ULTRASONIC DROPLET GENERATION JETTING TECHNOLOGY FOR ADDITIVE MANUFACTURING: AN INITIAL INVESTIGATION

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ULTRASONIC DROPLET GENERATION JETTING TECHNOLOGY FOR ADDITIVE MANUFACTURING: AN INITIAL INVESTIGATION

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<table>
<thead>
<tr>
<th>Symbol</th>
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<tbody>
<tr>
<td>(\lambda_c)</td>
<td>capillary wavelength</td>
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<tr>
<td>(\mu)</td>
<td>dynamic viscosity</td>
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<tr>
<td>(\rho)</td>
<td>density</td>
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<td>(\sigma)</td>
<td>surface tension</td>
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<tr>
<td>(c)</td>
<td>speed of sound</td>
</tr>
<tr>
<td>(d_j)</td>
<td>jet diameter</td>
</tr>
<tr>
<td>(d_n)</td>
<td>nozzle inner diameter</td>
</tr>
<tr>
<td>(f)</td>
<td>frequency</td>
</tr>
<tr>
<td>(f_n)</td>
<td>fundamental nozzle cavity resonance frequency</td>
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<tr>
<td>(f_p)</td>
<td>piezoelectric plate resonance frequency</td>
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<td>(h)</td>
<td>control volume height</td>
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<td>(h_n)</td>
<td>height of nozzle cavity</td>
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<td>entrance length</td>
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<td>(N_r)</td>
<td>piezoelectric thickness mode frequency constant</td>
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<td>Oh</td>
<td>Ohnesorge number</td>
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<tr>
<td>(p)</td>
<td>pressure</td>
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<td>(p_{\text{kinetic}})</td>
<td>kinetic (dynamic) pressure</td>
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<td>(p_{\text{surf}})</td>
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<td>(Q)</td>
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<tr>
<td>$r$</td>
<td>orifice radius</td>
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<td>$S$</td>
<td>surface tension parameter</td>
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<td>$t_U$</td>
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<tr>
<td>$U$</td>
<td>velocity magnitude</td>
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<tr>
<td>$\bar{U}$</td>
<td>average velocity magnitude</td>
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<tr>
<td>$\mathbf{v}$</td>
<td>fluid flow velocity vector</td>
</tr>
<tr>
<td>$v_j$</td>
<td>jet velocity</td>
</tr>
<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>CS</td>
<td>Continuous Stream</td>
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<tr>
<td>DOD</td>
<td>Drop-on-Demand</td>
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<tr>
<td>FDM</td>
<td>Fused Deposition Modeling</td>
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<tr>
<td>RP</td>
<td>Rapid Prototyping</td>
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<tr>
<td>RM</td>
<td>Rapid Manufacturing</td>
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<tr>
<td>SLA</td>
<td>Stereolithography</td>
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<td>SLS</td>
<td>Selective Laser Sintering</td>
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SUMMARY

Additive manufacturing processes, which utilize selective deposition of material rather than traditional subtractive methods, are very promising due to their ability to build complex, highly specific geometries in short periods of time. Three-dimensional direct inkjet printing is a relatively new additive process that promises to be more efficient, scalable, and financially feasible than others. Due to its novelty, however, numerous technical challenges remain to be overcome before it can attain widespread use. This thesis identifies those challenges and finds that material limitations are the most critical at this point. In the case of deposition of high viscosity polymers, for example, it is found that droplet formation is a limiting factor.

Acoustic resonance jetting, a technology recently developed at Georgia Institute of Technology, may have the potential to address this limitation because it generates droplets using a physical mechanism different from those currently in use. This process focuses ultrasonic waves using cavity resonances to form a standing wave with high pressure gradients near the orifice of the nozzle, thereby ejecting droplets periodically. This thesis reports initial exploratory testing of this technology’s performance with various material and process parameters. In addition, analytical and numerical analyses of the physical phenomena are presented. Results show that, while the pressures generated by the system are significant, energy losses due to viscous friction within the nozzle may prove to be prohibitive. This thesis identifies and begins evaluation of many of the process variables, providing a strong basis for continued investigation of this technology.
CHAPTER 1
INTRODUCTION

Additive manufacturing (AM) processes, so named because they build three-dimensional parts by selectively adding rather than subtracting material, are quickly gaining acceptance as viable alternatives to traditional manufacturing. Three-dimensional jetting, a recently developed subset of those additive manufacturing processes, involves building parts via deposition of tiny droplets of material onto a substrate.

Three-dimensional jetting machines have recently become available to industry, but there remain severe limitations on the materials used by these machines. A new technology, acoustic resonance jetting, developed recently by researchers at the Georgia Institute of Technology, creates droplet ejection using a physical mechanism different from those used in current jetting machines. However, its applicability as an additive manufacturing technology has not been evaluated due to its novelty.

This thesis will investigate the capabilities of the acoustic resonance system in the context of ejection of polymers, a class of materials exceptionally relevant to additive manufacturing. This chapter will frame the issues at hand by presenting background information about jetting as an additive manufacturing process and by identifying a number of research questions that will be addressed by the findings reported in this thesis. In addition, a roadmap for the remainder of the thesis is presented along with a summary of the content of the later chapters.
1.1 Framing: Jetting as an Additive Manufacturing Process

While additive manufacturing processes are currently used mainly in rapid prototyping (RP) and rapid manufacturing (RM) niche applications, it is foreseeable that they will be employed much more widely in the future. Common current AM technologies currently include, among others, stereolithography (SLA), selective laser sintering (SLS), 3D printing, and fused deposition modeling (FDM). Three-dimensional ink-jet style printing, based upon its two-dimensional counterpart used widely in the desktop printing industry, provides a number of advantages in comparison to these other additive manufacturing processes. It has, however, only recently been introduced as a three-dimensional technology; numerous challenges in its development therefore remain to be addressed. This section outlines the relationships between jetting and other AM technologies and highlights why jetting may have the potential to surpass other processes in the future and is thus worthy of investigation.

1.1.1 Characteristics of Additive Manufacturing Technologies

Each of these AM technologies begins with a continuous material medium, such as a liquid or a powder. The part design, conveyed from the designer’s computer to the machine in the form of a computer-aided design (CAD) file, is then realized by forming this material into a solid. Each machine technology, however, employs a unique method of creating this transition – the material may be sintered, cured, cooled, or otherwise forced to solidify into the desired shape. For example, stereolithography selectively cures areas within a vat of liquid photopolymer, using a laser to induce the polymerization reaction. Selective laser sintering also employs a laser as the energy source, but in this case the energy is used to sinter particles of metal or polymer in a bed of powdered
material. In 3D printing, a liquid binder is deposited into a powder bed, effectively gluing the powder together in the necessary areas. Fused deposition modeling extrudes melted filaments of polymer, which solidify in the deposited pattern upon cooling. In contrast, jetting deposits onto a substrate tiny droplets of liquid material, which are then solidified to create the resulting part. Each of these methods has benefits and limitations, in terms of both feasible geometry and materials available.

Most additive manufacturing processes rely on a layer-based fabrication approach. In this approach, a computer model of the part is created in a CAD software package. The 3D model is then ‘sliced’ into 2D layers. The information necessary to form each of these layers is then conveyed to the fabrication machine itself, which then builds up the final part layer by layer until it is completed. If the process uses a vat of material, as do stereolithography and selective laser sintering, each layer requires recoating, or depositing a new layer of material, over the top of the current volume. If, on the other hand, the process deposits directly onto a platform, as fused deposition modeling does, each layer may need to be leveled or otherwise prepared for the next deposition. In the majority of current processes, the layering is evident in the final part, which may therefore require postprocessing to achieve desired surface finish, appearance, or functional capabilities.

The most obvious advantage of building with these additive manufacturing processes is that geometric complexity is easily achieved, since material is being deposited only where it is needed. Whereas traditional machining processes have trouble forming internal voids or other geometry beyond the physical reach of the standard tools, AM processes can access all areas of the part due to the layer-based build method. AM
processes do not differentiate between internal and external geometry; feature size is limited only by the smallest area that can be created with the process’ laser, droplets, or any other deposition method used.

The cost of this capability, however, is evident in the need for part supports in these processes. Although AM technologies can easily create overhangs or undercuts, the resulting part must be supported against gravity in order for subsequent layers to be formed correctly on top of it. In a vat-based system, the material in the vat may inherently support the part. In processes that deposit onto an open platform, however, supports must be constructed to hold up the overhanging geometry.

1.1.2 Jetting as a Direct Deposition Process

One subset of these additive manufacturing technologies relies upon the deposition of droplets of liquid material via ink-jet type printheads. The general concept of jetting is derived from the desktop printing industry; its evolution is traced in section 2.1. For the sake of specificity, the term ‘jetting’ is defined for this thesis as a family of processes that build parts by non-contact deposition of patterned droplets of the final part material onto a substrate. It is important to note that this includes only direct jetting of the actual part material, as differentiated from those processes that jet sacrificial materials such as glues or binders into a substrate of the part material. Figure 1 shows the basic functionality of these jetting machines.
1.1.3 Advantages of Jetting

Direct jetting technologies are a promising frontier in rapid prototyping and rapid manufacturing, with a number of motivations for commercial and research use. While jetting machines are currently being used mainly for concept modeling or investment casting purposes, much ongoing research is looking into the possibilities of applying jetting in other realms. Jetting-based approaches provide a number of advantages over other additive manufacturing technologies such as SLA, SLS, 3-D printing, or FDM, mainly in the areas of economic efficiency and material capabilities.

Much of the economic benefit of inkjet-based technologies is derived from the elimination of the need for a high-power laser such as those used in stereolithography or selective laser sintering. The laser itself is a major portion of the cost of those machines, with a single laser unit costing from approximately $15,000 to $45,000 [2].
comparison, many ink cartridges that are commercially available for desktop printers, often priced less than $50, include an inkjet print head on the cartridge.

Moving from a laser or single extrusion head to nozzle print heads also provides the opportunity for significant time savings via parallel building. For example, Objet Geometries’ PolyJet machine (see section 2.1.2) employs a print head with an array of over 1500 nozzles [3]. Although this will depend to some extent on the relative speeds of the inkjet head and the laser beam or extrusion head movement, depositing material from hundreds or thousands of nozzles has the potential to be much faster than curing or extruding single linear paths. For the same reasons, jetting technologies that allow parallel deposition of entire swaths of material at once are much more promising in terms of their ability to be scaled up for applications that need to cover large deposition areas in a feasible timeframe.

Another source of economic benefit is the lack of an open resin or powder vat such as those found in the build areas of stereolithography, selective laser sintering, and 3D printing machines. In contrast, direct jetting machines deposit part and support materials only where needed. Direct jetting thus avoids the need to stock entire vats of material, which often represent an investment of thousands of dollars, and eliminates the possibility of contaminating them. Changing materials by interchanging cartridges rather than having to empty and refill a vat is also dramatically more efficient, resulting in less wasted material and less technician time spent.

In addition to economic and time-saving benefits, direct jetting technologies may eventually provide a number of capabilities that other RP methods may simply be unable to achieve. For example, direct jetting machines will likely be more able than vat-based
methods to implement the use of multiple materials or the creation of functionally or aesthetically graded materials. In fact, current machines already take advantage of this fact by using certain nozzles to jet the main build material and others to jet different support materials. This could easily be expanded to have nozzles jetting multiple colors of materials [4] or functionally different types of materials. Comparing this to a case such as the use of Materialise’ Stereocol resin for selective coloration in the stereolithography process, which requires complicated resin chemistry and multiple passes of the laser beam to accomplish the coloration [5], it is clear that the ability to directly deposit multiple materials is a distinct advantage. And just as 2-D inkjet printers today create documents with graded coloration, 3-D direct inkjet machines have the potential to easily create functionally graded materials by simply interspersing droplets of multiple materials; other rapid manufacturing techniques must rely on significantly more complicated processes to achieve these results.

Finally, inkjet-based processes have the potential to build with a large number of materials. One component of this flexibility is the opportunity for multiple solidification methods as introduced in section 1.1.1. Each of the other rapid prototyping technologies such as SLA, SLS, and FDM relies on a single hardening method – photocuring, sintering, and cooling respectively. In contrast, jetting can be used with solidification of a melted material, evaporation of the liquid portion of a solution, curing of a photopolymer, or other chemical reactions.
1.2 Motivation for Study

While the advantages discussed in the previous section identify jetting as a process with great potential, that potential has not yet been realized. One notable weakness of current three-dimensional jetting machines is the limited range of materials that are in use. Parts built in these machines tend to have poor physical properties, which means that they cannot be used in the majority of engineering situations. In order for this technology to be adopted on a widespread scale, it will need to achieve the mechanical robustness demanded by industrial applications.

Polymers, for example, comprise a huge segment of engineering materials. If jetting machines were able to deposit functional polymers such as polyurethanes, a whole new world of manufacturing processes would emerge. Current three-dimensional machines do jet a very few select polymers, but none that would be considered true engineering materials with functional properties.

It is apparent that the hardware currently in use may be one limiting factor in determining the range of jettable materials; viscosity in specific seems to be a significant challenge. While researchers have begun to investigate the applications of three-dimensional jetting, very few have considered the actual jetting systems themselves; almost all work has used technologies originally created for two dimensions. The development of the acoustic resonance system, which has been demonstrated to create very strong pressure gradients resulting in the ejection of tiny droplets at high frequencies, provides an opportunity to address this situation.
1.3 Research Motivation, Hypotheses, and Activities

As a result of the immaturity of three-dimensional jetting technologies, and especially acoustic resonance jetting, this thesis is mainly an exploratory investigation of the possibilities and capabilities available. The long-distance goal of this research is to understand the factors affecting jetting of functional polymers, with the intention of addressing in future work identified shortcomings of current technologies. The specific goal is to evaluate and gain insight into the functionality of the new acoustic resonance jetting system. This will answer the following primary research question: *To what extent does the acoustic resonance jetting system provide capabilities appropriate for polymer jetting?* Based on this general research thrust, specific points of research have been identified and will be addressed in this thesis. The motivations for each of these aspects, as well as the hypotheses that crystallize the specific interests, are outlined below.

1.3.1 Performance

In order to evaluate the capabilities of the acoustic resonance system, it is beneficial to achieve an understanding of certain process parameters that will allow improved performance for the acoustic resonance jetting system in terms of ejecting viscous fluids. Although there are many potential variables within the process, it is natural to consider the frequency of system operation; the acoustic resonances that drive ejection occur only at specific frequencies as determined by geometry of the system defined by the operator and by fluid properties.

*Hypothesis:* Coupling an acoustic resonance frequency with the resonance frequency of the piezoelectric transducer will create the strongest ejection capability.
1.3.2 Sensitivity

In addition to the process parameters of the acoustic resonance system, it is clear that the material properties of the liquid to be ejected are also crucial. However, it is not known how these properties affect the ejection or to which of these properties the ejection process is most sensitive. An understanding of the relative importance of material properties such as density, viscosity, and surface tension will enable further investigation to focus on aspects with the most significant effect upon final operational capabilities.

*Hypothesis:* Viscosity, and resulting energy losses, may dominate effects of other fluid properties in terms of fluid ejectability because its values vary by multiple orders of magnitude while other properties generally do not.

1.3.3 Capability

Ejection systems currently in use are generally tailored toward applications other than viscous polymers, and therefore have yet to successfully demonstrate ejection of those materials. In evaluating the acoustic resonance system and its applicability to this goal, it is necessary to consider unique features of the acoustic system that indicate potential capacity for ejection of these materials.

*Hypothesis:* Due to high pressure gradients formed very close to the tip of nozzle, ejection of viscous polymers may be possible.
1.3.4 Research Activities

In order to further the understanding of jetting for three dimensional fabrication, to investigate the acoustic resonance system, and to test the hypotheses presented above, a number of research activities were undertaken:

1. A thorough survey of the literature and patents regarding three-dimensional jetting was conducted and critically analyzed to identify gaps in current achievement. This involved investigating the techniques currently in use and identifying the crucial limitations thereof.

2. Because the acoustic resonance system was not originally designed for use with viscous fluids, only limited testing could be conducted with existing hardware. As a result, a partial redesign of the system housing was undertaken in order to make further testing feasible.

3. Experimental testing with a range of materials was conducted and results analyzed with respect to the viscosity and other properties of those materials as well as the process parameters. This experimental investigation allows evaluation of performance relative to material properties and to process parameters as well.

4. Analytical and model-based evaluations of the process were conducted to gain a further understanding of the phenomena involved. This evaluation allows a numerical and theoretical understanding of the experimental results.
This thesis contains eight chapters; a brief overview of the material covered in each chapter is presented here. The organization of this thesis is also outlined in Figure 2.

This first chapter is intended to provide a framework for the remainder of the thesis. A brief introduction to jetting has been presented, along with the motivations for study that has been conducted. The research objectives have been expressed concisely via motivating rationale; hypotheses have been put forth for each research point and the approach used to verify those hypotheses has been identified.
In Chapter 2, a review of the historical and current achievements in three-dimensional jetting is presented; this includes commercial systems as well as those developed in research. Although the concern of this thesis is the jetting of polymers, useful information can be gleaned from applications that involve other materials; these are therefore included as well. Chapter 3 continues the investigation of Chapter 2 on a more detailed level. Technical aspects of the jetting process reviewed in Chapter 3 allow identification of the challenges to be addressed. Together, Chapters 2 and 3 illuminate the achievements, but also the limitations, of technologies currently in use. It is with this awareness of the current limitations that improvements and progress can be made.

In the context of existing capabilities, the function of the acoustic resonance system can then be evaluated. Chapter 4 details the initial experimental investigation of the capabilities of the acoustic resonance system. Outcomes of testing conducted with a number of materials of varying properties are presented in the hopes of identifying the range of functionality of the system. Results achieved, however, were inconclusive due to a lack of repeatability in the data and a deviation from the expected behavior. At the end of Chapter 4, two main thrusts are identified as critical to achieving the research goals of this thesis: adaptation of the physical design of the system housing and investigation of the relevant physical phenomena.

Chapter 5 addresses the first of those needs – design of the housing for the acoustic jetting system. Requirements for the new design are identified, and possible embodiments that would fulfill those requirements are outlined. The specifications of the final design and manufacture are provided along with the results from a series of tests that demonstrate the ability of the new housing to provide efficiency and repeatability
during use. Finally, the new housing is evaluated relative to the requirements and found to be highly successful.

Chapter 6 reports on further experimental testing, intended to illuminate some of the physical processes relevant to the function of the acoustic jetting system. This involves testing various materials with different material and process parameter combinations in order to observe the effects of those variables. Discussion of possible interpretations of the data is also provided.

In order to better understand these experimental results, theoretical and model-based analysis of the physical processes involved in the jetting system are presented in Chapter 7. Results of modeling the acoustic field within the jet head provide insight regarding the effect of some physical parameters of the system. Analytical and model-based investigations of the fluid flow are also presented. Consideration of time scales and energy balances add qualitatively to the understanding developed and help bring together other findings. In all of these cases, the experimental results from the previous chapter are interwoven to demonstrate the relationships among experimental, numerical, and theoretical results. This chapter is concluded with discussion of the effects of process variables on functionality.

Chapter 8 serves to bring together conclusions and understanding developed throughout the previous seven chapters. The research hypotheses identified above are revisited and the current work evaluated in light of validating those hypotheses. The thesis concludes with a discussion of limitations of the current work and suggestions for future investigation.
CHAPTER 2
JETTING FOR THREE-DIMENSIONAL FABRICATION

Jetting technology has been extensively investigated, with the majority of that investigation historically based upon the applications of the two-dimensional printing industry. Recently, however, it has spread to numerous new application areas, including electronics packaging, optics, and rapid prototyping. Some of these applications, in fact, have literally taken the technology into a new dimension. The employment of jetting technologies in the creation of three-dimensional products has quickly become an extremely promising manufacturing practice, both widely studied and increasingly widely used. This chapter will summarize the three-dimensional jetting achievements made in industry and academia to date in order to provide a thorough background regarding the current abilities of jetting systems. Although the research reported in this thesis is targeted specifically at the fabrication of polymer parts via jetting, many of the same challenges are seen in the deposition of other industrial materials, which are therefore included in this chapter.

2.1 Evolution of Jetting as an Additive Manufacturing Process

Two dimensional inkjet printing has been in existence since the 1960’s, used for decades as a method of printing documents and images from computers and other digital devices. Inkjet printing is now widely used in the desktop printing industry, commercialized by companies such as HP and Canon. Le [6] provides a thorough review of the historical development of the inkjet printing industry.
2.1.1 Historical Development of 3D Jetting

Jetting as a three-dimensional building method was first evidenced in the 1980’s with patents related to the development of Ballistic Particle Manufacturing, which involved simple deposition of ‘particles’ of material onto an article [7]. The first commercially available technology was the ModelMaker from Sanders Prototype (now Solidscape), introduced in 1994, which jetted a basic wax material that was heated to liquid stage [3]. In 1996, 3D Systems joined the competition with the introduction of the Actua 2100, another wax-based jetting machine. The Actua was revised and re-released in 1999, marketed on the second round as the ThermoJet [3]. In 2001, Sanders Design International briefly entered the market with its Rapid ToolMaker, but was quickly restrained due to intellectual property conflicts with Solidscape [3]. It is notable that all of these members of the first generation of RP jetting machines relied on heated waxy thermoplastics as their build material; they are therefore most appropriate for concept modeling and investment casting.

