far-field regions of an ultrasonic wave.

1. Near-Field: It is a zone closer to the probe surface characterized by planar waves. This region is identified as the high intensity region.
2. Far-Field: It is a region adjacent to the near-field, where the ultrasonic wave starts spreading. Therefore, the regions that are present at a distance farther than the length of the far-field can be considered as far-field regions. These regions are characterized by low intensity ultrasonic waves.

For the current ultrasonic processing system, the probe diameter ($D_p$) of 1.27 cm and a wavelength ($\lambda$) of 7.35 cm generates a near-field length of 0.053 cm. The near-field region of the ultrasonic wave has a different scale in comparison to the scales of the geometric parameters involved. Therefore, the effect of near-field can be safely ignored. In the far-field region, the ultrasonic wave energy is an inverse function of the square of the distance from the probe surface [15]. The closer boundaries reflect higher intensity waves than the farther boundaries. The effect by positioning the probe surface closer to the bottom surface is presented in the subsequent sections.

The conclusion presented previously needs to be modified as,

*The effect of reflection from the inside wall is more dominant than the effect of reflection from the bottom wall when the diameter ratio, $D/D_p=2.80$.*

With the selected value of 2.8 for the diameter ratio, the immersion depth ratio is changed from 0.125:1 to 4.0:1 with an increment of 0.125:1. Figure 3.9 shows that the equivalent diameter of the acoustic cavitation zone rapidly increases with increasing the immersion depth ratio, and then the slope levels off as the ratio closes to 1:1. The reason would be also the interference of the ultrasonic waves and their reflections inside the ultrasonic processing cell. The largest equivalent diameter is 2.63 cm for the immersion depth ratio of 2.
This plot also helps test the second hypothesis presented in Chapter 1:

“The position of the ultrasonic probe significantly affects the cavitation distribution”

The increment in the acoustic cavitation size is a direct consequence of the reflection by the side surface of the probe. Initially, when the $d/D_p$ is small, the acoustic cavitation zone is small and confined to the region around the probe tip surface as shown in Figure 3.10. However, it shows a gradual increase in its size as the immersion depth increases. The ultrasonic processing cell diameter ratio to the probe diameter is constant and so the inside wall and the probe are at a constant distance. The change is only in the depth of the probe. The reflections between the probe side surface and the inside wall are determined to be the main reason for this change in the acoustic cavitation zone size.
Figure 3.10 Cavitation zone when Volume = 57 ml and $D/D_p=2.80$, $d/D_p=0.25$.

As shown in Figure 3.9, the equivalent diameter gradually increases value up to $d/D_p=2.0$, followed by a sudden reduction until $d/D_p = 3.0$. After that, the value increases again until $d/D_p = 4.0$. When the immersion depth is small, the divergence of the reflected ultrasonic wave from the inside wall is limited by space as shown in Figure 3.10. As the immersion depth increases, more space becomes available. When the immersion depth increases, there will be multiple reflections between the inside wall of the ultrasonic processing cell and the probe side surface resulting in different interference patterns. This can be observed in Figure 3.11 when $d/D_p=2.25$. The cavitation zone extends into the narrow channel between the inside sidewall and the probe side surface.

Figure 3.11 Cavitation zone when Volume = 57 ml and $D/D_p=2.80$, $d/D_p=2.25$. 

43
These result in the slight raise in the acoustic cavitation zone size, but after passing that point, the equivalent diameter tends to decrease until it reaches 3.0. The cavitation zone is limited to the region around the probe side surface.

From both the analyses, the geometric parameter and the immersion depth are selected for the liquid with a total volume of 57 ml as shown in Table 3.2.

Table 3.2: Geometric parameter and immersion depth selected for total volume of 57 ml.