More recently, the focus of development has been on the deposition of acrylic photopolymers – droplets of liquid monomer mixture are formed and then exposed to ultraviolet light to promote polymerization. The reliance upon photopolymerization is similar to that in stereolithography, but other process challenges are significantly different. The leading edge of this second wave of machines arrived on the market with the Quadra from Objet Geometries of Israel in 2000, followed quickly by the revised QuadraTempo in 2001. Both machines jetted a photopolymer using jet heads with over 1500 nozzles [3]. In 2003, 3D Systems launched a competing technology with its InVision 3D printer. Multi-Jet Modeling, the jetting system used in this machine, was
actually an extension of the technology developed with the ThermoJet line [3], despite
the change in material solidification strategy. The last major market change occurred in
2003, when Objet released the first of its Eden machines, a direct descendant of the
QuadraTempo [3]. The most recent versions of each of these companies’ lines are
discussed in the next section.

2.1.2 Commercially Available Jetting Machines

The three main companies involved in the development of the RP jetting industry
are still the main players offering jetting-based machines to the American market:
Solidscape, 3D Systems, and Objet Geometries (distributed in America by Stratasys).
Solidscape sells the T66 and T612, both descendents of the previous ModelMaker line
and based upon the first-generation melted wax technique. Each of these machines
employs two single jets – one to deposit a thermoplastic part material and one to deposit a
waxy support material – in forming layers 0.0005 inches thick [8]. Because of the slow
and accurate build style as well as the waxy materials, these machines are often used to
fabricate investment castings for the jewelry and dentistry industries.

3D Systems and Objet Geometries offer machines using the ability to jet and cure
acrylic photopolymers. Objet Geometries, based in Israel, markets the Eden series of
printers. The Eden machines jet a number of different acrylic-based photopolymer
materials in 0.0006 inch layers from heads containing 1536 individual nozzles. Each
photopolymer layer is cured by ultraviolet light immediately as it is jetted, producing
fully cured models without post-curing. Support structures are built in a gel-like
material, which is removed by hand and water jetting [9]. See Figure 3 for an illustration
of Objet’s Polyjet system, which is employed in all Eden machines.
In competition with Objet, 3D Systems of California markets the InVision printers, which print layers 0.0016 inches thick using heads with 448 nozzles, half for part material and half for support material [10]. Layers are then flashed with ultraviolet light, which activates the photoinitiated polymerization. The InVisions are the second generation of the Multi-Jet Modeling family from 3D Systems, following the ThermoJet described above. A comparison of the machines currently available is presented in Table 1.
### Table 1. Commercially Available Jetting-based RP Machines [8, 11, 12, 13, 14, 15]

<table>
<thead>
<tr>
<th>Company/Product</th>
<th>Cost (1000s)</th>
<th>Build Size XxYxZ (inches)</th>
<th>Min. Layer (inches)</th>
<th>Resolution X,Y,Z (dpi)</th>
<th>Material</th>
<th>Support</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solidscape</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T66</td>
<td>$40</td>
<td>6x6x6</td>
<td>0.0005</td>
<td>25M drops per sq. inch</td>
<td>Thermoplastic</td>
<td>Wax</td>
</tr>
<tr>
<td>T612</td>
<td>$50</td>
<td>6x6x12</td>
<td>0.0005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3D Systems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>InVision SR</td>
<td>$40</td>
<td>11.75x7.3x8</td>
<td>0.0016</td>
<td>328,328,606</td>
<td>Acrylic</td>
<td>Wax; heat removal</td>
</tr>
<tr>
<td>InVision HR</td>
<td>$65</td>
<td>5x7x2</td>
<td>0.0011</td>
<td>656,656,800</td>
<td>photopolymer</td>
<td></td>
</tr>
<tr>
<td><strong>Objet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eden 250</td>
<td>$60</td>
<td>10.2x9.8x8.1</td>
<td>0.0006</td>
<td>600,300,1600</td>
<td>Acrylic</td>
<td>Gel-like</td>
</tr>
<tr>
<td>Eden 260</td>
<td>$80</td>
<td>10.2x9.8x8.1</td>
<td>0.0006</td>
<td>600,300,1600</td>
<td>photopolymer</td>
<td>pressurized water removal</td>
</tr>
<tr>
<td>Eden 350(V)</td>
<td>$107/130</td>
<td>13.4x13.4x7.9</td>
<td>0.0006</td>
<td>600,600,1600</td>
<td>photopolymer</td>
<td>pressurized water removal</td>
</tr>
<tr>
<td>Eden 500V</td>
<td>$170</td>
<td>19.3x15.4x7.9</td>
<td>0.0006</td>
<td>600,600,1600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 2.2 Research Achievements in Jetting Deposition

While industry players have so far introduced jetting machines that use waxy polymers and acrylic photopolymers exclusively, research groups around the world have experimented with the potential for jetting machines that could build in those and other materials. Among those materials most studied and most promising for future applications are polymers, ceramics, and metals. This section highlights the achievements to date in those research areas.

#### 2.2.1 Polymers

Polymers consist of an enormous class of materials, representing a wide range of mechanical properties and applications; only a small fraction of that range is represented by the machines discussed in section 2.1.2. And although polymers are the only material currently used in jetting industry, there seems to be relatively little discussion on polymer
inkjet production of macro three-dimensional structures in the published scientific literature.

Gao and Sonin [16] present the first notable academic study of the deposition and solidification of groups of molten polymer microdrops. They discuss findings related to three modes of deposition: columnar, sweep (linear), and repeated sweep (vertical walls). The two materials used in their investigations were a candelilla wax and a microcrystalline petroleum wax, deposited in droplets 50mm in diameter from a print head 3-5mm from a cooled substrate. The authors first consider the effects of droplet deposition frequency and cooling on columnar formation. As would be expected, if the drops are deposited rapidly (≥ 50Hz in this case), the substrate on which they impinge is still at an elevated temperature, reducing the solidification contact angle and resulting in ball-like depositions instead of columns (Figure 4a). Numerical analyses of the relevant characteristic times of cooling are included. Gao and Sonin also consider horizontal deposition of droplets and the subsequent formation of lines. They propose that smooth solid lines will be formed only in a small range of droplet frequencies, dependent upon the sweep speed, droplet size, and solidification contact angle (Figure 4b). Finally, they propose that wall-like deposition will involve a combination of the relevant aspects from each of the above situations.
Reis et al. [17] also provide some discussion on the linear deposition of droplets. They deposited molten Mobilwax paraffin wax with a heated print head from Sanders Prototype. They varied both the print head horizontal speed and the velocity of droplet flight from the nozzle. For low droplet speeds, low sweep speeds created discontinuous deposition and high sweep speeds created continuous lines (Figure 5a-c). High droplet impact speed led to splashing at high sweep speeds and line bulges at low sweep speeds (Figure 5d-f).
Feng et al. [18] finally present a full system, based on a jet head from MicroFab Technologies Inc., that functions similarly to the commercially available machines. It jets a wax material which is heated to $80^\circ$C, more than ten degrees past its melting point, and deposits it in layers 13-60 microns thick. The deposition pattern is controlled by varying the droplet size and velocity, as well as the pitch and hatch spacing of the lines produced. An example of the result, a 2.5-dimensional gear, is presented in Figure 6.
2.2.2 Ceramics

One significant advance in terms of direct jetting for three-dimensional structures has been achieved in the area of ceramic suspensions. As in the case of polymers, studies have been conducted that investigate the basic effects of modifying sweep speed, drop-to-drop spacing, substrate material, line spacing and simple multi-layer forms in the deposition of ceramics [19]. These experiments were conducted with a mixture of zirconia powder, solvent and other additives, which was jetted from a 62 µm nozzle onto substrates 6.5 mm away. The authors found that on substrates that permitted substantial spreading of the deposited materials, neighboring drops would merge to form single, larger shapes, whereas on other substrates the individual dots would remain independent (see Figure 7). In examples where multiple layers were printed, the resulting deposition was uneven, with ridges and valleys throughout.

![Figure 7. Droplets on Two Different Substrates [19]](image)

A sizable body of work has been amassed in which suspensions of alumina particles are jetted via a wax carrier [20]. Suspensions of up to 40% solids loading have been successfully deposited; higher concentrations of the suspended powder have
resulted in prohibitively high viscosities. Because this deposition method results in a part with only partial ceramic density, the green part must be burnt out and sintered, resulting in a final product which is 80% dense but whose dimensions are subject to dramatic shrinkage [21]; a part created in this fashion is shown in Figure 8.

Figure 8. Sintered Alumina Impeller [21]

Similar attempts have been made with zirconia powder, using material with 14% ceramic content by volume [22], with an example shown in Figure 9, as well as with PZT, up to 40% ceramic particles by volume [23].
2.2.3 Metals

Much of the jetting work related to metal deposition has focused upon the use of jetting for electronics applications – formation of traces, connections, and soldering. Liu and Orme [24] present an overview of the progress made in solder droplet deposition for the electronics industry. Because solder has a low melting point, it is an obvious choice as a material for jetting. Liu and Orme [24] report use of droplets of 25-500 µm, with results such as the IC test board in Figure 10, which has 70 µm droplets of Sn63/Pb37. Many of the results to which they refer are those of researchers at MicroFab Technologies, who have also produced solder forms such as the 25 µm diameter columns shown in Figure 11.
Tseng et al. [26] deposited a tin-antimony soldering alloy, Sn95-Sb5, whose viscosity is approximately 2 cP at its melting point. They used a jet with a crucible heated to 257 °C and nozzles of diameters 203 µm to form single droplets which were collected in water for observation. Lines of material were also formed on a moving glass substrate, with a resulting line width of approximately five times the nozzle diameter, or about 1 mm.
There is, however, some work in true three-dimensional fabrication with metals. Priest et al. [27] provide a survey of liquid metal jetting technologies and history, including alternative technologies employed and ongoing research initiatives. At publication, metals that had been jetted included copper, aluminum, tin, various solders, and mercury. One major challenge identified for depositing metals is that the melting point of the material is often high enough to significantly damage components of the jetting system.

Orme et al. [28, 29] report on a process that uses droplets of Rose’s metal (an alloy of bismuth, lead, and tin). They employ nozzles of diameter 25-150 µm with resulting droplets of 47-283 µm. In specific cases, parts with porosity as low as 0.03% were formed without postprocessing, and the microstructure formed is more uniform than that of standard casting. In discussion of this technology, considerations of jet disturbance, aerodynamic travel, and thermal effects are all presented.

Yamaguchi et al. [30, 31] used a piezoelectrically driven actuator to deposit droplets of an alloy (Bi-Pb-Sn-Cd-In), whose melting point was 47°C. They heated the material to 55°C and ejected it from nozzles 200µm, 50µm, and less than 8µm in diameter. As expected, the finer droplets created parts with better resolution. The density, or ‘packing rate’, of some parts reached 98%. Figure 12 shows the effect of drop size on the resolution of the final part: the pyramid on the left was made with droplets 280 µm in diameter, whereas that on the right was made with 80 µm droplets. Other examples of fabricated parts are shown in Figure 13.
More recent results from Liu and Orme [32] introduce a process they term ‘precision droplet-based net-form manufacturing’, which involves jetting of molten aluminum droplets into an inert environment. Near-net shape components, such as those shown in Figure 14, have been formed from Al2024 alloy jetted from a 100 µm orifice.
Cao and Miyamoto [33] used pressure pulses of argon gas in the range of 20-100 KPa to eject droplets of molten aluminum at the rate of 1-5 drops per second. To achieve this, the aluminum was melted at 750 °C and the substrate to 300 °C. The nozzle orifice used was 0.3 mm in diameter, with a resulting droplet size of 200-500 µm and a deposited line of width 1.00 mm and thickness 0.17 mm. The final product was a near-net shape part of density up to 92%.

### 2.3 Summary of Chapter 2

As these examples have shown, jetting is well on its way to becoming a viable process for three-dimensional prototyping and manufacturing. While industry has only barely begun to use jetting in this arena, the economic and efficiency advantages that jetting provide ensure that it will be pursued extensively in the future. Researchers in academia have expanded the use of jetting to materials such as ceramics and metals, thus
providing additional prospective applications for the technology. Despite its great potential, however, the growth of jetting has been hampered significantly by technical challenges inherent to the jetting process. These challenges and possible solutions are investigated in Chapter 3.
CHAPTER 3
TECHNICAL CHALLENGES OF JETTING

As evidenced by the industry and research applications of jetting discussed in the previous chapter, jetting already has a strong foothold in terms of becoming a successful additive manufacturing technology. There are, however, some serious technical shortcomings that have prevented its development from further growth. In order to identify and address those problems, the relevant phenomena and strategic approaches taken by its developers must be understood. This chapter outlines the technical challenges of the jetting process, identifies the most important of its limitations relevant to the deposition of functional polymers, summarizes how those limitations are currently addressed, and introduces in detail the acoustic resonance system, which has the potential to provide new capabilities.

3.1 Functions of Jetting Process

Jetting for three-dimensional fabrication is an extremely complex process, with challenging technical issues throughout. The first of these challenges is formulation of the liquid material. As seen in Chapter 2, if the material is not in liquid form to begin with, this may mean suspending particles in a carrier liquid, dissolving materials in a solvent, melting a solid polymer, or mixing a formulation of monomer or prepolymer with a polymerization initiator. In many cases, other substances such as surfactants are added to the liquid to attain acceptable characteristics. Entire industries are devoted to
the mixture of inks for two-dimensional printing, and it is reasonable to assume that in
the future this will also be the case for three-dimensional fabrication.

The second hurdle to overcome is droplet formation. In order to use inkjet
deposition methods, the material must be converted from a continuous volume of liquid
into a number of small discrete droplets. This function is often dependent upon a finely
tuned relationship between the material being jetted, the hardware involved, and the
process parameters; a number of methods of achieving droplet formation are discussed in
section 3.2. Small changes to the material, such as the addition of tiny particles [34] can
dramatically change its droplet forming behavior as well, as can changes to the physical
setup.

A third challenge is control of the deposition of these droplets; this involves
issues of droplet flight path, impact and substrate wetting or interaction [35, 36, 37, 38,
39]. In jetting processes, either the jet head or the substrate is usually moving, so the
calculation of the trajectory of the droplets must take this issue into account. In addition
to the location of the droplets’ arrival, droplet velocity and size will also affect the
deposition characteristics, as mentioned in section 2.2, and must be measured and
controlled via nozzle design and operation. The quality of the impacted droplet must also
be controlled: if smaller droplets, called satellites, break off from the main droplet during
flight, then the deposited material will be spread over a larger area than intended and the
deposition will not have well-defined boundaries. In the same way, if the droplet
splashes on impact, forming what is called a ‘crown’, similar results will occur [40]. All
of the effects will negatively impact the print quality of the jetted material.
Concurrently, the conversion of the liquid material droplets to solid geometry must be carefully controlled; as discussed in section 1.1.1, direct jetting relies on a phase change of the jetted material. Examples of phase change modes employed in existing jetting technologies are: solidification of a melted material, evaporation of the liquid portion of a solution, and curing of a photopolymer or other chemical reactions. The phase change must occur either during droplet flight or soon after impact; the time and place of this conversion will also affect the droplet’s interaction with the substrate [41, 42] and the final deposition created. To further complicate the matter, drops may solidify non-uniformly, creating warpage and other undesirable results [43].

In three-dimensional jetting, an additional challenge arises: that of controlling deposition atop layers of previous deposition rather than only upon the initial substrate [16, 19]. The droplets will interact differently, for example, with a metal plate substrate than with a surface of previously jetted wax droplets. To create substantive three-dimensional parts, each layer deposited must be fully bound to the previous layer to prevent delamination, but must not damage that layer while being created. Commercially available machines tend to approach this problem by employing devices that plane or otherwise smooth the surface periodically [43, 44, 45].

Operational considerations also pose a challenge in process planning for jetting. For example, because nozzles are so small, they often clog, preventing droplets from exiting. Much attention has been given to monitoring and maintaining nozzle performance during operation [43]. Most machines currently in use go through purge and cleaning cycles during their builds in order to keep as many nozzles open as possible; they may also wipe the nozzles periodically [44]. Some machines may also employ
complex sensing systems to identify and compensate for malfunctioning or inconsistent nozzles [46, 47]. In addition, many machines have replaceable nozzles in case of permanent blockage.

Finally, to achieve the best print resolution, it is advantageous to produce many small droplets very close together. However, this requires high nozzle density in the print head, which is unattainable for many nozzle manufacturing processes. An alternative to nozzle density is to make multiple passes over the same area, effectively using process planning instead of hardware to create the desired effect [44]. Even in cases where high nozzle density is possible, however, problems arise due to crosstalk – basically an ‘overlapping’ of the thermal or pressure differentials used to drive adjacent nozzles.

In approaching a jetting process, these numerous challenges must in some sense be addressed sequentially: flight pattern cannot be studied until droplets are formed and layering cannot be investigated until deposition of single droplets is controlled. In terms of functional polymer deposition, the challenge of material preparation has effectively been addressed; numerous polymer resins and mixtures already exist. It is the second challenge – droplet formation – that is therefore the current limiting factor in deposition of these materials. To understand these limitations, section 3.2 reviews the dynamic processes that are currently used to form droplets and section 3.3 considers necessary methods of modifying the jetting material for use with those processes.
3.2 Droplet Formation Technologies

Over the time that two dimensional inkjet printing has evolved, a number of methods for creating and expelling droplets have been developed. The main distinction in categorizing the most common of technologies refers to the possible modes of expulsion: continuous stream (CS) and drop-on-demand (DOD). This distinction refers to the form in which the liquid exits the nozzle – as either a continuous column of liquid or as discrete droplets. Figure 15 shows the distinction between continuous (a) and drop-on-demand (b) formations.

![Figure 15. (a) Continuous and (b) Drop-on-Demand Deposition [48]](image)

3.2.1 Continuous Mode

In CS mode, a steady pressure is applied to the fluid reservoir of the jet, causing a pressurized column of fluid to be ejected from the nozzle. After departing the nozzle, this stream breaks into droplets due to Rayleigh instability. The breakup can be made more consistent by vibrating, perturbing, or modulating the jet at a fixed frequency close
to the spontaneous droplet formation rate, in which case the droplet formation process is synchronized with the forced vibration, and ink droplets of uniform mass are ejected [49]. Because droplets are produced at constant intervals, their deposition must be controlled after they separate from the jet. To achieve this, they are introduced to a charging field and thus attain an electrostatic charge. These charged particles then pass through a deflection field, which directs the particles to their desired destinations – either a location on the substrate or a container of material to be recycled or disposed. Figure 17 shows a schematic of the function of this type of binary deflection continuous system. A slightly more complex version is the multiple deflection system, in which the deposition location on the substrate can be varied [6]; see Figure 17.

Figure 16. Binary Deflection Continuous Jetting [48]
An advantage of CS deposition is the high throughput rate; it has therefore seen widespread use in applications such as food and pharmaceutical labeling [50]. Two major constraints related to this method of droplet formation are, however, that the materials must be able to carry a charge and that the fluid deflected into the catcher must be either disposed of or reprocessed, causing problems in cases where the fluid is costly or where waste management is an issue.

In terms of droplets formed, commercially available systems typically generate droplets that are about 150 µm in diameter at a rate of 80-100 kHz, but frequencies of up to 1 MHz and droplet sizes ranging from 6 µm (10 fl) to 1 mm (0.5 µl) have been reported [48]. It has also been shown that, in general, droplets formed from continuous jets are almost twice the diameter of the undisturbed jet [51].

A few investigators of three-dimensional deposition have opted to use continuous jetting methods. Blazdell et al. [52] used a continuous printer from Biodot, which was...
modulated at 66 kHz while ejecting ceramic ink from 50 µm and 75 µm nozzles. They used 280 kPa of air pressure. Blazdell [53] reports later results in which this Biodot system was modulated at 64 kHz, using a 60 µm nozzle that was also 60 µm in length. A representative ceramic ink used with this system was a suspension of ultra-fine particles 2.4% solid loading by volume, with a resultant viscosity of 1.11 cP and a surface tension of 24.5 mN/m [51]. In metal fabrication, Tseng et al. [26] used a continuous jet in depositing their solder alloy, which had a viscosity of about 2 cP at the jetting temperature. Orme et al. [28, 29] also report the use of an unspecified continuous system in deposition of solders and metals.

3.2.2 Drop-on-demand Mode

In DOD mode, in contrast, individual droplets are produced directly from the nozzle. Droplets are formed only when individual pressure pulses in the nozzle cause the fluid to be expelled; these pressure pulses are created at specific times by thermal, electrostatic, piezoelectric, acoustic, or other actuators [6]. Figure 18 shows the basic functions of a DOD setup. Liu and Orme [24] assert that DOD methods can deposit droplets of 25-120 µm at a rate of 0-2000 drops per second.
In the current DOD printing industry, thermal (bubble-jet) and piezoelectric actuator technologies dominate; these are shown in Figure 19. Thermal actuators rely on a resistor to heat the liquid within a reservoir until a bubble expands in it, forcing a droplet out of the nozzle. Piezoelectric actuators rely upon the deformation of a piezoelectric element to reduce the volume of the liquid reservoir, which causes a droplet to be ejected. As noted by Basaran [54], the waveforms employed in piezoelectrically-driven DOD systems can vary from simple positive square waves to complex negative-positive-negative waves in which the amplitude, duration, and other parameters are carefully modulated to create the droplets as desired; see Figure 20.
Numerous variations of each of these two designs exist and are used in practice. A thermal inkjet, for example, may be set up as a ‘roof-shooter’ or a ‘side shooter’, depending on the placement of the heating element relative to the nozzle orifice (see
Piezoelectric DOD nozzles also exist in a wide variety of designs, which can be categorized based on the mode of piezoceramic deformation employed and the location of the actuator: squeeze, bend, push, and shear [6]. A standard bend-mode design is displayed in Figure 22(a); when the piezoelectric element expands, it puts pressure on a diaphragm, which interfaces directly with the fluid reservoir. Push-mode configurations (Figure 22(b)) are similar, except that the polarization of the piezoelectric is perpendicular to the ejection path rather than parallel. In both cases, the electric field generated is parallel with the polarization of the piezomaterial. Shear-mode configurations, in contrast, create the piezoelectric deformation with an electric field perpendicular to the polarization of the piezoceramic element. Squeeze-mode jets (Figure 22(c)) contain cylindrical channels surrounded by thin tubes of piezoceramic; when the piezoelectric element is actuated it ‘squeezes’ the channels [6].