<table>
<thead>
<tr>
<th>$D/D_p$</th>
<th>$d/D_p$</th>
<th>Volume, ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.80</td>
<td>2</td>
<td>57</td>
</tr>
</tbody>
</table>
4. NUMERICAL MODELING II: ACOUSTIC STREAMING

4.1 Literature Review

Acoustic streaming provides the mixing mechanism to distribute the nanomaterials homogenously throughout the liquid. Therefore, during the ultrasonic processing, it is important to consider both the acoustic cavitation size and the acoustic streaming flow for a given geometric configuration of the ultrasonic processing cell. The acoustic streaming is also used as a stirring mechanism in the sonochemistry to aid in emulsification of species [43]. Recently, the acoustic streaming is also increasingly being investigated for the heat transfer applications. Researchers have reported an improvement of 390 % [44] in the heat transfer coefficient between a hot plate and the surrounding liquid when the plate is vibrated using an ultrasonic converter.

Due to the significance of acoustic streaming in different applications, several researches have been conducted to characterize the phenomenon. Laser Doppler velocimetry (LDV) [45] to experimentally measure the acoustic streaming velocities in water. Polystyrene spheres with a diameter of 1.6 µm are used as tracker particles. The Doppler shift in the frequency of the scattered light is measured to obtain the velocity of the particles. Others have [46, 47] also used similar technique to characterize the acoustic streaming flows in water. However, it has been reported that there was an uncertainty involved in the flow velocity measurement using particles. One major limitation in LDV is that it can only provide the temporal flow evolution in a limited space. In particle image velocimetry (PIV), two laser beams are irradiated with a predetermined time gap, and then the two beams illuminate the tracer particles in the liquid. A charge-coupled device (CCD) camera captures two sets of images, and the displacement of the particle can be obtained from the two images. This information is used to characterize the instantaneous flow velocity. Both LDV and PIV need sophisticated data acquisition and signal processing.
algorithms. Hot-wire anemometry was also used to measure the streaming velocities [48]. However, it is limited to be used only with low ultrasonic intensities. It should be noted that all these techniques have been used for water as the medium. They cannot be applied to molten metals because of the opaqueness of the melts and the high temperature environments.

Acoustic streaming is the resultant mean flow in a liquid caused by the attenuation of the ultrasonic wave. Rayleigh first reported streaming patterns right next to the surface of a ultrasonic source. Lighthill [49] attempted to model acoustic streaming by theorizing that the streaming is related to the momentum transfer by the Reynolds shear stresses. Several researchers have tried to simulate the acoustic streaming inside the sonochemical reactor with water as the liquid. A model developed to predict the acoustic streaming pattern assuming the horn as a jet inlet has been used regularly over the years [50,51]. Others have [52,53] used a similar model to investigate the acoustic streaming in a high frequency sonoreactor using CFD simulation. Both substituted the plane form of ultrasonic pressure waves using the Helmholtz equation and coupling it with the Naiver-Stokes equations

4.2 Modeling

The acoustic streaming was modeled by resolving the time-dependent acoustic wave equation. Upon considering the viscous losses, Eq. 4.1 becomes Eq. 4.2, where $\rho_c$ and $c_c$ are the complex density and complex sound speed, respectively. Solving this will give the time-dependent acoustic pressure field.

$$\nabla \left( \frac{1}{\rho} \nabla P \right) - \frac{1}{\rho c^2} \frac{\partial^2 P}{\partial t^2} = 0$$  \hspace{1cm} (4.1)

$$\nabla \left( \frac{1}{\rho} \nabla P \right) - \frac{1}{\rho_c c_c^2} \frac{\partial^2 P}{\partial t^2} = 0$$  \hspace{1cm} (4.2)
The attenuation losses of the acoustic pressure wave can be obtained from calculating the attenuation coefficient. The attenuation coefficient can be given by Eq. 4.3., where \( f \) is the frequency of the ultrasonic waves, \( \rho \) is the density of water and \( c \) is the sound speed in water. This is found out to be 0.01120 m\(^{-1}\)

\[
\alpha = \frac{8 \mu \pi f^2}{3 \rho c^3} \quad (4.3)
\]

The attenuation term is fed into Eq. 4.4 that gives the net force generated due to the change in the momentum of the liquid.

\[
F = \frac{2\alpha |P|^2}{\rho c^2} \quad (4.4)
\]

, where \(|P|\) is the instantaneous pressure at a given point inside the cell. The body force is calculated at each instant in every location and is used in Eq. 4.5. Solving the Navier-Stokes equation and the continuity equation (Eq. 4.6) gives the velocity profile of the acoustic streaming flow.