Figure 21. (a) Roof-shooter and (b) Side-shooter Thermal Ink-jet Designs [6]
In their review of polymer deposition, De Gans et al. [50] assert that DOD is the preferable method for all applications that they discuss due to its smaller drop size (often of diameter similar to the orifice) and higher placement accuracy in comparison to CS methods. They further argue that piezoelectric DOD is more widely applicable than thermal because it does not rely on the formation of a vapor bubble or on heating that can damage sensitive materials.

The preference for piezoelectrically driven DOD jetting is reflected in the number of investigators who use and study such setups. For example, Gao and Sonin [16] use this technology to deposit 50 µm droplets of two waxes, whose viscosity at 100 °C is about 16 cP. Sirringhaus et al. [56] and Shimoda et al. [57] both use piezoelectric DOD deposition for polymer solutions, as discussed in section 3.3.2. In ceramic deposition, Reis et al. [17] jet mixtures with viscosities 6.5 and 14.5 cP at 100 °C and frequencies of 6-20 kHz. Yamaguchi et al. [30, 31] also use a piezoelectrically driven DOD device at frequencies up to 20 Hz in the deposition of metal droplets. Similarly, the solder droplets on the circuit board in Figure 10 were also deposited with a DOD system.

Figure 22. (a) Bend- (b) Push- and (c) Squeeze-mode Piezoelectric Configurations [55]
3.2.3 Other Droplet Formation Methods

Aside from the standard CS and DOD methods, other technologies have been experimentally investigated but have not enjoyed widespread use in industry applications. Liquid spark jetting, a relative of thermal jetting, relies on an electrical spark discharge instead of a resistor to form a gas bubble in the reservoir [58]. The electrohydrodynamic inkjet employs an extremely powerful electric field to pull a meniscus and, under very specific conditions, droplets from a pressure-controlled capillary tube [58]; these droplets are significantly smaller than the tube from which they emanate. Electro-rheological fluid jetting uses an ink whose properties change under high electric fields; the fluid flows only when the electric field is turned off [58]. In their flextensional ultrasound droplet ejectors, Percin and Khuri-Yakub [59] demonstrate both drop-on-demand and continuous droplet formation with a system in which a plate containing the nozzle orifice acts as the actuator, vibrating at resonant frequencies and forming droplets by creating capillary waves on the liquid surface as well as an increased pressure in the liquid. Focused acoustic beam ejection uses a lens to focus an ultrasound beam onto the free surface of a fluid, using the acoustic pressure transient generated by the focused tone burst to eject a fluid droplet [60]. Fukumoto et al. [61] present a variant technology in which ultrasonic waves are focused onto the surface of the liquid, forming surface waves that eventually break off into a mist of small droplets. Overviews of these various droplet formation methods are given by Lee [58] and Basaran [54].
3.3 Material Modification Methods

For the droplet formation methods discussed above, the maximum jettable viscosity threshold is reported by a number of sources to be in the range of 20-40 cP at the jetting temperature [20, 50, 62], although De Gans, Kazancioglu et al. [63] contend that they have used a micropipette optimized for polymer printing applications that was able to print Newtonian fluids with viscosities up to 160 cP. While other factors such as liquid density or surface tension and jet head or nozzle design may affect the results, this limitation on viscosity quickly becomes the most problematic aspect for droplet formation of functional polymers and most other materials desirable for use in three-dimensional jetting settings.

The current method of addressing this issue is to lower the viscosity of the material to be jetted. The most common practices of using heat, solvents, or lower viscosity components are explored in the following sections. In addition to these methods, it is also possible that in some polymer deposition cases shear thinning might occur, dependent upon the material or solution in use; DOD printers are expected to produce strain rates of $10^3$-$10^4$, which should be high enough to produce shear-thinning effects [20, 64].

3.3.1 Hot Melt Deposition

The earliest and most often used solution to the problem of high viscosity is to heat the material until its viscosity drops to an acceptable point. As discussed in section 2.1.2, for example, commercial machines such as 3D Systems’ ThermoJet and Solidscape’s T66 all jet proprietary thermoplastics, which contain mixtures of various waxes and polymers that are solid at ambient temperatures but convert to a liquid phase
at elevated jetting temperatures [65]. In developing their hot melt materials, for example, 3D Systems investigated various mixtures consisting of, by weight, 20-60% low shrinkage polymer resin, 10-40% low viscosity material such as paraffin wax, 10-30% microcrystalline wax, 2-25% toughening polymer, and 1-5% plasticizer, with the possible additions of antioxidants, coloring agents, or heat dissipating filler [66]. These materials were formulated to have a viscosity of 18-25 cP and a surface tension of 24-29 dynes/cm at the jetting temperature of 130°C.

Much of the deposition of metals and ceramics, as well, is based upon this hot melt practice. Derby and Reis [20], for example, rely upon a melted wax as the carrier for their ceramic particles. The viscosities of these materials ranged from 2.9 to 38.0 cP at a measurement temperature of 100 °C. This is also the approach taken by all of the solder and metal deposition processes; they simply heat the metal past its melting point and until the viscosity drops sufficiently. Orme et al. [67], for example, use a solder whose viscosity is approximately 1.3 cP, continuously jetted under a pressure of 138 kPa.

3.3.2 Solution- and Dispersion-based Deposition

As hot-melt deposition has very specific requirements for the material properties of what is jetted, many current applications have turned to solution- or dispersion-based deposition. This allows the delivery of solids or high-molecular weight polymers in a carrier liquid of viscosity low enough to be successfully jetted. De Gans et al. [50] have recently provided a review of a number of polymeric applications in which this strategy is employed; additional representative examples of the most common current applications of this strategy are summarized here.
Although not discussed in Chapter 2 because the deposition is not true three-dimensional fabrication, a number of investigators have used solution and dispersion techniques in accurate deposition of very small amounts of polymer in thin layers for meso-scale applications such as polymer light-emitting displays, electronic components, and surface coatings and masks. Shimoda et al. [57] present a technique to develop light-emitting polymer diode displays using inkjet deposition of conductive polymers; three different electroluminescent polymers (polyfluorine and two derivatives) were jetted in organic solvents at 1-2 wt%. De Gans et al. [50] report a number of other results related to the creation of polymer light-emitting displays: polyvinylcarbazol (molecular weight 1.1x10^6) was deposited as a 10g/L solution in chloroform; poly[5-methoxy-(2-propanoxy-sulfonide)-1, 4-phenylene vinylene] (MPS-PPV) was jetted as a 2 wt% aqueous solution; a precursor of poly(p-phenylene vinylene) (PPV) was jetted as a 0.3%wt solution; and PPV derivatives were jetted in 0.5-2.0 wt% solutions in solvents such as tetraline, anisole, and o-xylene. De Gans et al. [63] report on the deposition of polymers to create micro-arrays of polymer droplets for the use in material property evaluation in the field of combinatorial material science. They used piezoelectrically actuated micropipettes to deposit 2 wt% solutions of polydisperse polystyrene. Researchers at MicroFab technologies have investigated the possibilities of using inkjet printing to create polymer coatings to be employed much as those produced by spin coating and photolithography are currently. They were able to jet the following polymers using either room temperature or raised temperature jet heads: polystyrene in aromatic solvents at a concentration of 5%, polymethylmethacrylate in mixtures of ketones and
aromatic solvents at a concentration of 1.5%, water soluble pre-polymers with 0.5wt% fumed silica particles, and thermosetting epoxy prepolymer [68].

In deposition of ceramics, the use of a low viscosity carrier is also a popular approach. Tay and Edirisinghe [19], for example, used ceramic powder dispersed in industrial methylated spirit with dispersant, binder, and plasticizer additives resulting in a material that was 4.5% zirconia by volume. The resulting material had a viscosity of 3.0 cP at 20 °C and a shear rate of 1000 s⁻¹. Zhao et al. [69] tested various combinations of zirconia and wax carried in octane and isopropyl alcohol, with a dispersant added to reduce sedimentation. The viscosities of these materials were 0.6 to 2.9 cP at 25 °C; the one finally selected was 14.2% zirconia by volume.

Despite the success of solution and dispersion deposition for these specific applications, however, there are some serious drawbacks, especially in considering the potential for building more macro structures. The low concentrations of polymer and solid used in the solutions and dispersions will restrict the total amount of material that can be deposited. De Gans et al. [63] note additionally that, in the case of polymer deposition, the maximum printable volume fraction of polymer in solution decreases with increasing molecular weight of the polymer, further restricting the deposition.

Because the solutions and dispersions contain such small amounts of the material of interest, it is also difficult to control the deposition pattern of this material within the area of the droplet’s impact. Shimoda et al. [57], among others, report the formation of rings of deposited material around the edge of the droplet. They attribute this to the fact that the contact line of the drying drop is pinned on the substrate. As the liquid evaporates from the edges, it is replenished from the interior, carrying the solutes to the
edge. They contend that this effect can be mitigated by control of the droplet drying conditions. Tay and Edirisinghe [19] report a very similar result in terms of zirconia migration during their deposition of ceramic ink droplets and give similar explanations as to the cause. Researchers at MicroFab Technologies [68] also found similar results in their polymer line deposition experiments. While they do not expressly discuss the causation, it seems plausible that the same effect is occurring. Figure 23 shows a selection of their results and a sample line height profile. Tekin et al. [70] argue that this effect can be counteracted in some cases by solvent selection and combination; their results showed that combining a low- and a high-boiling point solvent would improve this problem to the point that nearly uniform films could be created. However, this is not applicable in all cases and does not address the fact that only a tiny amount of material is being deposited.

![Figure 23](image)

**Figure 23.** (a) Lines Printed with 5% Polystyrene at (from left) 1 pass, 2 passes, 5 passes, 10 passes, 25 passes. (b) Profile of a Printed Line [68]

Another difficulty with solutions or dispersions, especially those based on volatile solvents, is that use of these materials can result in precipitations forming in the nozzle
after a very short period of time [63], which can clog the nozzle, making deposition unreliable or impossible.

### 3.3.3 Prepolymer Deposition

The most recent development in addressing the issues of viscosity is the use of prepolymer; this of course is only applicable to polymer deposition. This is the method currently employed by the two newest commercially available machine lines, as discussed in section 2.1.2. For example, 3D Systems investigated a series of UV-curable jetting materials, consisting of mixtures of, by weight, 20-40% high molecular weight monomers and oligomers such as urethane acrylate or methacrylate resins, 5-25% urethane waxes, 10-60% low molecular weight monomers and oligomers such as acrylates or methacrylates that function as diluents, 1-6% photoinitiators, and other additives such as stabilizers, surfactants, pigments, or fillers [65, 71]. These materials also benefited from the effects of hot melt deposition, as they were jetted at a temperature of 70 °C – 95 °C, with melting points between 45 °C and 65 °C. At the jetting temperatures, these materials had a viscosity of about 10-16 cP.

One problem encountered, and the reason that the jetting temperatures cannot be as high as those used in hot melt deposition, is that when kept in the heated state for extended periods of time before jetting, the prepolymer begins to polymerize, raising the viscosity and possibly clogging the nozzles when they are finally jetted [71]. Another complication is that the polymerization reaction, which occurs after jetting, must be carefully controlled to assure dimensional accuracy.
3.4 **Acoustic Resonance Jet Head**

Despite the successes achieved with hot melt, solution/dispersion, and prepolymer-based deposition, viscosity remains a formidable challenge in the jetting of viscous polymers and other materials intended for three-dimensional fabrication; it is clear that the droplet formation methods currently in use are not sufficient for applications involving these materials. Recently, however, a novel method of droplet generation has been developed that utilizes acoustic resonances and focusing within the nozzle cavity to achieve efficient ejection \[72\]; these mechanisms are inherently different from those employed by CS and DOD systems. Because of the recency of this method’s development, little is known about its capabilities in terms of ejecting viscous materials.

### 3.4.1 Design and Manufacture

The system, as described in \[73\], is composed of a simple design that uses three main components, shown in Figure 24: a piezoelectric ceramic transducer, a liquid reservoir formed by a vertical spacer at the perimeter, and a silicon plate containing micromachined ejector nozzles. The piezoelectric transducer is a purchased part; one can select the material and thickness as availability from the manufacturer dictates. The spacer that forms the liquid reservoir is effectively just a placeholder, dictating the height of the liquid volume. Of these three parts, the nozzle requires the most precise and extensive manufacturing process and is discussed in further detail below. A housing holds these components together while providing the fluid supply, electrical connections, and structural stability; further details are provided in section 5.2.
The nozzle array is etched into a standard silicon wafer; its fabrication relies upon the naturally established etch angle of 54.74° that silicon exhibits [74]. It is formed by masking everything except an array of squares with sides equal to those of the base of the pyramidal ejectors, then using KOH to etch pyramids into the bare areas of the wafer [72]. The size of the orifice is therefore determined by the thickness of the plate and the size of the unmasked squares. This manufacturing method as it relates to ink jet printing was first introduced by Bassous et al. [75, 76], who identify silicon etching as an excellent technique to create uniform, repeatable nozzle arrays. Examples of these nozzles are shown in Figure 25.
Because the result of the anisotropic etching depends to a great deal upon the thickness of the original wafer, it is difficult to precisely control orifice size. Therefore, a variant nozzle fabrication method is used to form even smaller, more precise orifices than can be created with the etching process alone. A thin nitride membrane is applied to the silicon, through which a small round hole is created. The resulting geometry is shown in Figure 26. A number of other investigators have employed variations on these two designs in attempts to improve their jetting characteristics [77, 78, 79, 80, 81]. All of those nozzles, however, were used with continuous jetting systems.

Figure 26. Etched Nozzles (a) without and (b) with Membranes (not to scale)
3.4.2 Functionality

In order to create the disturbance that ejects droplets, the piezoelectric ceramic element is subjected to a sinusoidally varying electrical input. When it is driven at the fundamental cavity resonant frequency or any of the cavity’s higher modes, a standing acoustic wave develops with the constructive interference. At the peak of each cycle, a steep pressure gradient is established near the nozzle [74]. Because of the shape of the cavity, the acoustic pressure field also forms a curved pressure peak that surrounds the orifice, as shown in Figure 27. After the pressure field is established, a droplet (or future droplet, in the case of continuous jet formation) is created with each pulse of the piezoelectric element as the pressure field creates a cyclic push-pull reaction within the fluid in the nozzle [74]. This application of pressure is one of the most notable features that distinguishes this process from standard DOD and CS ejection: it relies on transient pressure fields as DOD ejection does, but instead of the single pressure pulse used in DOD ejection it employs the resonance of an uninterrupted wave.

Figure 27. Pressure Field in Single Nozzle (Real Component)
Typical driving frequencies are in the range of 0.5 – 2.5 MHz [72], which is significantly higher than most other systems in use. In addition, both continuous jets and periodic droplets (as opposed to the aperiodic droplets seen with DOD ejection) have been observed with this mechanism [74]. Droplets of inviscid fluids of sizes 7 to 30 µm have been demonstrated using nozzle plates with orifice sizes just slightly smaller than the droplets produced [74]. Ejection of viscous fluids has not yet been investigated; the capabilities of this system in relation to jetting of functional polymers and other materials for three-dimensional jetting applications are therefore currently unknown.

3.5 Summary of Chapter 3

While the general challenges of jetting for three-dimensional fabrication are identified, there are many aspects that are not well or fully understood. Open research questions abound in almost all stages of the jetting process – droplet formation, deposition control, and multi-layer accumulation. For the case of functional polymer jetting, the most appropriate limitation to address is that of droplet formation. Because systems developed for inviscid materials are being used for these applications, numerous accommodations and limitations currently exist; users commonly handle this by modifying the materials to fit the requirements of the existing hardware. However, if the method of droplet formulation could be modified instead, this might allow the deposition of a wider range of materials. A recently developed acoustic focusing ultrasonic droplet generator, which employs a strategy different from those of existing technologies, is proposed as worthy of investigation to see whether it can provide the capabilities to fulfill this need. Following chapters detail the investigation of this technology, with the aim of
establishing an understanding of its potential for jetting high viscosity functional polymers and similar materials.
CHAPTER 4
INITIAL EXPERIMENTAL INVESTIGATION

In order to begin evaluation of the capabilities of the acoustic resonance system, a series of experiments was conducted using test fluids of varying properties. This chapter details the experimental apparatus, selection of materials, tests conducted, and results obtained from this initial investigation. Section 4.1 explains the experimental equipment and how it was arranged during the testing. Sections 4.2-4.4 review the materials, procedures, and results of testing three material families that were selected: aqueous glycerol solutions, polydimethylsiloxane blends (silicone oils), and aqueous polyethylene glycol solutions. These were selected as relatively common experimental fluids with documented properties and few safety hazards, whose viscosity could be varied with relative ease. They also represent a wide range of surface tensions, from approximately 20 mN/m to 65 mN/m. In addition to these materials, one representative photopolymer resin was also selected for testing; details are provided in Section 4.5. From these experiments, capabilities and limitations of the system were identified; these are explored in more depth in Chapters 5-7.

4.1 Experimental Equipment

As explained in section 3.4, the main functional aspects of the acoustic resonance system are the piezoceramic element, the liquid reservoir with height determined by a spacing element, and the nozzle array plate. However, actual test equipment includes a number of other elements, as shown in Figure 28. The electrical signal to the piezoelectric transducer is a pure sinusoidal voltage provided by a DS345 function
generator (Stanford Research Systems, Sunnyvale CA), with the amplitude and frequency varied by the user. This signal is then amplified by an ULTRA Series Amplifier (T&C Power Conversion, Rochester NY). The signal seen by the piezoelectric element is monitored with a TDS 2014 oscilloscope (Tektronix, Beaverton OR), triggered to display the repeating waveform. The liquid is supplied to the reservoir via a syringe of fluid connected by tubing to the main system.

![Jetting Experimental Equipment](image)

**Figure 28. Jetting Experimental Equipment (after [74])**

The piezoelectric transducer, reservoir spacer, and nozzle array are contained in a circular housing as designed and reported by Meacham [73]. This housing creates a sealed area for the liquid chamber and provides an interface with the electrical and liquid components shown in Figure 28. Figure 29 shows the assembly (a) without and (b) with the top half of the housing. The white colored parts are plastic and the grey colored parts are aluminum. The dark square at the top of (a) is the sandwich of the piezoelectric
transducer, the spacer, and the nozzle array, arranged in the same configuration as shown in Figure 28. The thick black band halfway down the inner plastic part is an O-ring, which forms a seal between the lower and upper halves of the housing. After all of these components in (a) are in place, a gasket is placed on top of the nozzle array and then the top part of the housing is bolted down over the whole system (b). A cross-sectional drawing is shown in Figure 30.

Figure 29. Jet Head Housing ([73])
4.2 Testing: Aqueous Glycerol Solutions

As a first step in investigation of the capabilities of the acoustic resonance system, a series of aqueous glycerol (C$_3$H$_8$O$_3$) solutions was tested. Glycerol is a common experimental fluid and one used extensively to investigate viscous effects in fluid flow. It is also Newtonian, which eliminates complexities that are associated with many other fluids.
4.2.1 Test Materials

Because glycerol is water soluble, aqueous solutions with a wide range of viscosities are easily created simply by varying the relative amounts of glycerol and water. Five samples were mixed from water and glycerol from Fisher Scientific (Fair Lawn, NJ), measured in proportions based on the ratios shown in Table 2. Other relevant fluid properties are also provided in the same table.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity* (cP)</th>
<th>Density* (kg/m³)</th>
<th>Surface Tension**† (mN/m)</th>
<th>Speed of Sound†† (m/s)</th>
<th>Glycerol (%wt)</th>
<th>Water (%wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>1168</td>
<td>66.7</td>
<td>1778</td>
<td>65</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>1222</td>
<td>65.1</td>
<td>1846</td>
<td>85</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1235</td>
<td>64.5</td>
<td>1862</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
<td>1240</td>
<td>64.1</td>
<td>1869</td>
<td>92</td>
<td>8</td>
</tr>
<tr>
<td>5</td>
<td>625</td>
<td>1251</td>
<td>63.3</td>
<td>1875</td>
<td>96</td>
<td>4</td>
</tr>
</tbody>
</table>

* at 20 °C
** at 25 °C
† linearly interpolated from values for increments of 10%wt
†† linearly interpolated from values for pure water and glycerol

4.2.2 Experimental Procedure

These five aqueous glycerol solutions were tested with the experimental equipment shown in Figure 29. The piezoelectric element was 1.5 mm thick, the nozzle array 500 µm thick, and the spacer 500 µm thick. The nozzle orifice size of the ejectors was approximately 8 µm. Each sample liquid was loaded into the syringe, which was then used to fill the cavity within the jet head itself. Because ~1.5 MHz had previously been identified as a frequency of operation for this device configuration, frequencies in a small range around ~1.5 MHz were investigated. After each test, the jet head was cleaned and the fluid lines flushed before the next test was commenced.
4.2.3 Experimental Results

In each trial, the aqueous glycerol solution was successfully jetted at the frequencies listed in Table 3. However, it was noted that these frequencies were most likely near the resonance frequency of the piezoelectric element itself since both water and the sample fluids jetted at similar frequencies; if the operation were not at the piezoelectric element’s resonant frequency, the operating frequency should have exhibited a greater dependence upon the liquid’s speed of sound, which varies significantly amongst the five samples. In addition, the piezoelectric element heated the materials and the nozzle array substantially and quickly during ejection. However, when the system was turned off and allowed to cool, ejection would still occur upon restarting the power amplifier. It was also noted that these liquids wetted the surface of the ejectors significantly, which may have inhibited ejection because the ejector orifices were not fully clear.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity at Room Temperature (cP)</th>
<th>Best Frequency (MHz)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>1.45</td>
<td>Jetting</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>1.45</td>
<td>Jetting</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1.46</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
<td>1.47</td>
<td>Jetting</td>
</tr>
<tr>
<td>5</td>
<td>625</td>
<td>1.47</td>
<td>Jetting</td>
</tr>
</tbody>
</table>

4.2.4 Observations

These tests were highly successful, but the lack of information about the actual phenomena in play to some extent overshadowed the results. The fact that the jet head
was heated so quickly and so significantly indicates that the operating viscosity of the material was certainly lower than the value of that property at room temperature. This is especially true for glycerin, which has a relatively steeply descending temperature-viscosity curve. In order to address this concern, materials that are less sensitive to temperature, such as those in the next section, were selected and all future tests included an approximate measurement of the heating that occurred during operation.

4.3 Testing: Polydimethylsiloxane Blends

Polydimethylsiloxanes are a family of silicone oils with the molecular structure \((\text{CH}_3)_3\text{SiO}[(\text{Si}(\text{CH}_3)_2\text{O})_n\text{Si}(\text{CH}_3)_3]\); they are used extensively in industry as stable, inert media for numerous applications. Polydimethylsiloxanes were selected because of their relatively low sensitivity to temperature; their viscosity temperature coefficient is approximately 0.60, meaning that the viscosity of this material at 99 °C is 40% of its viscosity at 38 °C [85]. For the viscosity range in use here, these materials behave like Newtonian fluids at shear rates up to \(10^4\) s\(^{-1}\) [85].

4.3.1 Test Materials

The four samples listed in Table 4 were mixed from two base materials: polydimethylsiloxane (molecular weight = 17,000) from Alfa Aesar (Ward Hill, MA) and 200 Fluid (polydimethylsiloxane) from Dow Corning (Midland, MI). The viscosities of these two fluids were 478 cS and 50 cS respectively, according to material provided by the manufacturers. These were mixed according to the ratios in Table 4, where component quantities were determined based on the following mixing relationship [86]:

62
\[
\left( \log X - \log Z \right) \times \frac{\log Y - \log Z}{\log Y} = \% Y. 
\]

Here, \(X\) is the desired resultant viscosity, \(Y\) is the viscosity of the less viscous fluid, and \(Z\) is the viscosity of the more viscous fluid. The resulting \(\% Y\) is the percent of the mixture that is composed of the lower viscosity fluid. Table 4 also provides other relevant fluid properties of the samples that were created.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity* (cP)</th>
<th>Density* (kg/m³)</th>
<th>Surface Tension* (mN/m)</th>
<th>Speed of Sound** (m/s)</th>
<th>478 cS (%vol)</th>
<th>50 cS (%vol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>971</td>
<td>20.8</td>
<td>979</td>
<td>2</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>967</td>
<td>20.9</td>
<td>985</td>
<td>32</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>964</td>
<td>21.0</td>
<td>985</td>
<td>63</td>
<td>37</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>961</td>
<td>21.1</td>
<td>986</td>
<td>94</td>
<td>6</td>
</tr>
</tbody>
</table>

* at room temperature
** interpolated from interval values at 30 °C from [85]

4.3.2 Experimental Procedure

These four samples were tested with the experimental equipment shown in Figure 29. The piezoelectric element was 2.5 mm thick, the nozzle array 500 µm thick, and the spacer 640 µm thick. The nozzle orifice size of the ejectors was approximately 40 µm. Each sample liquid was loaded into the syringe, which was then used to fill the cavity within the jet head itself. A wide range of frequencies, 0.5 – 2.5 MHz, was scanned over during the testing to identify any possible frequencies where ejection might occur. A thermocouple, attached to a multimeter, was placed in contact with the surface of the nozzle array during testing to provide an approximate measurement of the temperatures.
seen by the fluids during operation. After each test, the jet head was cleaned and the fluid lines flushed before the next test was commenced.

4.3.3 Experimental Results

Despite significant visually detectable bubbling on the surface of the ejectors, no ejection was achieved with any of these samples during any of the tests. Table 5 provides the frequency and temperature at which each sample seemed to bubble most vigorously. Once again, it is notable that the frequencies are clustered, although in this case the speed of sounds of the various samples are nearly identical so this is less surprising than in the case of the aqueous glycerol samples. However, due to the high temperatures seen by the materials, it was also expected that this frequency correlated to the main resonant frequency of the piezoelectric transducer. During these tests, wetting of the face of the nozzle array was a significant problem; it was nearly impossible to keep the surface clean even after repeated attempts to wipe residual fluid away. Section 8.5.1 outlines possible ways to address the problems encountered here.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity at Room Temp. (cP)</th>
<th>Best Frequency (MHz)</th>
<th>Operating Temperature (°C)</th>
<th>Viscosity at Operating Temp. (cP)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>0.84</td>
<td>70</td>
<td>28</td>
<td>Bubbling</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
<td>0.83</td>
<td>80</td>
<td>46</td>
<td>Bubbling</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>0.80-0.90</td>
<td>60</td>
<td>131</td>
<td>Bubbling</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>0.75-0.90</td>
<td>60</td>
<td>262</td>
<td>Bubbling</td>
</tr>
</tbody>
</table>

* calculated from viscosity temperature coefficient data [85]
4.3.4 Observations

The main effect witnessed during these experiments was that of very low surface tension. Apparently, with a material such as this, the liquid wets the face of the nozzle immediately, which prevents ejection of any type. Subsequent investigation revealed that the critical surface tension of a silicon wafer is approximately 27 mN/m, which means that any liquid with surface tension less than or equal to that value will wet the surface of the solid [87]. Since the polydimethylsiloxane blends fall in the range of 20-21 mN/m, this seems to be a reasonable explanation of their failure to eject.

4.4 Testing: Aqueous Polyethylene Glycol Solutions

Polyethylene glycols are polymers of the structure HO(CH₂CH₂O)ₙH and are used very commonly in industry as base materials for a large number of applications. They have a surface tension between those of the glycerol mixtures and the polydimethylsiloxane blends, rounding out the range of surface tensions tested. In addition, their viscosity is somewhat less sensitive to temperature than that of the glycerol solutions and should thus be more constant under heating.

4.4.1 Test Materials

Polyethylene glycol is water-soluble, so solutions of varying proportions of polymer and water can be made in order to create samples of varying viscosity. The material used in these experiments was polyethylene glycol (average molecular weight = 8,000) from Alfa Aesar (Ward Hill, MA), which is a white powder at room temperature. Polyethylene glycol solutions are considered Newtonian because their behavior so closely
resembles truly Newtonian materials [88]. Table 6 indicates the mixing ratios and other materials properties of the samples.

### Table 6. Aqueous Polyethylene Glycol Solution Test Materials [88]

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity (cP)</th>
<th>Density* (kg/m³)</th>
<th>Surface Tension* (mN/m)</th>
<th>Speed of Sound** (m/s)</th>
<th>PEG 8000 (%wt)</th>
<th>Water (%wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>1060</td>
<td>53</td>
<td>1716</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>1075</td>
<td>52</td>
<td>1763</td>
<td>45</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>1085</td>
<td>51</td>
<td>1786</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>1090</td>
<td>50</td>
<td>1809</td>
<td>55</td>
<td>45</td>
</tr>
</tbody>
</table>

* interpolated from [88]  
** linearly interpolated from data in Appendix A

#### 4.4.2 Experimental Procedure

These four samples were tested with the experimental equipment shown in Figure 29. The piezoelectric element was 2.5 mm thick, the nozzle array 500 µm thick, and the spacer 640 µm thick. The nozzle orifice sizes of the ejectors were approximately 40-45 µm. Each sample liquid was loaded into the syringe, which was then used to fill the cavity within the jet head itself. In the most viscous case, however, the fluid could not be loaded in this way due to the small diameter of the fluid conduits. In this case, the fluid was manually pooled under the nozzles before closing the housing, which unfortunately risks enclosing air bubbles in the system. A wide range of frequencies, 0.5 – 2.5 MHz, was scanned over during the testing to identify any possible frequencies where ejection might occur. A thermocouple, attached to a multimeter, was placed in contact with the surface of the nozzle array during testing to provide an approximate measurement of the temperatures seen by the fluids during operation. After each test, the jet head was cleaned and the fluid lines flushed before the next test was commenced.
4.4.3 Experimental Results

Two of the four samples of this material were successfully ejected. However, it was noted that in all cases, a significant amount of heating occurred, which was accompanied by bubbling of the liquid up onto the face of the plate. This generally occurred before any ejection was seen. Ejection took place only after the system had heated up; ejection would not occur immediately upon turning on the power supply. When ejection did occur, a white snow of polymer solid was evident on the surface surrounding the ejector, indicating that the polymer had indeed been deposited and that the water had evaporated. It should be noted that samples 1 and 3, which saw higher temperatures and were successfully ejected, were tested on a different occasion than samples 2 and 4. In addition, the frequencies of best actuation are similar to those seen with the polydimethylsiloxane samples, once again near the resonant frequency of the piezoelectric transducer.

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity at Room Temp. (cP)</th>
<th>Best Frequency (MHz)</th>
<th>Operating Temperature (°C)</th>
<th>Viscosity at Operating Temp.* (cP)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>0.85</td>
<td>85</td>
<td>15</td>
<td>Jetting</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>0.84</td>
<td>60</td>
<td>90</td>
<td>Bubbling</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>0.85</td>
<td>90</td>
<td>45</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>0.84-0.85</td>
<td>40</td>
<td>300</td>
<td>Bubbling</td>
</tr>
</tbody>
</table>

* interpolated from [88]

4.4.4 Observations

One apparent trend is that the samples successfully jetted were those that saw higher temperatures and which therefore had lower viscosity values at the operating
temperature. In addition, however, it was also noted that the results from this set of testing were somewhat inconsistent; retesting of sample 1, for example, was not able to repeat the ejection demonstrated during the first trial. Due to the high temperatures in testing of samples 1 and 3, it is hypothesized that the material may have been effectively boiling since the solvent for these materials is water and those temperatures noted are close to water’s boiling point.

4.5 Testing: Representative Material of Interest

In addition to the test materials that were identified because of their various fluid properties, a specific material of interest to polymer-based applications was also selected for testing. A representative of functional polymers that might be used with jetting systems, Waterclear 10120 is a stereolithography resin from DSM Somos (New Castle, DE). This material is an acrylate-epoxy photopolymer mixture commonly used for rapid prototyping applications with stereolithography. However, because it is already formulated as a photopolymer it could easily be converted to a material for an ultraviolet-curing jetting system.

4.5.1 Experimental Procedure

The Waterclear resin was tested with the experimental equipment shown in Figure 29. The piezoelectric element was 2.5 mm thick, the nozzle array 500 µm thick, and the spacer 640 µm thick. The nozzle orifice size of the ejector was approximately 45 µm. The resin was loaded into the syringe, which was then used to fill the cavity within the jet head itself. A wide range of frequencies, 0.5 – 2.5 MHz, was scanned over during the
testing to identify any possible frequencies where ejection might occur. A thermocouple, attached to a multimeter, was placed in contact with the surface of the nozzle array during testing to provide an approximate measurement of the temperatures seen by the resin during operation.

4.5.2 Experimental Results

This test followed the trends established in previous attempts. Jetting was achieved, but only at significantly raised temperatures and at a frequency near the resonance frequency of the piezoelectric transducer. While the operating viscosity of this resin was not known, it is expected to be much lower than the room temperature value of 130 cP. Table 8 details the material itself and the operating conditions and results during testing.

<table>
<thead>
<tr>
<th>Sample Material</th>
<th>Viscosity* (cP)</th>
<th>Density** (kg/m³)</th>
<th>Surface Tension† (mN/m)</th>
<th>Speed of Sound†† (m/s)</th>
<th>Best Frequency (MHz)</th>
<th>Operating Temp. (°C)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterclear 10120</td>
<td>130</td>
<td>1120</td>
<td>38.0</td>
<td>1606</td>
<td>0.85</td>
<td>65</td>
<td>Jetting</td>
</tr>
</tbody>
</table>

* at 30 °C  
** at 25 °C  
† measured with a Videocontact Angle VCA2500XE system (AST Products, Billerica MA)  
†† see Appendix A for measurement method

4.5.3 Observations

The successful jetting of this material demonstrated that polymer mixtures in a basic form are potentially jettable. It also demonstrated that a relatively low surface
tension of 38.0 mN/m did not prohibit jetting. However, the viscosity of this resin at operating temperatures was lower than would be the case with many other photopolymer mixtures of interest, whose room temperature viscosity can be an order of magnitude higher than 130 cP. On a positive note, no significantly observable problems with in-nozzle polymerization were encountered during testing, despite the heating of the polymer resin.

4.6 Summary of Chapter 4

The initial tests reviewed in this chapter were intended to be an exploration of the capabilities and limitations of this acoustic jetting system. As such, they were quite fruitful; they indicated that successful ejection was possible for many of the materials tested but also that there were a number of hurdles to be overcome both in the physical instantiation of the system and in our understanding of its operation.

In terms of macro-scale observations, a number of problems arose during the tests reported in this chapter. As mentioned in the comments about testing polyethylene glycol solutions, there was a good deal of inconsistency in the results obtained across multiple trials. Further proof of this issue was the fact that jetting of the aqueous glycerol samples was not replicable when retested a second time. Another significant problem was the breakage of the nozzle arrays, which are extremely limited in supply due to manufacturing constraints; these brittle silicon pieces had a tendency to crack as the housing was tightened down upon them. Finally, the housing itself was not particularly conducive to the type of testing being conducted – the capillary fluid passages in the housing made loading viscous materials nearly impossible in some cases, and the
extensive setup time required for each test made repeated testing prohibitive. All of these issues are addressed in the next chapter, which details the design and fabrication of a new housing for the test assembly.

On a more micro-scale, these tests also indicated that further experimentation and analysis was needed in order to understand the phenomena governing the function of this jetting system. The lack of jetting at frequencies other than that of the piezoelectric element, for example, indicates that the acoustic focusing and its resultant ejection was not occurring successfully in these cases. Similarly, it was unknown whether the changing of various experimental parameters was partially responsible for the inconsistencies mentioned above. Chapters 6 and 7 proceed with further experimental testing and with theoretical and model-based analysis in the hopes of clarifying these types of issues and of illuminating the processes relevant to the function of this acoustic jetting system.
CHAPTER 5
NEW HOUSING DESIGN

In order to address the macro-scale issues identified at the end of the last chapter and thereby to enable further experimental testing with the acoustic jetting system, a redesign of the housing was undertaken. This was an exercise in adaptive design, meaning that the resultant product is not completely new, but rather an improved version of a previously existing system. In this case, the design was built upon that of the housing pictured in Figure 29. This chapter outlines the requirements laid out for the new design, the possible configurations considered to address those requirements, and the final design selected. It also provides experimental validation of the new design and an evaluation of its success in meeting the initial requirements identified.

5.1 Design Requirements for Housing

In an adaptive design situation, the major functions of the system are, in general, predetermined by the original system. It then becomes the responsibility of the designer to identify shortcomings of the design and to address those shortcomings with new or modified implementations of those system functions. This section is dedicated to determining the functional requirements that must be met by this second-generation design; section 5.2 details the implementations of these requirements.

5.1.1 Evaluation of Previous Design

The original housing design described in section 4.1 is well designed, but for applications somewhat different from this study. It is most appropriate for situations in
which it can be set up once, loaded with an inviscid fluid, and left that way while testing is undertaken. In the case of these investigations, however, it is necessary to set up and break down the assembly between each material trial, as was done in the testing described in sections 4.2-4.5. However, a number of difficulties were encountered while doing this, as was outlined at the end of the last chapter. To summarize, the most problematic aspects were that the testing results were not replicable; that electrical connections and, more importantly, nozzle arrays broke repeatedly; that the time cost of setup was prohibitive; and that loading of viscous fluids was nearly impossible in some cases due to the fluid channels within the housing. The following sections lay out requirements that the new design must meet in order to address these challenges.

5.1.2 Requirements for Reliability and Repeatability

In order for testing results to be useful and for actual applications to be feasible, the jet head must be designed to emphasize reliability and repeatability in use. To achieve this, potential areas of variability must be excluded or minimized. Perhaps most importantly, the piezoelectric element, the spacer, and the nozzle array must all be stationary; the individual parts should not move relative to one another during setup or use. Because the height of the reservoir is a variable to which the jetting process is extremely sensitive, the placement and fixturing of the spacer, which defines the reservoir height, is especially crucial.

5.1.3 Requirements for Extended Testing

As opposed to testing that investigates aspects of the jetting process using a single liquid, testing that considers varying material properties inherently requires that the jet head allow ease of use with a large number of fluid samples. This means that fixed time
costs of setup and disassembly must be minimized; filling, flow, and drainage of fluids should also be expeditious. In addition, cleaning of the apparatus necessary between material trials should be minimized or expedited whenever possible.

Because of the great deal of handling that will ensue with extended testing, emphasis must also be placed on the robustness of the jet head. This means that small parts such as electrical attachments should not break during repeated handling; the silicon ejector plates should likewise be especially protected since they are the components that are most scarce and difficult to replace.

5.1.4 Requirements for Viscous Fluids

Because viscous fluids are to be tested with the jet head, allowances must be made for the properties of these materials. For example, flow channels should be designed in shape and volume appropriate for viscous fluids. A strategy must be devised to successfully load the liquid into the reservoir between the piezoelectric element and the nozzle array without damage to any components of the assembly.

Because the viscous test materials to be used are numerous and varied, this range must also be taken into account. The assembly should allow cleaning sufficient to prevent intercontamination of the various materials. In addition, it must not react with or otherwise be adversely affected by contact with the test fluids.

5.1.5 Requirements List

These requirements are now enumerated in a requirements list, shown in Table 9.
Table 9. Requirements List for Housing Design

<table>
<thead>
<tr>
<th>#</th>
<th>Requirement</th>
<th>Demand/Wish</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Should hold nozzle array stationary</td>
<td>D</td>
</tr>
<tr>
<td>2</td>
<td>Should keep height of reservoir accurate</td>
<td>D</td>
</tr>
<tr>
<td>3</td>
<td>Should hold piezoelectric transducer stationary</td>
<td>D</td>
</tr>
<tr>
<td>4</td>
<td>Should not leak</td>
<td>D</td>
</tr>
<tr>
<td>5</td>
<td>Should not break under repeated handling</td>
<td>D</td>
</tr>
<tr>
<td>6</td>
<td>Should not damage nozzle arrays</td>
<td>D</td>
</tr>
<tr>
<td>7</td>
<td>Fixed setup time should be less than 5 minutes</td>
<td>W</td>
</tr>
<tr>
<td>8</td>
<td>Fixed cleanup time should be less than 10 minutes</td>
<td>W</td>
</tr>
<tr>
<td>9</td>
<td>Should allow user to verify reservoir height</td>
<td>W</td>
</tr>
<tr>
<td>10</td>
<td>Should allow use of piezoelectric elements 0.5 – 2.0 mm</td>
<td>D</td>
</tr>
<tr>
<td>11</td>
<td>Should allow reservoir height of 0.2 – 2.0 mm</td>
<td>D</td>
</tr>
<tr>
<td>12</td>
<td>Should allow use with fluids of viscosities O(1) – O(1000) cp</td>
<td>D</td>
</tr>
<tr>
<td>13</td>
<td>Should withstand temperatures up to 100 °C</td>
<td>D</td>
</tr>
<tr>
<td>14</td>
<td>Should not react detrimentally to contact with test fluids</td>
<td>D</td>
</tr>
</tbody>
</table>

## 5.2 Jet Head Housing Design

Based on the requirements list above, numerous design implementations were identified and evaluated. From those concepts, the best options were chosen for each function of the assembly. Those options were then compiled to form the final design of the housing, which was then fabricated in full. This section provides a summary of the concepts considered as well as a description of the final design solution.
5.2.1 Variants: Ideation and Evaluation

A number of functions that the design needed to fulfill were ideated and are listed in the first column of Table 10. Subsequent columns list potential solutions that were considered and, in some cases, prototyped and tested. Those marked with an asterisk are the methods used in the original design; those selected for the final design here are marked in italics. Table 11 is presented in the same manner, but contains manufacturing, fabrication, or material aspects rather than functional ones.