\[
\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u = -\nabla P + \eta \nabla^2 u + F \quad (4.5)
\]

\[
\nabla u = 0 \quad (4.6)
\]

### 4.3 Modeling Parameters

From the ANOVA and parametric analysis, the following geometric configuration has been selected for the acoustic streaming modeling:

\[
\left( \frac{D}{D_p} \right) = 2.80, \left( \frac{d}{D_p} \right) = 2.0, \text{ and volume } = 57 \text{ ml}
\]

In order to study the effects of geometric configuration on the acoustic streaming flow, two different configurations are also selected as shown in Table 4.1.
Table 4.1: Geometric configurations selected for acoustic streaming modeling.

<table>
<thead>
<tr>
<th>Name</th>
<th>(D/D_p)</th>
<th>(d/D_p)</th>
<th>D_{eq}, cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2.8</td>
<td>2.0</td>
<td>2.63</td>
</tr>
<tr>
<td>B</td>
<td>2.8</td>
<td>4.0</td>
<td>2.12</td>
</tr>
<tr>
<td>C</td>
<td>4.0</td>
<td>2.0</td>
<td>0.58</td>
</tr>
</tbody>
</table>

4.4 Results

The model developed is resolved using COMSOL Multiphysics 4.4 (COMSOL, USA) on 24 processing cores with 128 GB RAM on the Clemson Palmetto cluster. The time taken for one simulation to be resolved is about 12 hours. The flow evolutions of the acoustic streaming for all the configurations are obtained at the same time intervals. Figure 4.1 shows the acoustic streaming in A. The velocity scales at times t=0.05 ms and t= 0.1 ms are different from the scales at t= 1s and t= 3s. The vast difference in the velocity magnitudes could not be captured using a consistent velocity magnitude scale. The acoustic flow originates from the tip surface of the ultrasonic probe and moves towards the bottom surface. The flow changes its direction at the bottom surface and moves upward along the inside wall. In order to understand the flow mechanism better, the streamlines are presented in Figure 4.2 for the same time intervals. At t = 0.05 ms and 0.1 ms (milli seconds) the velocity magnitude is extremely small. This is due to the time scales of the streaming flow being much larger than that of the acoustic wave propagation.
Figure: 4.1 Acoustic streaming flow evolution A at a) $t = 0.05\,\text{ms}$, b) $t = 0.1\,\text{ms}$, c) $t = 1\,\text{s}$ and d) $t = 3\,\text{s}$. 
Figure 4.2: Acoustic streaming, streamlines A at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s.
The formation of the first acoustic vortex can be observed at the bottom surface. This is due to the formation of the boundary layer at the corner. The flow keeps moving upward forming additional acoustic vortices caused by the interaction with the downward streaming flow and the inside wall. The vortices cause a swirling motion in the fluid. The vortices formed in the upper part of the ultrasonic processing cell are not prominent. As the time goes on, the flow gets stronger and the fluid settles into a streaming pattern that does not change drastically. The streamline patterns looks similar at \( t = 1 \) s and \( 3 \) s. The magnitudes are still considerably small in the order of 0.1 m/s. One important point to be noted is that the flow is not originated uniformly from the surface of the probe. The velocity magnitude at the center of the probe is the highest, and towards the edge, the flow has a zero velocity. The streamline present in \( t = 0.05 \) ms can show this clearly. This is caused of two things,

1) Acoustic streaming is generated when the acoustic momentum lost due to the attenuation is transferred to the liquid mass. The pressure wave is emitted from the tip surface of the probe in such a way that the majority of the power is concentrated towards the center of the wave and it becomes weaker towards the edge of the probe. This results in greater attenuation at the center of the probe than at the edge. The greater the attenuation, more the momentum transfer, which results in the flow. Figure 4.3 shows a typical acoustic streaming flow in water. It can be seen the flow is mainly generated from the center of the probe and not throughout the surface.