<table>
<thead>
<tr>
<th>Function</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical nozzle immobilization</td>
<td>none</td>
<td>compression*</td>
<td>permanent attachment</td>
<td>enclosure</td>
</tr>
<tr>
<td>Lateral nozzle immobilization</td>
<td>none*</td>
<td>compression</td>
<td>permanent attachment</td>
<td>enclosure</td>
</tr>
<tr>
<td>Reservoir height control</td>
<td>none</td>
<td>separate spacer*</td>
<td>integrated spacer</td>
<td>micrometer-driven platform</td>
</tr>
<tr>
<td>Reservoir height confirmation</td>
<td>none*</td>
<td>acrylic ‘window’</td>
<td>transparent housing</td>
<td>micrometer measure</td>
</tr>
<tr>
<td>Piezoelectric immobilization</td>
<td>none</td>
<td>compression</td>
<td>permanent attachment*</td>
<td>enclosure</td>
</tr>
<tr>
<td>Fluid supply</td>
<td>external reservoir*</td>
<td>internal reservoir</td>
<td>external pump</td>
<td>--</td>
</tr>
<tr>
<td>Leakage prevention</td>
<td>O-ring*</td>
<td>gasket</td>
<td>fluid conduit fittings*</td>
<td>adhesive*</td>
</tr>
<tr>
<td>Dimensional flexibility</td>
<td>none</td>
<td>piston-in-cylinder design*</td>
<td>multiple sizes of components</td>
<td>spring-loaded assembly</td>
</tr>
</tbody>
</table>
Table 11. Matrix of Component Fabrication and Materials

<table>
<thead>
<tr>
<th>Component</th>
<th>Option 1</th>
<th>Option 2</th>
<th>Option 3</th>
<th>Option 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer housing</td>
<td>machined plastic*</td>
<td>machined metal</td>
<td>SLA plastic</td>
<td>off-the-shelf components</td>
</tr>
<tr>
<td>Gaskets</td>
<td>neoprene</td>
<td>silicone gel</td>
<td>latex</td>
<td>gum rubber</td>
</tr>
<tr>
<td>Electrical connections</td>
<td>single strand, soldered*</td>
<td>multi-strand, soldered</td>
<td>integrated</td>
<td>--</td>
</tr>
<tr>
<td>Spacer</td>
<td>brass*</td>
<td>Kapton*</td>
<td>SLA plastic</td>
<td>aramid/ Buna-N</td>
</tr>
<tr>
<td>Fluid conduits</td>
<td>capillary tubing*</td>
<td>macro tubing</td>
<td>integrated channels*</td>
<td>--</td>
</tr>
</tbody>
</table>

5.2.2 Final Design

The design of the final assembly is shown in Figure 31. The black square in the center of the top surface is the nozzle array; the droplets are ejected vertically from it. The main concept of this system is that of a sandwich, where the piezoelectric element and the nozzle array are held together between lower and upper parts of a housing, which also provides the electrical and fluid interfaces for the system; an exploded view is presented in Figure 32.

Figure 31. New Housing
The main body was built in a Viper Si2 stereolithography machine (3D Systems, Valencia CA) using Waterclear 10120 resin (DSM Somos, New Castle DE); this method of manufacture provides numerous advantages. Because it is an additive process, detail and contouring of internal geometry is easily achieved and is exploited in this design. In addition, because SLA is a rapid manufacturing process, multiple versions of the housing...
with varying dimensions or features can be created efficiently. Finally, the transparency of the build material allows visual confirmation of the placement of nozzle array and spacer, even after the housing is assembled. Other internal aspects of the process, such as fluid filling and flow, can be visually monitored with this SLA housing; this would be impossible with the use of almost any other fabrication material and method.

![Cross-sectional View of New Housing](image)

**Figure 33. Cross-sectional View of New Housing**

The upper housing has a protective ‘pocket’ for the nozzle array; a gasket between them forms a liquid barrier and cushions the nozzle array, as can be clearly seen in the cross-section and close-up views in Figure 33. The other side of the nozzle array is adjacent to the spacer, which is made of a compliant but incompressible aramid/Buna-N
gasket covered with Kapton tape. Selection of a compliant material also reduces stresses on the nozzle array that occur when it is compressed against harder, possibly irregular surfaces, thus preventing breakage. Two quick-turn Luer lock fluidic fittings are attached to the upper housing; these allow the user to quickly and easily attach any tubing with a Luer connection to the fluid inlet or outlet of the housing. In fact, in the testing conducted for this thesis, disposable tubing was used to prevent intercontamination among different materials. The internal fluid pathways are contoured and integrated in the main housing to create barrier-free flow for viscous materials; they widen at the interface areas with the nozzle array to provide the best possible filling efficiency. Details specific to the upper housing are shown in Figure 34.

![Figure 34. New Housing: Details of (a) Upper and (b) Lower Halves](image)

The piezoelectric transducer is attached to the lower housing, and the two electrical leads are soldered directly to the top and bottom of the piezoelectric element. The lower housing also has stiffening bars, shown in Figure 34, that prevent warpage
when the connectors are tightened in the corners. This allows a uniform pressure on the interior components, which is another method of preventing nozzle array breakage.

One significant difference between this and the original design is that this system is actually loaded upside down, in that the user turns over the upper housing and places the small gasket, the nozzle array, and the spacer into the pocket in that order. The lower housing, which carries the piezoelectric transducer and a large gasket that fills the gap between the two housing halves, thus preventing leakage during use, is placed on top. The entire assembly can then be bolted together and turned right side up for use. By using this method of loading, the nozzle array’s motion is fully constrained, preventing it from sliding around during loading, as was the case in the original design.

5.3 Experimental Testing & Design Validation

In order to validate the new design, testing was undertaken to demonstrate reliability and repeatability of results. Two separate tests were performed. The first involved testing some of the same material samples that were previously tested on the original jet head and comparing the results with those reported in Section 4.4; this is intended to demonstrate that the new system housing will provide results consistent with those of the original one. The second consisted of ejecting water a number of times and comparing the results among trials; this was intended to demonstrate the repeatability of the results achieved.

5.3.1 Comparison Testing: Glycerol and Polyethylene Glycol Solutions

In order to compare this housing to the original, the series of tests using aqueous glycerol and aqueous polyethylene glycol solutions first reported in sections 4.2 and 4.4
were repeated using the new housing. In this situation, the piezoelectric transducer was 1.5mm thick, the nozzle array 500 µm thick, the spacer 590 µm, and the nozzle orifice 45 µm. A wide range of frequencies, 0.5 – 2.5 MHz, was investigated during the testing to identify any possible frequencies where ejection might occur. All other aspects of the experimental procedure remained the same as the earlier tests. The results of the tests with the new housing are detailed in Table 12.

Table 12. Testing Results for New Housing

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity at Room Temp. (cP)</th>
<th>Best Frequency (MHz)</th>
<th>Operating Temperature (°C)</th>
<th>Viscosity at Operating Temp.* (cP)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous Glycerol Solutions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>1.47</td>
<td>60</td>
<td>4</td>
<td>Jetting</td>
</tr>
<tr>
<td>3</td>
<td>110</td>
<td>1.48</td>
<td>90</td>
<td>6</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>220</td>
<td>1.48</td>
<td>58</td>
<td>25</td>
<td>Jetting</td>
</tr>
<tr>
<td>5</td>
<td>310</td>
<td>1.48</td>
<td>78</td>
<td>14</td>
<td>Jetting</td>
</tr>
<tr>
<td>6</td>
<td>625</td>
<td>1.49</td>
<td>85</td>
<td>17</td>
<td>Jetting</td>
</tr>
<tr>
<td>Aqueous Polyethylene Glycol Solutions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>80</td>
<td>1.40-1.60</td>
<td>51</td>
<td>35</td>
<td>Bubbling</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>1.30-1.50</td>
<td>66</td>
<td>60</td>
<td>Bubbling</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>1.45-1.60</td>
<td>58</td>
<td>100</td>
<td>Bubbling</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>1.30-1.50</td>
<td>62</td>
<td>150</td>
<td>Bubbling</td>
</tr>
</tbody>
</table>

* interpolated from table [82] for glycerol solutions and from chart [88] for polyethylene glycols

The results for the glycerol solutions are almost identical to those found during testing with the original housing. Ejection was achieved with all samples, as was found in the first series of testing, but which was found to be unrepeatable when attempted again with the original housing. The frequencies of ejection are also quite similar to the original tests; the small variations in ejection frequency can be attributed to tiny differences among piezoelectric transducers. As before, these frequencies around 1.5 MHz are at the piezoelectric resonant frequency. The polyethylene glycol results are
quite similar as well, although the inconsistency of results from the original testing makes it difficult to draw direct comparisons. Because the temperatures seen during this second set of trials were not as high as those during the first, it is expected that ejection might not occur in all of the same cases.

5.3.2 Repeatability Testing: Water Trials

In order to gauge repeatability of results with the new housing, a series of tests involving water were performed. On four separate occasions, water was loaded into the housing with the same experimental procedures used in previous tests. The piezoelectric element was 1.5 mm, the nozzle array 500 µm thick, the spacer 590 µm, and the nozzle orifice 16 µm. Driving signal amplitudes up to 35 Vrms were allowed. Ejection at four specific frequencies was tested, as determined via methods described in detail in section 6.1: the first three cavity resonances at ~0.75, ~1.30, and ~1.79 MHz, respectively, and the piezoelectric transducer resonance at ~1.47 MHz. Results are shown in Table 13.

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Result</th>
<th>Temp (°C)</th>
<th>Result</th>
<th>Temp (°C)</th>
<th>Result</th>
<th>Temp (°C)</th>
<th>Result</th>
<th>Temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Jetting</td>
<td>28</td>
<td>Jetting</td>
<td>31</td>
<td>Jetting</td>
<td>50</td>
<td>Jetting</td>
<td>29</td>
</tr>
<tr>
<td>2</td>
<td>Jetting</td>
<td>35</td>
<td>Jetting</td>
<td>34</td>
<td>Jetting</td>
<td>40</td>
<td>Jetting</td>
<td>36</td>
</tr>
<tr>
<td>3</td>
<td>Jetting</td>
<td>33</td>
<td>Jetting</td>
<td>32</td>
<td>Jetting</td>
<td>39</td>
<td>Bubbling</td>
<td>--</td>
</tr>
<tr>
<td>4</td>
<td>Jetting</td>
<td>36</td>
<td>Jetting</td>
<td>43</td>
<td>Jetting</td>
<td>43</td>
<td>Jetting</td>
<td>43</td>
</tr>
</tbody>
</table>

As expected, the first and second cavity resonance and the piezoelectric transducer resonance were all very reliable across the four trials. Ejection was achieved
in all cases, and the temperature ranges were fairly consistent, with higher temperatures seen around the piezoelectric transducer frequency. Ejection at the third cavity resonance was extremely weak in all cases; on the third trial ejection did not occur at all. Poor ejection at cavity resonances significantly higher than the piezoelectric transducer resonance is a phenomenon seen consistently with this acoustic jetting system, although it is not fully understood. With the exception of the third cavity resonance results, however, the rest of the trials are quite consistent. These trials, along with the material testing described in the previous section, sufficiently demonstrates that the function of the new housing design will provide consistent, useful data in subsequent testing.

5.4 Evaluation of Requirements Satisfaction

It has been established in the previous section that the housing functions well. However, to fully evaluate the success of the new housing, the initial requirements list must be revisited in order to gauge the degree to which each requirement was met. To this end, Table 14 repeats the requirements list, with an additional column titled ‘Evaluation’ in which the new housing’s success is evaluated. For each requirement, a rating of 1, 2, or 3 is given, where a 1 means that the requirement was fully satisfied, a 2 that it was partially satisfied, and a 3 that it was not at all satisfied.
<table>
<thead>
<tr>
<th>#</th>
<th>Requirement</th>
<th>Demand/Wish</th>
<th>Evaluation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Should hold nozzle array stationary</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Should keep accurate height of reservoir</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Should hold piezoelectric transducer stationary</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Should not leak</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Should not break under repeated handling</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Should not damage nozzle arrays</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Fixed setup time should be less than 5 minutes</td>
<td>W</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Fixed cleanup time should be less than 10 minutes</td>
<td>W</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Should allow user to verify reservoir height</td>
<td>W</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Should allow use of piezoelectric elements 0.5 – 2.0 mm</td>
<td>D</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td>Should allow reservoir height of 0.2 – 2.0 mm</td>
<td>D</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>Should allow use of fluids of viscosities O(1) – O(1000) cp</td>
<td>D</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Should withstand temperatures up to 100 °C</td>
<td>D</td>
<td>1?</td>
</tr>
<tr>
<td>14</td>
<td>Should not react detrimentally to contact with various fluids</td>
<td>D</td>
<td>1?</td>
</tr>
</tbody>
</table>

Requirements 1-3 define the need for physical structure within the print head, as the process is sensitive to small geometrical changes. The nozzle array ‘pocket’ as well as the compression of layers in the housing fully immobilizes all components without breakage; thus all three requirements are fully satisfied.

The robustness of the housing is reflected in requirements 4-6. During the testing covered in this chapter as well as all the testing that will be reported in Chapter 6, leakage was negligible, no electrical connections or small parts broke, even with extensive handling, and the single nozzle array that was damaged was a victim of user error. These are all significant achievements and therefore warrant the ‘fully satisfied’ rating given.
In terms of usability, great improvements were made with this second generation housing. Setup and cleanup were efficient due to the simple basic structure and few connectors; the time constraints mentioned in the requirements list were met. Another achievement of this housing is the ability of the user to visually confirm that all internal components are situated properly and to monitor fluid flow and other internal processes. As a result, requirements 7-9 are also considered to be fulfilled completely.

One area in which this housing does not greatly improve on the original design is flexibility. By giving up the piston-in-cylinder design for a sandwich design, some of the ability to use internal components of varying dimensions is lost. With this design, separate gaskets must be made to correspond with each spacer height, whereas the original design was continuously variable. Because of this limitation, requirements 10 and 11 are evaluated as having been only being partially fulfilled. The housing does better, however, with the various fluids tested. Wider, contoured fluid flow channels and careful inlet and outlet placement make it easy to load and test viscous fluids, resulting in the full satisfaction of requirement 12.

Requirements 13 and 14 are given a provisional ‘1’ due to the fact that the temperature and materials have not been extreme in testing to date. While the new housing has performed well in all testing undertaken, it cannot be pronounced fully successful in these areas without a more thorough exploration of its limits.

With these evaluations, it is clear that this new design achieves all of the main requirements set out. Of course, further improvements can always be made, but for the application at hand this housing has been shown to be very appropriate.
5.5 Summary of Chapter 5

In response to a need identified during the initial investigation reported in the Chapter 4, the design of a new housing was undertaken. In order to direct the design process, a number of requirements were identified as important to the functionality of the new system. As a variant of an existing design, many of the basic functionalities of the system had been previously identified. However, the implementation of many of these functions and the manufacturing and material choices made during the design process resulted in a significantly improved assembly. The new design, as described in this chapter, maintains the basic functions provided by the original housing while improving usability, protection of the nozzle arrays, ease of use with viscous fluids, reliability, and robustness. This consistency with the previous design and the success of the changes made were demonstrated in a series of tests directly specified for that purpose. Finally, the requirements identified earlier in the design process are revisited for evaluation, after which it is clear that the new design satisfies almost all of the requirements in full. With this system-scale goal accomplished, the more micro-scale objectives identified after the initial experimental investigation can be addressed. The next chapter details in-depth experimental testing conducted with the new housing described here as a means to gather information and insight into the ejection process itself.
Although the results reported in Chapter 4 provided beneficial insight into the acoustic jetting process, further experimental testing was required in order to fully understand and evaluate it. This chapter describes additional testing conducted to provide that insight; information about experimental configuration, procedures, and results are presented. The testing reported here was intended to address a wide range of process circumstances and, specifically, to investigate the relationship between the nozzle cavity resonances and the resonance of the piezoelectric transducer itself. Materials used previously were again employed in order to keep consistency and comparability among the data. Significant changes from the experimental testing reported in Chapter 4 are that the nozzle used in this testing was 16 µm for all trials and that the housing used here is the one developed as described in Chapter 5.

### 6.1 Selection of Testing Parameters

This section details how the geometrical and process parameters were selected for the testing reported in this chapter. The parameters identified are intended to provide a wide range of insight about the process so that conclusions about its function and capabilities can be reached.
6.1.1 Selection of Materials

For this testing, the same materials that were used in Chapter 4 were again considered. However, due to the extremely low surface tension of the polydimethylsiloxane blends and their resulting tendency to wet the surface of the nozzle array, they were not selected for this testing. Therefore, the testing reported here utilizes the aqueous solutions of glycerol and polyethylene glycol described in Chapter 4.

6.1.2 Selection of Testing Frequencies

Since it is known that the resonant frequency of the piezoelectric transducer is the point where it most efficiently converts the electrical energy input into mechanical energy, it is important to evaluate not only the general performance of the system at any cavity resonant frequency but also to consider the effect that the piezoelectric transducer’s natural resonant frequency has upon the process. Thus, it is instructive to evaluate the performance of the acoustic resonance system when the cavity resonance frequencies lie close to and far from, as well as above and below, the resonant frequency of the transducer itself.

The natural resonant frequency of the piezoelectric element depends on its material, geometry, and dimensions. For a flat plate transducer, the resonant frequency $f_p$ is defined by the equation

$$f_p = \frac{N_T}{h_p},$$

(2)

where $N_T$ is the thickness mode frequency constant and $h_p$ is the thickness of piezoelectric element [90]. For the piezoelectric material used here, APC 880 (APC International, Mackeyville PA), $N_T = 2110$ m/s. Thus for a transducer of thickness 1.5 mm, as used in

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In this research, the resonant frequency is calculated at 1.41 MHz. Small manufacturing and dimensional variations, of course, mean that this value is nominal only; the true value can lie in a small range around that point.

One way to control the frequencies at which the cavity resonances appear is to vary the height of the liquid reservoir inside the nozzle assembly, which is achieved by employing spacers of different heights. In order to establish the standing wave within the nozzle cavity, the height of that cavity must be, approximately, an integer multiple of the half-wavelength. The fundamental resonant frequency of the nozzle cavity is then

\[ f_n = \frac{c}{2h_n}. \]  

Multiples of this fundamental frequency will also result in resonance. As was shown in Figure 33, the spacer and nozzle array together determine the height of the fluid cavity, but since the nozzle array is of fixed thickness due to manufacturing methods, the spacer is the main option in terms of affecting fluid reservoir height.

### 6.1.3 Selection of Spacer Thickness

Although equation 3 provides an approximation of the relationship between fluid cavity height and operating frequency, this relationship can vary a significant amount. A more precise method of determining cavity resonance frequencies is to use a model of the acoustic activity, developed by Meacham et al. [72]. In this model, the commercial finite element analysis software ANSYS 9.0 (Canonsburg, PA) is used to simulate the pressure field generated in the fluid chamber due to periodic excitation of the piezoelectric transducer and its interactions with the spacer and ejector plate [73]. The simulation is conducted as a harmonic response analysis over the frequency range of interest and is
based upon a two-dimensional representation of the device geometry. Details of the model can be found in Appendix B and in Meacham [73].

One very useful result obtained from the acoustic simulation is a calculation of the electrical impedance at each frequency of the harmonic analysis. The impedance values can be illustrated in graphs such as that in Figure 35. This example corresponds to the jet head filled with water, using an 840 \( \mu \text{m} \) thick spacer and a 1.5 mm thick piezoelectric transducer with a signal amplitude of 10 V. This simulation involved a nozzle with 40 \( \mu \text{m} \) orifice, but changes of orifice size are not expected to significantly alter the frequencies at which resonances occur. The peaks of the real component of the complex impedance correspond to resonant frequencies of the device, although not all of those frequencies correspond to cavity resonances [73]. For example, in Figure 35, the peaks labeled 1, 2, and 3 are the first, second, and third cavity resonances, at \( \sim 0.74 \), \( \sim 1.29 \), and \( \sim 1.84 \) MHz, respectively. The peak labeled N is a resonance of the system, but does not result in focusing within the nozzles. The large peak in the center corresponds to the resonant frequency of the piezoelectric transducer itself but, again, does not result in focusing within the nozzle area.
Although it is not possible to distinguish the types of resonances from the impedance graph, cavity resonances can be identified by considering contour plots of the pressure field within the nozzle, which can be generated from the same acoustic simulation. Figure 36 shows two pressure fields derived from the simulation that was used to generate Figure 35. The first pressure field, shown in (a), is at ~0.74 MHz, which is the first cavity resonance for that situation. The second is at ~0.89 MHz, which is a non-cavity resonance of the system. These images show only the real portion of the complex pressure field as reported by ANSYS; the darker regions correspond to more extreme (negative or positive) pressure values.
In order to test cavity resonances near and far from the piezoelectric transducer’s natural resonant frequency, the acoustic simulation methods described above were used to select a spacer height of 840 µm, which would place the cavity resonances at the desired frequencies. Since the materials to be tested are all solutions of a material in water, considering the resonant frequencies of those two liquids in their pure form provides bounds on a range of frequencies that would apply to the solutions. For example, Figure 37 shows the impedance curves for a jet head with a 1.5 mm thick piezoelectric element, an 840 µm spacer and a signal amplitude of 10 V. The fluid has a density $\rho$ of 1250 kg/m$^3$ and a speed of sound $c$ of 1900 m/s, approximately the values of pure glycerol. Here, the first cavity resonance falls at ~0.92 MHz, the second at ~1.67 MHz, and the third at ~2.29 MHz.
Given the cavity resonant frequencies for water and glycerol shown in Figure 35 and Figure 37, the resonant frequencies for the solutions can be expected to fall between them. So, in this case, solutions of glycerol and water are expected to have their first cavity resonance between ~0.74 and ~0.92 MHz, their second between ~1.29 and ~1.67 MHz, and their third between ~1.84 and ~2.29 MHz. Because the glycerol solutions have only a modest quantity of water, the values should tend toward the higher end of that range. Even with the sophisticated model employed to derive these values, some variation is inevitable due to small changes in the experimental conditions; hence these ranges are used as guides rather than as predictors. As these ranges indicate, the selection of a spacer height of 840 µm provides exactly the range of resonance desired: one well below the piezoelectric transducer’s resonance, one very close to it, and one well above.
it. Since polyethylene glycol’s density and speed of sound fall between those of water and glycerol, these ranges are expected to apply to all materials tested.

6.2 Experimental Procedure

For this testing, the equipment and procedures were similar to those reported in Chapter 4. The electrical apparatus remained as shown in Figure 28, although the housing for the jet head was of the design described in Chapter 5. During this testing, the piezoelectric element was 1.5 mm thick, the nozzle array 500 µm thick, and the spacer 840 µm thick, as suggested in the previous section. The nozzle orifice size of the ejectors was approximately 16 µm. Each sample liquid was loaded into the syringe, which was then used to fill the cavity within the jet head itself. A wide range of frequencies, 0.5 – 2.5 MHz, was scanned over during the testing to identify any possible frequencies where ejection might occur, keeping the voltage across the piezoelectric element as close as possible to 35 V\textsubscript{rms} without exceeding 40 V\textsubscript{rms} or 15 W of consumed power. A thermocouple, attached to a multimeter, was placed in contact with the surface of the nozzle array during testing to provide an approximate measurement of the temperatures seen by the fluids during operation. Separate syringes and tubing were used for each liquid and other parts of the equipment in contact with the test fluids were cleaned thoroughly between trials.
6.3 Experimental Results

6.3.1 Aqueous Glycerol Solutions

Although a wide range of frequencies was investigated in this testing, ejection was witnessed only at three frequencies: the first and second cavity resonances and the piezoelectric transducer’s resonance, the frequency of which falls between the prior two resonances. No ejection was seen at the third cavity resonance. Table 15 provides details about the performance observed with these materials. For each of the materials and each of the three resonances at which ejection was seen, the frequency at which the qualitatively best ejection was seen, the lowest temperature at which ejection was possible, and the calculated viscosity at that temperature are given.

Table 15. Aqueous Glycerol Solutions Test Results

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Viscosity at Room Temp. (cP)</th>
<th>Best Ejection Frequency (MHz)</th>
<th>Operating Temperature (°C)</th>
<th>Viscosity at Operating Temp.* (cP)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Cavity Resonance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>0.97</td>
<td>34</td>
<td>9</td>
<td>Jetting</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>No Jetting</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>0.99</td>
<td>51</td>
<td>34</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>No Jetting</td>
</tr>
<tr>
<td>5</td>
<td>625</td>
<td>0.99</td>
<td>60</td>
<td>45</td>
<td>Jetting</td>
</tr>
<tr>
<td>Piezoelectric Transducer Resonance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>1.42</td>
<td>47</td>
<td>5</td>
<td>Jetting</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>1.47</td>
<td>50</td>
<td>21</td>
<td>Jetting</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1.47</td>
<td>50</td>
<td>36</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
<td>1.46</td>
<td>66</td>
<td>23</td>
<td>Jetting</td>
</tr>
<tr>
<td>5</td>
<td>625</td>
<td>1.47</td>
<td>65</td>
<td>38</td>
<td>Jetting</td>
</tr>
<tr>
<td>Second Cavity Resonance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>1.63</td>
<td>32</td>
<td>9</td>
<td>Jetting</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>1.65</td>
<td>43</td>
<td>30</td>
<td>Jetting</td>
</tr>
<tr>
<td>3</td>
<td>220</td>
<td>1.65</td>
<td>50</td>
<td>36</td>
<td>Jetting</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
<td>1.66</td>
<td>40</td>
<td>78</td>
<td>Jetting</td>
</tr>
<tr>
<td>5</td>
<td>625</td>
<td>1.63</td>
<td>40</td>
<td>142</td>
<td>Jetting</td>
</tr>
</tbody>
</table>

* linearly interpolated from [82]
It is notable that at the first cavity resonance, which is quite far from the transducer’s resonant frequency, ejection was observed to be somewhat weak and unreliable; this is confirmed by the data in Table 15, which shows that two of the samples did not eject at all at that resonance.

6.3.2 Aqueous Polyethylene Glycol Solutions

Although the noted material properties of the polyethylene glycol solutions are not dramatically different from the glycerol solutions, they nevertheless behaved quite differently during testing. Instead of ejection at resonant frequencies, they simply bubbled up onto the face of the nozzle array, filling the area with liquid. It is not known whether this pooled liquid prevented ejection that might have otherwise occurred, as it was impossible to keep the face clear long enough to evaluate the ejection capabilities. This bubbling was noted at the first cavity resonance as well as over a range of frequencies that encompassed both the piezoelectric and second cavity resonances. Section 8.5 details some implications of and possible solutions to this occurrence.

6.4 Conclusions

As was expected, the ejection capabilities were shown to depend not only on the resonant frequencies of the nozzle fluid cavities, but also on the resonant frequency of the piezoelectric transducer. The most apparent trend of the ejection observed is that ejection at frequencies far from the transducer’s resonant frequency is weak or nonexistent; this is especially true at frequencies above the transducer’s resonance and to a lesser extent at those below it. Thus, a cavity resonance must be placed proximally to that of the transducer in order for it to function successfully.
Another notable result is that the viscosities of ejection at the second cavity resonance are slightly higher than those at the nearby piezoelectric resonant frequency; this trend is shown in Figure 38. This indicates that the acoustic focusing does positively affect the ejection capabilities of the system. It should be noted when considering these results that there is possibility for error in the measurement of temperature, as the temperature at the surface of the nozzle array may not exactly coincide with the temperature seen locally by the liquid during ejection and temperature fluctuations were quite rapid. Thus, these results should be viewed cautiously, especially since small errors in temperature measurement are magnified when the operating viscosity is calculated for samples whose original viscosity was high, as the operating viscosity values were interpolated from values at 10 °C intervals; this would apply to samples 4 and 5 especially.

![Figure 38. Viscosities at Piezoelectric and Cavity Resonance Ejection](image)
In terms of the absolute value of the material properties of the liquids ejected, it seems that the range of ejection capability is mainly confined to viscosities less than approximately 100 cp if the most outlying data point is discarded. Based on qualitative observations, this limit could most likely be raised by increasing the driving voltage of the system. However, this would probably elevate the value only incrementally; it would likely not achieve ejection of viscosities of a much higher order of magnitude.

Conclusions about surface tension are limited since only glycerol solutions were successfully ejected here. However, that may be a conclusion in itself – those materials have the highest surface tension of all test liquids; their values are closest to that of water, which can also be ejected.

### 6.5 Summary of Chapter 6

In this chapter, the results of further experimental investigation conducted to illuminate the capabilities of the acoustic ejection system were reported. Here, aqueous glycerol and aqueous polyethylene glycol solutions were used as the test materials. The geometry of the jet head was set up such that cavity resonance frequencies occurred at three places: frequencies significantly lower than the resonance of the piezoelectric element, very close to it, and significantly higher than it. The geometry needed to achieve this frequency placement was identified through the use of an acoustic model of the system.

Results for the aqueous glycerol solutions demonstrate that cavity resonances far from the piezoelectric transducer’s resonant frequency produce poor results, especially at frequencies higher than that of the transducer. The cavity resonance near the transducer’s
resonance demonstrated an ability to eject fluids of viscosity slightly higher than those jettable at the transducer’s resonant frequency. This confirms the first hypothesis presented in Chapter 1; coupling an acoustic resonance frequency with the resonance frequency of the piezoelectric transducer does appear to create the strongest ejection capability. However, even with this enhancement, ejection seems limited to approximately 100 cP. No polyethylene glycol solutions were successfully ejected. One possible conclusion from this fact is that higher surface tension materials are more conducive to ejection.

Although these experimental results are informative, they provide little explanation of the phenomena observed. In order to gain a higher understanding of the functioning of the system, and therefore its capabilities and limitations, Chapter 7 provides insight on the physical processes via analysis and modeling in the hopes of shedding light on the experimental results reported in this chapter.
CHAPTER 7
ANALYSIS OF PHYSICAL PHENOMENA

Investigating the function of the acoustic resonance jetting system involves approaches from multiple fronts; acoustic phenomena determine the pressure field created in the nozzle, while fluidic laws define the resultant flow. This coupling is affected further by the periodic nature of the system due to the sinusoidal cycling of the transducer; both pressure fields and fluid flow are therefore transient during the entire time of function. Based on this general complexity and the resultant large number of interdependent variables, it is difficult to arrive at categorical conclusions about the function of this system.

This chapter, however, aims to shed some light on the function of the system in order to provide a context in which the experimental results of previous chapters can be framed. The first half of the chapter considers all stages of the ejection by structuring the situation in an energy balance formulation. Each source or use of energy is considered both individually and in relation to the others; this consideration quickly shows that the ejection process is a fine balance of competing factors. In order to investigate specific aspects within this framework, numerical and analytical tools are used to identify trends in functionality. The second half of the chapter summarizes the concepts of the first half by identifying individual important variables and outlining their effect upon the process. While it would not be judicious to make all-encompassing numerical predictions at this point, this chapter highlights trends in order to achieve that goal.
7.1 Conservation of Energy

One basic principle that is instructive in the case of jetting is that of conservation of energy. Effectively, in this situation it means that the energy imparted by the actuation method to the liquid must be sufficient to balance three requirements: fluid flow losses, surface energy, and kinetic energy. The losses originate from a conversion of kinetic energy to thermal energy due to the viscosity of the fluid within the nozzle; this conversion can be thought of as a result of internal friction of the liquid. The surface energy requirement is the additional energy needed to form the free surface of the jet or droplets. Finally, the resulting jet or droplets must still retain enough kinetic energy to propel the liquid from the nozzle towards the substrate. This energy conservation is summarized as:

\[ E_{\text{imparted}} = E_{\text{loss}} + E_{\text{surface}} + E_{\text{kinetic}} \]  
\[ (4) \]

This conservation law can be considered in the form of actual energy calculations or in the form of pressure, or energy per unit volume, calculations. Sweet, for example, uses the following approximation for the gauge pressure (pressure above ambient) required in the reservoir of a continuous jetting system [92]:

\[ \Delta p = 32\mu d_j^2 v_j \int_{r_i}^{r_f} \frac{d\ell}{d_n^4} + \frac{2\sigma}{d_j} + \frac{\rho v_j^2}{2} \]  
\[ (5) \]

Here, \( \Delta p \) is the total gauge pressure required, \( \mu \) is the dynamic viscosity of the liquid, \( \rho \) is the density of the liquid, \( \sigma \) is the surface tension of the liquid, \( d_j \) is the diameter of the resultant jet, \( v_j \) is the velocity of the resultant jet, \( d_n \) is the inner diameter of the nozzle or supply tubing, and \( \ell \) is the length of the nozzle or supply tubing. The first term on the right side of Equation 5 is an approximation of the pressure loss due to viscous friction.
within the nozzle and supply tubing. The second term is the internal pressure of the jet due to surface tension; the third term is the pressure required to provide the kinetic energy of the droplet or jet. These are the same three energy requirements mentioned in Equation 4.

This conservation can also be thought of as a balance among the effects before the fluid crosses a boundary at the orifice of the nozzle and after it crosses that boundary. Before the fluid leaves the nozzle, the positive effect of the driving pressure gradient accelerates it, but energy losses due to viscous flow decelerate it. The kinetic energy with which it leaves the nozzle must then be enough to provide the kinetic energy of the traveling fluid as well as the surface energy of the new free surface. The next four sections look into each of these aspects of the energy balance in further detail.

7.1.1 Generation of Driving Pressure

In the acoustic jetting system, standing ultrasonic waves in the fluid cavity of the nozzle create the pressure changes that drive ejection. Because the simulation of the acoustic field discussed in Section 6.1.3 calculates the pressure within the nozzle cavity, this same simulation can be used to analyze the pressure gradients seen at the tip of the nozzles, where the droplets or jets are formed. The simulation was conducted in ANSYS 9.0 (Canonsburg, PA); a representative input file is included in Appendix B.

In order to depict the simulations in light of the experimental results reported in Chapter 6, Figure 39 and Figure 40 show graphs of the cyclic peak pressure gradients seen at the tips of the nozzles, versus operating frequency for materials with properties approximately those of water and glycerol. The cyclic peak values are defined as the highest values that are reached during one full cycle of the driving waveform. Because
the pressure field, as seen in Figure 36, is not uniform across the nozzle array, each individual nozzle of the twenty that are modeled may see a different pressure gradient. As a result, both the average pressure gradient and the maximum pressure gradient are reported. The average values are probably better indicators of overall performance, as the maximum values could represent extreme cases such as the value at a single node in the simulation of a single nozzle.

The simulations used to develop Figure 39 and Figure 40 both used a 1.5 mm thick piezoelectric transducer, an 840 µm thick spacer, and a 500 µm thick nozzle plate of the type shown in Figure 26(b). The nozzle array had a 2.5 µm thick membrane with a 16 um orifice in it. A frequency step size of 10 kHz was used in the harmonic analysis; results around points of interest such as the piezoelectric and cavity resonances were then resolved to a 1 kHz step size, which is the step size used during experimental testing. A voltage of 10V was applied as a boundary condition. The simulation generating Figure 39 used liquid with density $\rho$ of 1000 kg/m$^3$ and sound velocity $c$ of 1500 m/s; the simulation generating Figure 40 used liquid with density $\rho$ of 1250 kg/m$^3$ and sound velocity $c$ of 1900 m/s.

Another way of considering these results is to look at the peak pressure at the focal point in the nozzle instead of the gradient at the orifice. Figure 41 and Figure 42 are derived by defining a path through the centerline of each of the twenty nozzles, from the piezoelectric transducer to the orifice, and identifying the highest pressure along that path. Thus, the maximum value shown in the graphs is the peak value for a single nozzle, whereas the average value is for all twenty nozzles. The trends shown in these two graphs are almost identical to those displayed in the graphs of the pressure gradients.
Figure 39. Simulated Pressure Gradients in Water as a Function of Frequency

Figure 40. Simulated Pressure Gradients in Glycerol as a Function of Frequency
Figure 41. Simulated Peak Path Pressure in Water as a Function of Frequency

Figure 42. Simulated Peak Path Pressure in Glycerol as a Function of Frequency
In Figure 39 and Figure 41, five peaks are noted in left to right order: the first and second cavity resonances, the piezoelectric transducer resonance, and the third and fourth cavity resonances. In Figure 40 and Figure 42, four peaks are noted: the first cavity resonance, the piezoelectric transducer resonance, and the second and third cavity resonances. The shift in cavity resonance locations is due mainly to the difference in the speed of sound for the liquids. As was noted in Chapter 6, the experimental fluids were solutions of glycerol and water, but because glycerol composed the majority of each sample, experimental results would be expected to more closely resemble Figure 40 and Figure 42.

The correlation of frequencies and strength of ejection between experimental results and the simulation presented here is strong. As would be expected, higher peak pressures and pressure gradients resulted in the ability to eject higher viscosities. So, for example, the second cavity resonance is the highest average peak in all graphs; this is the frequency at which the best ejection was observed during testing. The piezoelectric resonance peaks are also significant; ejection was generally observed there as well. The simulations of the first cavity resonances bring in an interesting variation: the pressure gradient and pressure peaks in the graphs are high but very narrow. This may explain why ejection occurred but was unreliable at those frequencies: the resonance frequency would have to be hit very precisely in order to obtain a strong ejection result. Finally, cavity resonances with frequencies above that of the piezoelectric transducer’s resonance lose strength quickly as the frequency increases. So, although the third cavity resonance of water is still significant, mixtures like the experimental fluids that contain mainly glycerol would reflect the small value of glycerol’s third cavity resonance.
7.1.2 Fluid Flow Within Nozzles: Viscous Losses

While the liquid to be ejected travels through the nozzle, before forming droplets or jets, its motion is governed by the standard equations for incompressible, Newtonian fluids, as we are assuming these flows to be. The flow is fully described by the Navier-Stokes equation (Equation 6) and the continuity equation (Equation 7); the gravity body force has been excluded, as it is negligible due to the small size scale of the jetting processes involved:

\[
\rho \frac{\partial \mathbf{v}}{\partial t} + \rho (\mathbf{v} \cdot \nabla \mathbf{v}) = -\nabla p + \mu \nabla^2 \mathbf{v}, \quad (6)
\]

\[
\nabla \mathbf{v} = 0. \quad (7)
\]

Here, \( \rho \) is the density, \( \mathbf{v} \) the velocity vector, \( p \) the pressure, and \( \mu \) the dynamic viscosity of the liquid. The Navier-Stokes equations, however, are very difficult to solve analytically except in simple cases where numerous assumptions can be made that allow elimination of terms.

The first term on the right side of Equation 5 takes advantage of one situation for which an analytical solution is possible: that of steady, incompressible, laminar flow through a straight circular tube of constant cross section. The solution in this situation is the Hagen-Poiseuille law \([83]\), which reflects the viscous losses due to wall effects:

\[
\Delta p = \frac{8Q \mu \ell}{\pi r^4}, \quad (8)
\]

where \( \Delta p \) is the total gauge pressure required, \( Q \) is the flow through the tube, \( \mu \) is the dynamic viscosity of the liquid, \( \ell \) is the length of the tube, and \( r \) is the radius of tube. In fully developed laminar pipe flow, the pressure gradient is constant, which is why it can
be defined as $-\Delta p/\ell$ where $\Delta p$ is the pressure drop and $\ell$ is the length of the pipe [93].

The integral portion of this term of Equation 5 effectively adds up the contributions from multiple cylinders with different lengths and diameters, using an integration of pipe flow equations to approximate two-dimensional flow. This approximation, however, is most appropriate when the nozzle and other geometry are generally long, narrow and cylindrical, such as that found in nozzles made from drawn glass tubing.

Another assumption made by using the Hagen-Poiseuille equation is that the flow within the nozzle is fully developed. For the case of laminar flow in a cylindrical pipe, the length of the entry region $\ell_e$ where flow is not yet fully developed is defined as 0.06 times the diameter of the pipe, multiplied by the Reynolds number [83]:

$$\ell_e = 0.06d \text{Re} = 0.06 \rho U d^2 \mu^{-1}.$$  \hspace{1cm} (9)

In the case of the orifice of the nozzle used in testing, where the length of the channel through the membrane is 2.5 $\mu$m and the diameter is 16 $\mu$m, the entry length would be over 150 $\mu$m for water traveling at 10 m/s. Thus, entrance losses [94, 95] compose another consideration that affects fluid flow in this case, but are not reflected in the analytical solution in Equation 5. Entrance losses are dependent upon the entrance rounding and aspect ratio of the nozzle itself and result in part from an inefficient deceleration of the fluid where kinetic energy is lost to viscous dissipation [83] while the fluid enters the nozzle or, especially, the orifice. Entrance losses and similar effects are usually termed ‘minor losses’ because their magnitude in comparison to that of the losses dictated by the Hagen-Poiseuille law (‘major losses’) is small in long pipe flow situations. However, with short nozzle geometries they become more important.
As a result of these complexities, many studies turn to numerical modeling as a way to investigate this type of flow pattern. In order to evaluate the flow within a nozzle with geometry such as that used in the experimental testing reported in Chapter 6, a numerical model was implemented using the CFD software FLUENT (Lebanon, NH), version 6.2.16. The nozzle was modeled axisymmetrically, meaning that the corners of the square pyramid were neglected but that other round geometry, such as the cylindrical orifice in the membrane, were preserved. Figure 43 shows the mesh geometry used in the model; further details and a representative input file of the implementation are provided in Appendix C. It should be noted that the model includes only the very tip of the nozzle; the axial length of the meshed region is slightly longer than 50 μm. This reflects the fact that the peak pressure within the acoustic field is focused very close to the nozzle orifice. The axial length of the model is not expected to affect results significantly, since the majority of the pressure drop occurs near or in the orifice itself. The curved inlet boundary correlates to the shape of the pressure field identified in the acoustic simulation and acts as the area where the driving pressure is applied.

![Figure 43. Mesh Used in Numerical Model of Fluid Flow](image-url)
Steady flow was simulated in the nozzle via application of three different pressures at the inlet boundary: 1 atm (101,325 Pa), 5 atm, and 10 atm. The density of the liquid was held constant at 1000 kg/m$^3$; the viscosity was raised incrementally from 1 to 500 cP. Figure 44 shows the resulting average velocity of the fluid as it exits the nozzle as a function of its viscosity. Data points with black markers indicate numerical results of the simulation. For comparison, the results provided by Equation 5 are included in grey. The obvious trend is that the velocity of the liquid leaving the nozzle drops rapidly with increasing viscosity, as expected. The drop is most significant at lower viscosities; more than 50% of the velocity is lost in all cases by the time the viscosity is 100 cP.

![Figure 44. Average Steady Flow Velocity of Liquid Leaving Nozzle](image-url)
This numerical model of the fluid flow can also be used to estimate energy loss within the nozzle. As mentioned above, pressure can be considered a measure of energy per unit volume, so by comparing the inlet and outlet pressures the loss can be approximated. Figure 45 shows the results of imposing the same 1 atm, 5 atm, and 10 atm boundary conditions on the system mentioned above. The grey lines represent those inlet boundary values; the black data points and lines represent the resultant pressure of the fluid as it leaves the orifice. The difference between them is a measure of the pressure lost. It should be noted that the pressure values reported represent the total gauge pressure of the fluid (meaning static plus dynamic pressure relative to atmospheric); at the inlet this is mainly static pressure while at the outlet it is dynamic pressure.

Figure 45. Steady Flow Pressure Drop Within Nozzle
The pressure loss, then, can be estimated by comparing the inlet and outlet pressures for any given trial. For a fluid of viscosity 100 cP, for example, where a pressure of 10 atm (1,013,250 Pa) was applied to the inlet boundary, the pressure at the outlet was 68,186 Pa. These two values can be seen on the graph by comparing the dotted line at 10 atm and the data point at 100 cP on the curve labeled Outlet Pressure (10 atm). In this case, a loss of 945 kPa was seen during the fluid flow through the nozzle. By looking at the graph, it becomes clear that in all but the lowest viscosity cases, the large majority of the energy input to the system is lost to viscous friction within the nozzle.

7.1.3 Stream Breakup and Surface Energy

In order to understand the surface energy requirement of the process, it useful to consider the form in which the liquid departs the nozzle: as droplets or as a continuous jet. Although the jet may eventually break up into droplets, the energy requirements at the time of exit from the nozzle depend on the form in which the liquid departs.