2) There is a weak flow at the edge of the probe. The liquid is moving from the top towards the surface of the probe. This is caused by the continuum nature of the liquid. Once the flow is generated, the liquid at the top surface moves down to replace the displaced liquid mass adjacent to the probe surface.
A similar trend can be observed in Figure 4.4, Figure 4.5, Figure 4.6, and Figure 4.7, the acoustic streaming velocities and the streamlines in the configurations of B and C respectively. It should be noted that the input conditions for all the cases are similar as mentioned in Chapter 2. The only difference between cases A, B and C is in the positioning of the ultrasonic probe below the top surface of the liquid and the ultrasonic processing cell diameter. The three configurations offer visibly different streaming flow patterns, proving a strong geometric effect. The streaming flow in the cases of B and C is considered unfavorable because a large area of the ultrasonic processing cell shows no streaming flow at all. The acoustic vortex formation is limited to the lower regions of the cell. In the case of A, the probe is located at a relatively larger distance from the bottom surface, which enables the streaming flow to evolve completely. It has been reported that the velocity magnitude of the acoustic streaming increases with increasing the distance from the source within a certain range before decreasing again [54]. It can be observed that in the configuration of A the bottom surface is at an appropriate distance to create a strong backflow.
Figure 4.4: Acoustic streaming evolution in B at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s.
Figure 4.5: Acoustic streaming, stream lines B at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s.
Figure 4.6: Acoustic streaming evolution in C at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s.
Figure 4.7: Acoustic streaming, streamlines at a) $t = 0.05$ ms, b) $t = 0.1$ ms, c) $t = 1$ s and d) $t = 3$ s.

Upon comparing the three cases, it was observed that the acoustic streaming flow in the case of A can reach the top surface, whereas that in the cases of B and C does not. The flow throughout the cell in the case A can more uniformly distribute the nanomaterials dispersed by the acoustic cavitation.
4.5 Experimental Verification

An experiment was conducted to study the effectiveness of ultrasonic processing using the geometric parameters determined in the previous numerical modeling results. The experimental procedure and setup is closely followed from previously published work [55]. A master nanocomposite is first prepared using the composite gas generator (CGG) process developed by Foosung Precision Industry Co., Ltd. (South Korea). Carbon nanofibers and silicon carbide (SiC) micro powders were mechanically mixed together with a pressurizing inert gas (Ar at 100 kPa) and introduced into aluminum molten metal at 700 °C by stirring a rotor with a rotation speed of 1000 rpm. After the introduction of composite gas into the melt for 30 minutes, additional stirring was carried out for 30 minutes for a degassing process, and the composite melt was poured into the forging die preheated to 300 °C. A load of 150,000 kg was applied to produce a slug with a diameter of 100 mm and a thickness of 30 mm in the melt forging process.

For the metal matrix nanocomposite, aluminum alloy A4000 (Al-11.5 Si-4.25 Cu-0.65 Mg) has been used as a matrix. As shown in Figure 4.8, carbon nanofibers with a diameter of 150 nm and a length of 6 μm (CM-150, Hanwha Chemical, South Korea) and SiC micro powders with a diameter of 5.5 μm (Greendensic GC, Showa Denko K.K, Japan) have been used to form a hybrid powder.

![Image](image.png)

*Figure 4.8: SiC micro particles and Carbon nanofibers.*
The ultrasonic system used in this study is shown in the Figure 4.9. It consists of three key components: a converter, a booster, and the ultrasonic probe. The converter is the source where layered piezo-electric crystals are electrically excited to generate mechanical vibrations. The booster amplifies the vibration amplitude, and the ultrasonic probe delivers the ultrasonic energy to the liquid. A commercial system, Q700 Sonicator (Qsonica, USA) is used as the ultrasonic system.

![Figure 4.9: Ultrasonic system.](image)

The ultrasonic probe is important for the whole system to function properly. It receives energy from the booster and vibrates longitudinally along its nodal point. Since the probe will be used for the aluminum melt at high temperatures, a probe made of a niobium alloy (C103, ATI, USA) was used, which is a refractory material with a good acoustic property. A K-type thermocouple (chromel-alumel) is used to monitor the temperature of the molten metal. A portion of the thermocouple, which will be immersed into the melt, is protected with a ceramic shielding tube to prevent a chemical reaction of the thermocouple sheath material with the Al melt. The thermocouple is carefully placed in a position inside the crucible, which is 5 mm below the surface of the melt and slightly away from the crucible walls to obtain an accurate measurement and avoid any interference for the ultrasonic processing. The temperature controller system (Omega, USA) has an accuracy of ± 14 °C. An electric resistance-heating furnace was used to melt the Al sample in a graphite crucible with a diameter of 3.6 cm and a depth of 7.8 cm. A
protective Ar gas shield is used over the top surface of the molten metal inside the crucible to prevent oxidation of the melt. A schematic of the experimental setup is shown in Figure 4.10.