Meacham et al. [74] present a time scale analysis of the acoustic jetting process as a way to gain basic insight into the periodic physics of ejection. The characteristic time scale of the process is defined as $1/f$, the inverse of the driving frequency, due to the periodic nature of the ejection process and voltage signal. The surface tension, or capillary, time scale is the time scale at which the surface tension acts at the interface, thereby giving a time constant that defines the dynamics of the interface deformation [74]. It is defined as the square root of a relationship between the liquid density $\rho$, the liquid surface tension $\sigma$, and the radius of the orifice $r$. Equations 10 and 11 summarize these time scales:
process: \[ t_f = \frac{1}{f} \] (10)

capillary: \[ t_o = \sqrt{\frac{\rho r^3}{\sigma}} \] (11)

Meacham et al. [74] argue that the distinction between the ejection of individual droplets and continuous jets, when ejection occurs at all, is defined by the relationship of these two time scales. When \( t_o < t_f \), the surface tension of the fluid acts quickly enough to separate a single droplet before the pressure cycle recurs. On the other hand, when \( t_f < t_o \), the process pressure cycles faster than the surface tension can act to separate a droplet, thus resulting in a continuous jet.

This scaling argument can be rearranged to clarify the relationship between orifice size and driving frequency that affects the droplet-jet transition. Figure 46 shows the frequency of that transition as a function of orifice size for water; moderate variations in surface tension and density have little qualitative effect because diameter is the most relevant factor.

**Figure 46. Droplet to Jet Transition for Inviscid Fluid (Water)**
It is notable, however, that the relationships described above characterize the ejection of inviscid fluids, such as water, where breakup is driven by the capillary timescale. Investigators studying other droplet formation scenarios [96, 97] propose that the timescale for interfacial breakup in other cases depends on the relationship between viscosity and surface tension; this relationship is characterized by the Ohnesorge number:

\[ \text{Oh} = \frac{\mu}{\sqrt{\rho r \sigma}}. \]  

(12)

Table 16 summarizes the relevant information; rows are defined by the value of the Ohnesorge number as listed in the first column. The second column serves as a reminder that in the case of the acoustic system, the process timescale reflects the periodic nature of the process. The third column summarizes the timescales for interfacial breakup proposed in [96, 97]. The fourth column lists the transition frequency identified by setting the unsteady process and breakup timescales equal to each other.

<table>
<thead>
<tr>
<th>Ohnesorge Number</th>
<th>Unsteady Process Timescale</th>
<th>Breakup Timescale</th>
<th>Transition in Terms of ( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oh &lt;&lt; 1</td>
<td>( \frac{1}{f} )</td>
<td>( \sqrt{\frac{\rho r^3}{\sigma}} )</td>
<td>( f = \frac{\sigma}{\sqrt{\rho r^3}} )</td>
</tr>
<tr>
<td>Oh ~ 1</td>
<td>( \frac{1}{f} )</td>
<td>( \frac{\mu^3}{\rho \sigma^2} )</td>
<td>( f = \frac{\rho \sigma^2}{\mu^3} )</td>
</tr>
<tr>
<td>Oh &gt;&gt; 1</td>
<td>( \frac{1}{f} )</td>
<td>( \frac{\mu r}{\sigma} )</td>
<td>( f = \frac{\sigma}{\mu r} )</td>
</tr>
</tbody>
</table>
This indicates that the transition frequency for viscous materials may be even lower than that shown in Figure 46. As a comparison to Figure 46, a curve for glycerol, the Ohnesorge number for which is 59.8, is shown in Figure 47 as computed by using the information in the last line of Table 16. Note, however, that the scales for the frequency on the two graphs differ by three orders of magnitude. Based on these two curves, it can be assumed that with an orifice size of 16 µm in testing, any material used in this research would be ejected as a continuous stream.

![Figure 47. Droplet to Jet Transition for Viscous Fluid (Glycerol)](image)

If the wavy jet is approximated as a smooth cylinder, the surface energy of the jet can then be expressed as a pressure by considering the ratio of surface energy and volume:

\[ p_{\text{surf}} = \frac{2\pi rh \sigma}{\pi r^2 h} = \frac{2\sigma}{r}. \]  

(13)
The range of this can be appreciated by considering two extreme examples. With a very low surface tension of 0.020 N/m and a large radius of 20 \( \mu \text{m} \), this pressure is 2000 Pa. With a very high surface tension of 0.080 N/m and a small radius of 3\( \mu \text{m} \), this pressure is 53.3 kPa. For water and glycerol ejected from a 16\( \mu \text{m} \) nozzle, the values are 18.3 kPa and 15.8 kPa.

### 7.1.4 Kinetic Energy

In addition to the surface energy of the ejected fluid, the kinetic energy of the moving jet or droplets is the other energy requirement outside the nozzle. Effectively, any energy imparted to the fluid that is not consumed by viscous losses or free surface energy becomes kinetic energy of the traveling jet or droplets. The kinetic energy must simply be enough to carry the fluid to the substrate upon which it is to be deposited. This value could in theory be very small, but in practice must be enough to overcome air resistance and therefore must be at least a few meters per second.

Again, framing this kinetic energy as a pressure can be achieved by considering the ratio of kinetic energy to volume:

\[
 p_{\text{kinetic}} = \frac{1}{2} \rho U^2.
\]  

(14)

If, for example, the desired velocity of travel were 5 m/s, this would give pressures of 12.5 kPa for water and 15.6 kPa for glycerol. This range of values is quite similar in magnitude to that of the surface energy discussed in the last section.

### 7.1.5 Ejection Velocity

Although surface and kinetic energies provide one way of considering energy requirements outside the nozzle, another approach may be useful as well. In addition to
the time scales discussed above, Meacham et al. also define an inertial time scale $t_U$, which represents the fluid motion and is defined as the ratio of the characteristic length scale $r$ to the ejection velocity $U$ of the fluid as it leaves the nozzle [73, 74]:

$$ t_U = \frac{r}{U}. \quad (15) $$

No details are provided as to whether $U$ is a maximum or average (over space or time) value. They propose that for any ejection to occur, the inertial time scale must be smaller than the process time scale, implying that the fluid must be sufficiently accelerated during a cycle to exit the nozzle: $t_U < t_f$. This relationship can be then rearranged to derive a minimum ejection velocity for the droplets or jet as $U = rf$. This gives, for example, a minimum velocity on the order of 12 m/s for an orifice diameter of 16µm and a driving frequency of 1.5 MHz. Converted into a kinetic pressure using equation 14, this yields approximately 72 kPa for water or 90 kPa for glycerol.

### 7.1.6 Relative Effects of Energy Components

Based on the previous sections, the three energy requirements can be compared. As seen in section 7.1.2, the pressure losses due to viscous friction within the nozzle can easily reach 100’s of kPa while still resulting in only a relatively small fluid velocity (and therefore kinetic pressure). In comparison, the requirement outside the nozzle, computed either by adding the surface and kinetic energies discussed in 7.1.3 and 7.1.4 or by simply using the baseline described in section 7.1.5, totals less than 100 kPa for the types of parameters in use here. So the viscous energy losses within the nozzle will most likely dominate all other energy requirements of the system.
One caution is required in this discussion of energy considerations: the majority of the expressions and values presented in the previous sections related to steady flow through the nozzle. In the acoustic system, however, the flow is oscillatory and would therefore demonstrate different behavior. Despite this difference, similar trends would be expected to emerge.

Comparing the energy needs of the viscous, surface, and kinetic components of the system to the peak pressures reported in Figure 41 and Figure 42, which can then be scaled appropriately for the voltage boundary condition in use, it would seem that the system may provide more pressure than is needed. However, this is not demonstrated experimentally; it is known experimentally that even with water, a higher power is necessary in order to achieve ejection. In addition, if the energy loss due to the viscous friction of highly viscous fluids in the nozzle is compared to that loss when using water, it is clear that the system will need to impart a great deal more energy in those cases. Thus the conclusion must be that, numerically, the acoustic model and the energy analysis cannot be connected on an absolute level. Regardless, the trends should still hold and provide insight into the function of the system.

7.2 Effects of Individual Variables

Having considered the system as a whole via energy arguments, attention is now turned to specific aspects of the process. Unfortunately, the number of variables related to the process of ejection here is great: the liquid has density, viscosity, surface tension and speed of sound values; the driving voltage can vary in frequency and in amplitude; the geometry of the system includes the orifice size, the nozzle shape, the fluid cavity
height (spacer height), and the piezoelectric element thickness; the temperature of the
system fluctuates during operation, thereby further changing the fluid properties. While
the overall number of variables related to this ejection process is large, some observations
about the impact of certain specific variables can be made. This section steps through a
number of those variables, commenting on the impact each has on the performance of the
system based on the analyses and results in previous sections.

### 7.2.1 Effect of Orifice Size

Both experimental and theoretical results point to the orifice diameter as a significant variable in the ejection process. Based on the experimental results reported in Chapters 4 and 6, it becomes clear that orifice size plays a significant role in the success of ejection. In all tests conducted, ejection with a ~40um nozzle could be achieved only at the piezoelectric resonant frequency and not at any of the cavity resonant frequencies. In test using a 16 um nozzle, however, ejection was possible at both. Although the reason for this is not completely clear, there are some possible explanations.

The first relates to the use of ultrasonic waves for droplet creation. Perçin and Khuri-Yakub (2003) propose an explanation of the relationship between orifice size, frequency and fluid properties for droplets to be formed via ultrasonic actuation. The relationship is based upon the idea that if the driving frequency is too high, the pressure in the fluid does not remain above atmospheric during the positive part of its cycle long enough to eject a droplet. They explain that if the wavelength $\lambda_c$ of linear capillary waves is much smaller than the diameter of the orifice, the ultrasonic actuation will simply set up small ripples on the liquid surface. This leads to the identification of a dimensionless surface tension parameter,
\[ S = \frac{2\sigma}{\rho r^3 f^2}, \] (16)

which should be on the order of 1 or greater to enable the breakup of the drop from the liquid-air interface; otherwise, the wavelength of the ripples is too small for a drop to pinch off from the liquid surface. The values for water and glycerol are shown as examples in Table 17. Although none of the values for \( S \) is actually \( O(1) \), the values for the smaller orifice are much closer.

A second possibility for the lack of ejection with the larger orifice is that the minimum velocity as discussed in Section 7.1.5 scales with \( r \). As a result, ejection out of an orifice of diameter 40 \( \mu \text{m} \) would require a fluid velocity more than twice that of ejection from a 16 \( \mu \text{m} \) orifice. This in turn requires a higher pressure gradient to accelerate the fluid.

The preferability for smaller orifices, however, competes with viscous losses, which increase with decreasing radius of the ejection channel. In the simplified pipe flow solution, for example, the pressure drop scales with \( 1/r^2 \), or \( Q/r^4 \). A possible solution in each case is to vary the frequency rather than the orifice size; reducing the frequency would increase the parameter \( S \) and decrease the threshold velocity.
7.2.2 Effect of Thickness of Piezoelectric Transducer

While the effects of varying the thickness of the piezoelectric transducer were not specifically investigated in terms of pressure or pressure gradients, that dimension of the geometry defines the resonant frequency of the piezoelectric element. Therefore, if it were desirable to have the piezoelectric transducer’s resonant frequency lowered to promote ejection at a lower frequency, a thicker transducer could be employed.

7.2.3 Effect of Fluid Cavity Height and Liquid Speed of Sound

Because the acoustic focusing relies on the reflection of ultrasonic waves through the fluid, the speed of sound influences the distance the waves travel in each periodic cycle. This in turn defines the half-wavelength of which the fluid cavity height must be an approximate integer multiple in order to take advantage of the resonance phenomena. No observations have been made that would indicate that either of these variables significantly changes the magnitude of the pressure gradients formed; they rather determine the frequencies at which resonances appear. This indirectly affects the pressure gradient magnitude because it controls the proximity to the resonant frequency of the piezoelectric transducer.

7.2.4 Effect of Surface Tension

In terms of whether or not ejection will occur, surface tension seems mainly to establish baseline criteria for the process. As mentioned in Section 4.3.4, the surface tension of the liquid must be greater than the critical surface tension of the material of the nozzle in order to allow ejection of droplets rather than simple wetting of the surface. In fact, the fluids with the highest surface tension were ejected most consistently.
The surface tension also establishes a threshold energy needed for the ejection of a droplet or jet, since each of those inherently involves the formation of a new free surface. If the fluid moving out of the nozzle does not have enough kinetic energy to be converted into surface energy for the new surface, the droplets or jets will be unable to form.

7.2.5 Effect of Viscosity

Viscosity plays two roles in this scenario, the first relating to flow inside the nozzle and the second relating to flow outside the nozzle. Within the nozzle, the fluids of higher viscosity lose more energy during flow, resulting in their having a lower velocity upon exiting the nozzle. Very narrow channels, such as the one that forms the orifice in the nozzle used in the testing reported in Chapter 6, cause significant losses. Making the channel shorter by using a thinner membrane, even if feasible in a manufacturing sense, might make the membrane so fragile that it would not stand up to the pressure generated in the nozzle. Outside the nozzle, the viscosity of the fluid also affects the breakup of the interface. Generally, it appears that the interfaces of viscous fluids take longer to rupture.

7.3 Summary of Chapter 7

In this chapter, a multi-pronged investigation of the phenomena governing ejection with the acoustic resonance system shows that the process can be described as a balance among competing requirements. In terms of pressure generation, cavity resonances are important but must fall at frequencies proximal to that of the piezoelectric transducer. For droplet formation, it intuitively seems plausible that larger orifices would be easier to eject from, simply because of the viscous wall effects of very small orifices.
This is found in practice, however, not to hold true relative to ejection utilizing cavity resonances, where a smaller orifice produces better results. As a result of using nozzles with a smaller cross-section, much energy is lost due to viscous dissipation, thus resulting in lowered fluid velocity at the nozzle orifice. This in turn may prevent the liquid from reaching the threshold velocity needed to enable ejection.

This chapter, therefore, addresses the issues raised by the second and third research hypotheses presented in Chapter 1. The viscosity is found to dominate, at least in an energy sense, the surface tension and kinetic energy needs of the system in many cases. In addition, the results of analyzing the energy needed to overcome the viscous friction in the nozzle imply that it may be difficult to achieve this goal.

There are limitations, however, in converting these trends to specific numerical predictions. For example, both the acoustic and fluidic numerical models used are two-dimensional representations of three-dimensional activity. The acoustic model also does not consider viscous effects on the ultrasonic propagation. In addition, much of the fluidic analysis presented is based upon a steady flow through the nozzle; this is not the case with the acoustic jetting system, whose pressure field and resulting ejection function periodically rather than continuously.

Chapter 8 considers these results and limitations relative to the goals of the research reported in this thesis and identifies the advancements that have been achieved via the understanding developed in this chapter. Also outlined are the next steps that will be needed in order to further develop this understanding.
CHAPTER 8
CONCLUSIONS & RECOMMENDATIONS

Because the use of jetting for three-dimensional additive fabrication is at such a young stage of development, a seemingly infinite number of open research questions remain to be answered. For the same reason, physical systems in use today for jetting-based additive manufacturing will require much development in order for the technology to grow to its potential as an additive fabrication process. This thesis investigates several aspects of the subject: What are the capabilities and limitations of current systems? What benefit can the acoustic system provide in the case of ejection of viscous polymers? How do process and material parameters affect the capabilities of that system?

This final chapter of the thesis serves to bring together the understanding and findings presented throughout the entire document. To achieve this, the research conducted and results achieved are summarized in the next section. Based on these results, the hypotheses posed in the first chapter can be revisited and evaluated in light of the new awareness provided by this research; this evaluation is presented in the second section. In addition, the third section outlines specific achievements and contributions of this work. As with any research, however, the limitations of the work conducted must be considered; these are outlined in the fourth section of this chapter. Because this research was intended to be an initial investigation, one major implicit goal was to identify gaps in knowledge, and directions for future research. Thoughts about areas of potential interest and progress are outlined in the fifth section. The chapter concludes with a few closing remarks about the place of this thesis in the larger scope of research.
8.1 Review of Thesis

This thesis originates from a long-term vision of the future of jetting as an additive manufacturing process. Because of the scalability and financial efficiency inherent to the process, jetting has the potential to become a highly useful manufacturing technology. In addition, it may provide capabilities that are not achievable with the majority of other additive manufacturing processes currently in use. However, much work remains before this will become a reality. This thesis provides a number of steps towards that goal.

The first major component of this thesis comprises an extensive background search targeted at evaluating the current state of the art. Because ejection of any material will face similar challenges and may have similar solutions, this review encompassed deposition of not only polymers but also ceramics and metals, which are the other materials focused upon in current research. Investigation found that challenges in jetting abound, reaching from the formulation of the liquid material to the formation of droplets to their control and deposition on substrates. It also became clear that the majority of current industrial and research systems are based upon hardware technology that was developed for two-dimensional printing and therefore is geared toward a different set of objectives. Because of the large number of challenges involved, however, the current general approach has been to alter materials to fit the manufacturing system, rather than to allow the material goals to drive system design and development. Of the various effects this approach has had upon material ejection capabilities, a significant one appears to be the evolution of problems related to droplet formation, and the most limiting factor appears to be viscosity.
The second component of this thesis is an experimental investigation into the function and capabilities of the acoustic resonance system. Because the system was not originally intended for this purpose, a significant amount of preparation was required. This included evaluation and identification of suitable test materials, which was essential in light of competing priorities of temperature insensitivity, viscosity modulation, etc. Initial testing did not demonstrate the desired resonance activity, but served to identify a number of areas on which attention needed to be focused in order for later testing to be productive. One of those areas regarded the physical implementation of the system; a significant redesign of the system housing was required in order to make further testing feasible. Later experimental testing demonstrated that acoustic resonances near the piezoelectric transducer’s resonance are the most favorable for ejection of viscous fluids, but that even at those frequencies the higher viscosity fluids would eject only upon heating, which decreased their viscosity significantly. With the process parameters used during this testing, the range of ejection appeared to be limited to materials of viscosity ~100 cP.

In order to understand the physical phenomena affecting the performance of the acoustic resonance system, the final component of this thesis involved numerical and theoretical analysis of the process. Simulation of the acoustic field showed a good correlation with the experimental results achieved, in terms of the frequencies and strength of ejection; pressure and pressure gradients were highest at the cavity resonance frequency nearest that of the transducer, which is where the best ejection was seen. Modeling of the fluid flow within the nozzle, combined with theoretical analysis based on an energy balance throughout the ejection process, pointed to viscosity as a dominant
material parameter; the amount of energy converted into internal thermal energy as a result of viscous friction within the nozzle overshadows in most cases the amount of energy required for formation of the free surface and motion of the ejected fluid. As a result, this is expected to be a strong determining factor in the amount of energy needed to achieve ejection.

8.2 Evaluation of Hypotheses

A number of research hypotheses were put forth in Chapter 1 with the intention that they would be investigated through the research reported in this thesis. Each of those hypotheses, along with a summary of its motivating factors, is now revisited and evaluated in light of the results reported in previous chapters.

Performance

Motivation: Understanding performance of the acoustic resonance system will directly affect the ability to explore its capabilities.

Hypothesis: Coupling an acoustic resonance frequency with the resonance frequency of the piezoelectric transducer will create the strongest ejection capability.

Evaluation: In Chapter 6, testing was reported that supports this hypothesis. Specifically, ejection at a second cavity resonance, which was the closest to that of the piezoelectric transducer, was better in terms of viscosity than ejection at the transducer’s resonant frequency and in terms of viscosity and reliability compared to the first and third cavity resonances. In addition, simulation reported in Chapter 7 confirms that the acoustic fields at cavity resonances in this coupled configuration are stronger than others.
that are not. These results reinforce an intuitive understanding that the deflection of the piezoelectric transducer is greatest at its own resonance frequency, and that it is beneficial to take advantage of that feature when selecting and positioning cavity resonance frequencies.

**Sensitivity**

*Motivation:* In addition to understanding the physical acoustic resonance system, consideration of the fluid to be ejected is essential to the evaluation of the ejection process. Observation of the important properties of this fluid will allow attention to be focused upon those areas.

*Hypothesis:* Viscosity, and resulting energy losses, may dominate effects of other fluid properties in terms of fluid ejectability because its values vary by multiple orders of magnitude while other properties generally do not.

*Evaluation:* The energy-based analysis presented in Chapter 8 demonstrates that this is certainly the case in terms of energy consumption. While density or surface tension may affect the energy balance quantitatively, it appears that the viscous energy requirement will in most cases dominate and is therefore a threshold that cannot be avoided. It seems that the experimental results support the trends seen in the energy and fluid flow analysis, as the materials that were successfully ejected all fall on the portion of the curve in Figure 45 before it becomes distinctly flat. This would suggest that both experimental and analytical results point to an energy-related barrier in the ejection process.
**Capability**

*Motivation:* Understanding and investigating the unique capabilities of the acoustic resonance system allows an evaluation of its applicability to ejection of viscous polymers.

*Hypothesis:* Due to high pressure gradients formed very close to the tip of nozzle, ejection of viscous polymers may be possible.

*Evaluation:* Based upon the acoustic simulations presented in Chapter 7, the acoustic resonance system certainly does create high pressure gradients near the tip of the nozzle. However, the energy analysis presented later in that chapter suggests that even with this gradient it may be difficult to impart the large amounts of energy that would be necessary to eject extremely viscous fluids. Unfortunately, neither the experimental testing nor the simulation and analysis were able to account for all process and material parameters and variables, of which there are many. As a result, further testing and simulation will be necessary in order to identify the exact range of capability of the acoustic system.

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**8.3 Contributions**

Through the work entailed in completing this thesis, a number of specific contributions have been realized. This section will highlight those achievements and provide a brief explanation of each one.