![Schematic of the experimental setup.](image)

Figure 4.10: Schematic of the experimental setup.

Two different samples were prepared using the master nanocomposite and the experimental setup as shown in Figure 4.11. For the first sample, the Al alloy master nanocomposite is melted in the graphite crucible and then poured into a stainless steel disk mold as shown in Figure 4.12. The disk with a diameter of 63.5 mm and a thickness of 12.7 mm will be prepared without the ultrasonic processing. In the second experiment, the melt is ultrasonically processed with amplitude of 60 µm for 15 minutes. The ultrasonic probe is placed inside the molten metal at depth of 2.54 cm (following the Table 3.2). The melt is then poured into the mold when the melt temperature reaches at 740 °C.
A Rockwell hardness tester was used to measure the hardness of the produced samples. It should be noted that a Rockwell ‘B’ scale would generally be used to test Al samples. However, considering the improved hardness of the MMNC, a ‘C’ scale was used in this study, which is generally used for high strength steels. Figure 4.13 shows the pictures of samples. The sample 2 on the right is ultrasonically processed, whereas sample 1 is not. The hardness data can be found out in the following Table 4.2.
Table 4.2: Hardness data measured.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Hardness, HRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>74±8.7</td>
</tr>
<tr>
<td>2</td>
<td>72±4.7</td>
</tr>
</tbody>
</table>

This shows that there has been a 46.0% reduction in the deviation of hardness in the sample 2. This would be caused by more uniform distribution of the carbon nanofibers inside the metal matrix. This could be a direct consequence induced by the acoustic streaming. The porosity is measured using image processing software, Image J (NIH, USA). The pore area can be seen in Table 4.3

Table 4.3: Surface pore area measurements.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Pore area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4989</td>
</tr>
<tr>
<td>2</td>
<td>0.2668</td>
</tr>
</tbody>
</table>

A 46.5% reduction of pores was observed when the sample was ultrasonically processed. In a casting part, porosity is a major defect that influences the properties such as ductility and strength. Gases dissolved in the metal melt produce pores during solidification. The acoustic cavitation and the acoustic streaming of the ultrasonic processing removed the dissolved gases resulting in the reduction of pores inside the casting. Therefore, the reduction of the pore area is an indication of acoustic cavitation effect on the degassing process.
Figure 4.13: Samples produced during the experiment.
5. CONCLUSIONS AND FUTURE WORKS

5.1 Conclusions

In this study, numerical modeling has been used to understand the acoustic cavitation and the acoustic streaming during the ultrasonic processing of liquids. A finite element analysis (FEA) model has been developed to solve for the acoustic pressure field and acoustic streaming field inside the ultrasonic processing cell. The non-linear effects like viscous losses have been considered. All the modeling was conducted in COMSOL Multiphysics 5.1 (COMSOL, USA). Once the model has been successfully validated using experimental results published in literature [35], a new method to characterize the acoustic cavitation process has been introduced. This was done by measuring the acoustic cavitation zone size and defining it as a new quantity $D_{eq}$. This helped to compare the acoustic cavitation in different geometric configurations of the ultrasonic processing set up.

ANOVA and parametric analysis have been used to investigate the dimensional effects of different equipment involved in the processing. It was observed that the two other newly introduced parameters namely the ultrasonic processing cell diameter ratio to the probe diameter, and the immersion depth ratio to the probe diameter have significant effect on the acoustic cavitation zone size. It was determined that a probe immersion depth of 2.54 cm would produce a maximum acoustic cavitation zone and a relatively uniform acoustic streaming flow in the ultrasonic processing cell with a diameter of 3.59 cm for processing 57 ml of liquid sample.

The acoustic streaming flow has been solved for three different geometric configurations A, B, and C. A is the configuration that is determined to parameters found from the parametric analyses. The results were discussed in detail to understand the fundamental mechanism behind the acoustic streaming and how it is affected by the geometric configuration of the setup. An
experiment was conducted to prepare MMNCs of aluminum alloy A4000 (Al-11.5 Si-4.25 Cu-0.65 Mg) matrix with carbon nanofibers (diameter: 150 nm, length: 6 mm) and SiC micro particles (diameter: 5.5 µm). The parameters found from the parametric analyses were used to process the MMNC. It was found out that the ultrasonically processed sample has a similar hardness value but with a reduced spatial deviation of about 46 %, indicating a more uniformly distribute nanomaterials. Also the pore area was reduced by 46.5 %, which indicates the reduction in the dissolved gas content as a result of the acoustic cavitation.

5.2 Future work

Current work essentially provides a methodology to characterize the cavitation from the acoustic pressure field obtained from the numerical model. The plots obtained with the parametric analyses can be experimentally verified, by comparing the properties of the samples prepared by different geometric configurations.

There is a great potential to build on this work to create a proper design methodology for a more effective ultrasonic processing of liquids. This can be achieved by:

1) Extending the current model to take into account the attenuation of the ultrasonic field due to the cavitation bubbles.

2) Studying the effect of process parameters like probe size, input amplitude, frequency, or probe incident angle.

3) Experimental validation of the acoustic streaming model can be performed using laser Doppler velocimetry (LDV) or particle image velocimetry (PIV) techniques. These techniques can be implemented in a modified setup to suit the high temperature environment for processing of molten metals.
6. REFERENCES


7. APPENDIX I

7.1 ANOVA Data points

Table 7.1: Data used for ANOVA.

<table>
<thead>
<tr>
<th>D/D_p</th>
<th>di/D_p</th>
<th>V</th>
<th>D_eq</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>0.250</td>
<td>50</td>
<td>1.648860</td>
</tr>
<tr>
<td>1.50</td>
<td>1.125</td>
<td>50</td>
<td>2.177509</td>
</tr>
<tr>
<td>1.50</td>
<td>3.000</td>
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<td>0.993130</td>
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</tr>
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</tr>
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<td>2.359743</td>
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</tr>
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<td>1.125</td>
<td>200</td>
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<td>3.000</td>
<td>200</td>
<td>2.157870</td>
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<td>50</td>
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</tr>
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<td>3.00</td>
<td>3.000</td>
<td>200</td>
<td>0.502210</td>
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</table>
# 7.2 Minitab Output

## Analysis of Variance

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<th>Source</th>
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<th>Adj MS</th>
<th>F-Value</th>
<th>P-Value</th>
</tr>
</thead>
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<td>Model</td>
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<td>7.6882</td>
<td>1.28137</td>
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<tr>
<td>Linear</td>
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<td>Total</td>
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## Model Summary

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<td>51.53%</td>
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## Coded Coefficients

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</tr>
<tr>
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<td>0.224</td>
<td>0.110</td>
<td>2.03</td>
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<td>-0.044</td>
<td>0.114</td>
<td>-0.39</td>
<td>1.02</td>
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<td>D/Dp*di/Dp</td>
<td></td>
<td>0.237</td>
<td>0.118</td>
<td>0.135</td>
<td>0.88</td>
<td>1.00</td>
</tr>
<tr>
<td>D/Dp*V</td>
<td></td>
<td>-0.589</td>
<td>-0.294</td>
<td>0.138</td>
<td>-2.13</td>
<td>1.00</td>
</tr>
<tr>
<td>di/Dp*V</td>
<td></td>
<td>-0.121</td>
<td>-0.060</td>
<td>0.135</td>
<td>-0.45</td>
<td>1.00</td>
</tr>
</tbody>
</table>

## Regression Equation in Uncoded Units

\[
\text{Deq} = 1.620 - 0.248 \text{D/Dp} - 0.023 \text{di/Dp} + 0.01214 \text{V} + 0.115 \text{D/Dp*di/Dp} - 0.00523 \text{D/Dp*V} - 0.00058 \text{di/Dp*V}
\]
Figure 7.1 PARETO chart