1. Before the exploration provided in this thesis, no body of work was found that contained an overarching, up-to-date review of jetting as a true three-dimensional
fabrication process. Achievements in specific areas have been reported by researchers working in those areas, but an overview of the topic as a whole was not found in the literature. Without this perspective, it is impossible to identify the common challenges and approaches to those challenges taken by current investigators. This thesis brings together that general picture with more detailed technical information, which enables greater understanding of current shortcomings and identification of resulting needs and research directions.

2. As part of the development of the acoustic system to a point where it could be reliably testable with viscous fluids, the housing that holds the internal components was significantly redesigned. This resulted in improved performance and consistency of the system and greater ease of use. The new design can be quickly loaded and unloaded, which means that future testing will be expedited. In addition, the ability to conduct extensive testing without breaking nozzle arrays is a critical achievement as the manufacture of those parts is extremely difficult and availability therefore limited. One final major advantage of the new housing is the fact that it was built using SLA rapid prototyping technology. In addition to providing functional advantages such as transparent parts and detailed inner geometry, this means that if future applications require small changes to the design, it can simply be modified via computer and easily rebuilt; multiple copies can also be made if future testing needs variant versions.

3. Using the acoustic resonance system, ejection was achieved that falls outside of the standard range of ejection capability. While it has been proposed that the inverse of the
Ohnesorge number presented in Equation 12 falls between the values of 1 and 10 for most DOD printers [20], ejection was demonstrated here at values between 0.5 and 1. This shows that the proposed range is not a physical law but rather a guideline.

4. As a necessary first step in evaluating the performance of the acoustic resonance system for the ejection of viscous fluids, an inventory of the process and material variables that influence system capability was compiled. Initial investigation into specific components of that inventory provided a preliminary understanding of the relative importance of those variables and therefore of the driving forces behind the functioning of the acoustic resonance system. These findings were reported in detail in section 7.2. Identification of the effect and relative importance of at least some of the process parameters and material properties, as presented here, will allow future work to optimize system performance and to continue investigation effectively.

5. Because viscosity was identified as a critical hurdle in the ejection of polymer materials, it was a central parameter being addressed in the evaluation of the acoustic resonance system. An understanding of the effect of viscosity upon ejection was furthered via experimentation, simulation of fluid flow, and analysis of the related energy losses. Together, these provide quantitative confirmation of intuitive trends and enable progress towards quantification of the impact of viscosity on the ejection process.
8.4 Critical Analysis

As with any research, it is beneficial to future investigation to identify the limitations of the work presented in this thesis. Due to the wide range of investigation and large number of variables that affect jetting in general and the performance of the acoustic resonance system in particular, it is impossible to provide a full investigation of all aspects of the situation. Outlined here are some of the limitations of this research project; this will lead to the identification of future areas of investigation, as presented in section 8.5.

Background research conducted for this thesis focused upon reports directly related to inkjet printing or three-dimensional jetting. However, much literature exists regarding fluid flow, interface breakup, and other areas that was not reviewed for this thesis but might nonetheless be relevant to the implementation and functionality of jetting systems. This means, of course, that the review provided cannot be considered an all-encompassing summary.

The experimental fluids used, while exhibiting important properties such as general availability, safety, and the ability for the experimenter to mix multiple viscosities without dramatically altering other properties, had numerous limitations. Most obvious was the fact that many fluid properties such as speed of sound, surface tension, and especially viscosity all change with temperature. In addition, it was not feasible to measure all of these properties for each material at all combinations of operating conditions, so most values were calculated or interpolated using information from the manufacturer or measured under specific conditions. This to some extent affects accuracy.
Due to the time-consuming nature of the data collection for this system, fewer data points were collected than would have been, in the ideal scenario. As a result, small errors may become magnified because they are not averaged over a large sample set. Therefore, data should be viewed as indicative of trends and ranges rather than absolute, specific results.

Due to computational limitations, all of the acoustic and fluidic modeling was conducted as two-dimensional simulations of three-dimensional processes. This inherently decreases accuracy because relevant aspects of the three-dimensional features are not considered. For example, it is probable that the angular corners of the pyramidal nozzle cavity affect both the acoustic and fluidic behavior, yet were reflected in neither type of simulation.

In addition, each of the simulations makes assumptions that are necessary to successfully create the models but which do not necessarily reflect reality. For example, the fluid in the acoustic simulation is assumed to be both static and inviscid. This means that any effect of fluid motion or viscous attenuation is not captured with the model. Similarly, the fluid model assumes purely incompressible, laminar flow of fluid with a constant density and viscosity. Perhaps most importantly, the interaction between the acoustic actuation and the moving fluid, which is highly complex, is captured in neither simulation.

Finally, the energy arguments presented in Chapter 7 do not fully capture the actual activity ongoing during the ejection process. The oscillatory nature of the acoustic resonance driving brings further complexity and demands, which are not considered by the steady-state calculations and approximations. As a result, the energy arguments must
be considered as a baseline or threshold; they represent necessary, but not necessarily sufficient, conditions.

8.5 Future Work

Because this thesis was a preliminary investigation into both the field of direct jetting for additive manufacturing and the specifics of the acoustic resonance system, many more questions were opened than answered. This section will outline a number of those questions and, in some cases, propose approaches to address them.

8.5.1 Continued Characterization of Acoustic Resonance System

In order to gain additional specific data about the functionality of this experimental system, further testing should be carried out to augment results reported in Chapters 4 and 6. Tests similar to the ones reported in those chapters should be conducted using mixtures of lower viscosity than the ones used here. Because of their lower viscosity, these materials would produce smaller errors due to temperature fluctuations and would perhaps display more specific response to small changes in operating parameters. This would allow more full evaluation of the third hypothesis that was presented in Chapter 1 and revisited earlier in this chapter.

Because the new housing design allows greater ability to conduct testing, it should be possible for future researchers to examine the properties of fluids other than those used in this study, as well as the mixtures proposed in the last paragraph. Accuracy of the results could also be improved, even without changing fluids, by increasing the sample size of the tests presented earlier in this thesis and or by conducting more extensive measurements of the material properties for those fluids used in testing.
As was demonstrated experimentally, the coupling of the resonant frequency of the cavity with that of the piezoelectric transducer does play a critical role in determining the performance of the system. This should be taken to the logical extreme, meaning that further experimental testing should investigate the performance of the system when those two resonances coincide exactly. Another possibility to investigate is to place the cavity resonance just slightly offset from the piezoelectric resonance. This would take advantage of the large transducer displacement at frequencies near the piezoelectric element’s resonance frequency while reducing the heating that occurs at that frequency.

In addition, testing should be undertaken to establish the effect of driving voltage upon performance. While it can be assumed that the strength of ejection would increase with increased voltage provided to the transducer, the actual relationship between incremental change and behavioral response is unknown. Simulations show a direct correlation – doubling voltage doubles pressures – but this has not been experimentally quantified. Further exploration of this would allow a more complete evaluation of the second hypothesis, as it would provide information about energy supply parallel to the information about viscous energy use already presented in this investigation.

While it has been argued here that the frequency of the cavity resonance must be close to the piezoelectric transducer’s resonance, it is not known how the cavity resonance mode affects performance. For example, the testing in Chapter 6 involved use of parameters that employed the second cavity resonance as the best frequency of operation. It should be investigated whether the first or third resonances, for example, if placed similarly relative to the resonance frequency of the piezoelectric transducer, would provide different responses.
It is known that the orifice size is a significant variable in terms of viscous loss, time scales, and other aspects of the system performance. However, because of the lack of availability of nozzle plates, little investigation was conducted experimentally into the effect of orifice size upon functionality: only two hole sizes were used during testing (40 µm and 16 µm). Since no cavity resonance ejection was achieved with the larger orifice size, little quantitative comparison can be drawn. Further testing should involve a parametric study to investigate experimentally and numerically the effect of orifice size upon performance.

In testing reported here, only materials of quite high surface tension were successfully ejected. However, with the limits of the experimentation presented here, this must be considered as correlation rather than causation. Regardless, the effects of surface tension should be further investigated as the theory outlined here provides little explanation as to the failure of ejection for any material with surface tension higher than the critical value for the material of the nozzle plate. One specific effect to investigate is the allowance of bubble nucleation due to low surface tension of the fluid; bubbles will destroy the acoustic focusing. Possible changes to investigate include putting additives into the fluid to raise the surface tension, coating the ejector with a hydrophobic substance, and degassing the fluid.

Effects of the periodicity of the acoustic system should be considered in greater detail than they have been to this point. This will most likely show further losses due to repeated acceleration and deceleration of fluid in the nozzle and should be taken into account in terms of the energy balance. One possible method to approach this periodicity would be to use power rather than energy or pressure considerations.
In order to increase transducer displacement and reduce losses, system operation at lower frequencies should be considered and tested. This can be accomplished by employing thicker piezoelectric transducers with lower resonant frequencies. This may also help in improving viscous interfacial breakup.

Although the ejection from this system is currently in the form of either continuous jets or periodic droplets, it might be possible to convert this to a more DOD-type arrangement. This could be accomplished by establishing a resonant wave with energy just below the threshold necessary for ejection, then ‘pulsing’ a tone burst to eject a single droplet. This would also aid in reducing heating of the system.

8.5.2 Improvements to Experimental System

Because the acoustic resonance system is still in development, improvements will continue to be made in the future as it is applied to new situations and as its function is tailored to specific applications.

For example, heating was a significant hindrance to the accuracy and consistency of data available during previous testing. If a method could be devised to cool the fluid reservoir, that would improve result reliability and accuracy. It would be important, however, to ensure that the actual temperature within the cavity was being affected; a simple convection situation on the outer faces of the system might cool the surface, where the temperature is currently measured, without actually cooling the internal components or liquid. One possibility to consider is to cool the back side of the piezoelectric transducer with an air jet or other device; this would pull heat without disturbing the ejection process.
One previously known problem that was encountered during testing is the sensitivity of the membranes in which the smaller nozzle orifices are formed. Whereas the larger holes without membranes are etched directly into the silicon, the smaller orifices do not have that bulk material support. Because the membranes are so thin, they have a tendency to ‘blow out’ when the pressure is increased. This then changes the size and shape of the orifice. This is significantly limiting factor in terms of the amount of pressure that can be applied to the system without breakage. A manufacturing process that would eliminate the need for the membrane would significantly improve the robustness of the nozzle component.

Another design change that could improve the performance of the system also relates to nozzle fabrication. Current nozzles were not designed for viscous fluids, and therefore are not tailored to that application. New nozzle manufacturing processes that use more robust materials and that create geometry suitable for viscous flow could significantly improve efficiency and success of ejection. This could include entrance rounding, wider orifices, or other adjustments.

8.5.3 Investigation of Fluid Behavior

Because so much of the performance of any jetting system is linked to the behavior of the liquid material both inside and outside the nozzle, further investigation into this area should be conducted, perhaps both numerically and via review of previous research.

For the acoustic jetting system or any other jetting device, the viscous losses that arise from flow through the nozzle depend largely upon dimensions and geometry of the flow channels. It would therefore be beneficial to further investigate current knowledge
of flow of viscous fluids through orifices and the effects of various geometrical and other parameters upon this activity. Because of the complexity of the geometries and the governing equations involved, general analytical solutions may be difficult to achieve, but numerical simulation should provide a useful tool in this situation.

Once polymers can be successfully ejected from the nozzles, the formation of droplets in a form conducive to controlled deposition may still pose a significant challenge. In order to understand this challenge, further investigation of the phenomena that characterize the breakup of single droplets from a nozzle or the breakup of a viscous jet into individual droplets should be undertaken. This may involve research regarding the rupture of fluid interfaces in the case of a viscous material [96, 97]. Other aspects of breakup that may be important but have only recently been approached include the behavior of the free-surface flow of a droplet or jet due to effects of elasticity [98] and non-Newtonian behavior [99].

Of course, this list is only a starting point for further investigation; any number of avenues may be followed in pursuing the goal of polymer ejection and in development of the acoustic resonance system. The suggestions presented here are intended to identify areas in which that future search may be most fruitful.

8.6 Closure

The future of direct jetting as an additive manufacturing process is, at this point, largely unknown but full of potential. In order for researchers to achieve that potential of the technology, an understanding about feasibility and the relative importance of various aspects of the process will be invaluable. In addition to increasing knowledge, physical
systems will need to be further developed in parallel in order to put that knowledge into practice. While applying existing technologies is a good start, systems will eventually have to be designed with the specific requirements of three dimensional fabrication in mind. By providing insight about jetting systems in general and about the acoustic resonance system in specific, this thesis serves as a starting point for both the increase of basic understanding and subsequent system development. It is hoped that in doing so, this thesis will serve as a motivation and a roadmap for the journey towards making jetting as a widely applicable additive manufacturing technology a future reality.
APPENDIX A:
MEASUREMENT OF SPEED OF SOUND

In order to measure the speed of sound for materials whose properties were not available in the open literature, a homemade measurement system was created. Two 1.0 MHz ultrasonic transducers (Panametrics A303S) were set up opposing each other in a water bath, one fixed and one on a micrometer-driven stage, as shown in Figure 48. The placement of the second one was calibrated such that a 7 mm gap existed between the two. A Wavetek 80 function generator was attached to the first transducer and a Tektronix TDS 3014 oscilloscope to the second. A small plastic zipper bag full of the material was placed between the transducers such that the contact between the bag and each of the transducers was complete.

Bursts of six full sine waves of 16 V\text{pp} amplitude were generated once per second from the first transducer. The time of travel for the bursts was measured across small
zipper bags of each material. From this information, the speed of sound of the material could be calculated. Baseline measurements showed that the effect of the plastic bags was negligible as demonstrated by the measurements for water in Table 18. The amount of error in this measurement method is not known, but was estimated to be in the range of 50 m/s for the final value of the speed of sound.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Time of Travel (µs)</th>
<th>Speed of Sound (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (no bag)</td>
<td>4.52</td>
<td>1549</td>
</tr>
<tr>
<td>Water (bag)</td>
<td>4.52</td>
<td>1549</td>
</tr>
<tr>
<td>Waterclear 10120</td>
<td>4.36</td>
<td>1606</td>
</tr>
</tbody>
</table>

Table 18. Speed of Sound Measurements I

A second series of testing with additional materials was conducted in the same manner. All experimental parameters were the same, except that the function generator used was a Tektronix AFG5101 and the sinusoidal signals were 20 Vpp. Results are shown in Table 19.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Time of Travel (µs)</th>
<th>Speed of Sound (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (no bag)</td>
<td>4.68</td>
<td>1496</td>
</tr>
<tr>
<td>Polyethylene Glycol (35%)</td>
<td>4.08</td>
<td>1716</td>
</tr>
<tr>
<td>Polyethylene Glycol (50%)</td>
<td>3.92</td>
<td>1786</td>
</tr>
<tr>
<td>Glycerol (65%)</td>
<td>3.84</td>
<td>1823</td>
</tr>
<tr>
<td>Glycerol (100%)</td>
<td>3.64</td>
<td>1923</td>
</tr>
</tbody>
</table>

Table 19. Speed of Sound Measurements II
APPENDIX B:

ACOUSTIC NUMERICAL MODEL

The numerical model employed to simulate the acoustic field within the nozzles is created in ANSYS 9.0 (Canonsburg, PA). It was originally developed by Dr. Mark Meacham and Dr. Andrei Fedorov at the Georgia Institute of Technology. A sample command file is reprinted here for reference. This version of the model includes the membrane containing an orifice. Separate postprocessing commands are included after the main file.

! J. Mark Meacham and Andrei Fedorov
! Woodruff School of Mechanical Engineering
! Georgia Institute of Technology

! Acoustic Atomizer Simulation
! This program is used to investigate the pressure distribution within the fluid of one chamber of the acoustic atomizer array.

***PROGRAM INITIALIZATION***!

FINISH                                ! Finish and exit any existing job
/CLEAR,NOSTART                        ! Clear the database
/FILENAME,water,1             ! Set the jobname and start new error and log files

***INPUTS***!

!*GEOMETRIC PARAMETERS*!
! P-880 Piezoelectric
T_PIEZO = 0.001500                  ! Thickness of the piezo [m]
W_PIEZO = 0.024000                  ! Width of the piezo [m]

! Spacer
T_SPACE = 0.000590                  ! Thickness of the spacer [m]
W_SPACE = 0.00200                   ! Width of the spacer [m]

! Nozzles
T_SIL = 0.000500                    ! Thickness of the silicon ejector plate [m]
T_NIT = 0.0000025 ! Thickness of the nitride layer [m]
W_BASE = 0.000750 ! Width of the nozzle base [m]
W_NOZ = 0.000016 ! Width of the nozzle [m]
PITCH = 0.000790 ! Center-to-center pitch between nozzles [m]
N_NOZ = 15 ! Number of nozzles

! Fluid
T_INT = 0.000005 ! Thickness of the fluid interface [m]

!*SOLUTION VARIABLES*!
LFREQ = 0.500E6 ! Low frequency limit [Hz]
HFREQ = 2.500E6 ! High frequency limit [Hz]
SUBSTEPS = 200 ! Number of substeps for the frequency sweep

!*MATERIAL NUMBERING*!
PZT = 1 ! P-880 Piezoelectric
SI = 2 ! Silicon
F_INT = 3 ! Interfacial fluid
F_BULK = 4 ! Bulk fluid
NI = 5 ! Nitride

!***PREPROCESSING***!
/PREP7 ! Enter the preprocessor

!***ELEMENT CONFIGURATION***!
!*P-880 Piezoelectric*!
ET,PZT,PLANE13,7,0,0,0,0 ! 2D coupled field element for the piezo with
ux,uy,volt dof's

! Material properties
! Scaling parameters
S_DENS = 1.0 ! Scaling applied to density
S_PER = 1.0 ! Scaling applied to relative permittivity

! Scaled values
MP,DENS,PZT,(S_DENS*7600) ! Density of piezo (kg/m3)
MP,DAMP,PZT,10E-10 ! Damping coefficient in piezo
MP,MURX,PZT,0 ! Relative permeability of piezo (not used)
MP,KXX,PZT,0 ! Thermal conductivity of piezo (not used)
MP,PERX,PZT,(S_PER*1290) ! Relative permittivity of piezo in x direction
MP,PERY,PZT,(S_PER*1000) ! Relative permittivity of piezo in y direction
MP,PERZ,PZT,(S_PER*1290) ! Relative permittivity of piezo in z direction

! Stiffness matrix of piezo - assume transverse isotropic (only 5 independent parameters)
! Baseline values
E_OFF = 9e10                      ! Young's modulus in x and z direction [Pa]
E_POL = 7.2e10                    ! Young's modulus in y (polarized) direction [Pa]
NU_OFF = 0.333                    ! Poisson's ratio in unpolarized plane
NU_POLOFF = 0.345                 ! Poisson's ratio for strain in polarized direction
affecting unpolarized strain
GZP = 1.57e10                     ! Shear modulus in polarized direction

! Scaling parameters
S_E_OFF = 1.0                     ! Scaling applied to Young's modulus in x and z direction
S_E_POL = 1.2                     ! Scaling applied to Young's modulus in y (polarized)
direction
S_NU_OFF = 1.0                 ! Scaling applied to Poisson's ratio in unpolarized plane
S_NU_POLOFF = 1.0           ! Scaling applied to Poisson's ratio in polarized direction
S_GZP = 1.0             ! Scaling applied to shear modulus in polarized direction

! Stiffness matrix entries
C11NUM = ((S_E_OFF*E_OFF)*(-
(S_E_POL*E_POL)+(S_E_OFF*E_OFF)*(S_NU_POLOFF*NU_POLOFF)*(S_NU_P
OLOFF*NU_POLOFF)))
C11DEN = ((1+(S_NU_OFF*NU_OFF))*((S_E_POL*E_POL)*(-
1+(S_NU_OFF*NU_OFF))+2*(S_E_OFF*E_OFF)*(S_NU_POLOFF*NU_POLOFF)*(
S_NU_POLOFF*NU_POLOFF)))
C11 = C11NUM/C11DEN
C12NUM =
((S_E_OFF*E_OFF)*(S_E_POL*E_POL)*(S_NU_POLOFF*NU_POLOFF))
C12DEN = ((S_E_POL*E_POL)-(S_E_POL*E_POL)*(S_NU_OFF*NU_OFF)-
2*(S_E_OFF*E_OFF)*(S_NU_POLOFF*NU_POLOFF)*(S_NU_POLOFF*NU_POLO
FF))
C12 = C12NUM/C12DEN
C13NUM = (-1)*((S_E_OFF*E_OFF)*((S_E_POL*E_POL)*(S_NU_OFF*NU_OFF)+(S_E_OFF*E
OFF)*(S_NU_POLOFF*NU_POLOFF)*(S_NU_POLOFF*NU_POLOFF)))
C13DEN = ((1+(S_NU_OFF*NU_OFF))*((S_E_POL*E_POL)*(-
1+(S_NU_OFF*NU_OFF))+2*(S_E_OFF*E_OFF)*(S_NU_POLOFF*NU_POLOFF)*(
S_NU_POLOFF*NU_POLOFF)))
C13 = C13NUM/C13DEN
C22NUM = ((S_E_POL*E_POL)*(S_E_POL*E_POL)*(-1+(S_NU_OFF*NU_OFF)))
C22DEN = ((S_E_POL*E_POL)*(-
1+(S_NU_OFF*NU_OFF))+2*(S_E_OFF*E_OFF)*(S_NU_POLOFF*NU_POLOFF)*(
S_NU_POLOFF*NU_POLOFF))
C22 = C22NUM/C22DEN
C44 = 2*(S_GZP*GZP)
C66 = (S_E_OFF*E_OFF)/(2*(1+(S_NU_OFF*NU_OFF)))

! Define stiffness matrix
TB,ANEL,PZT  
TBDATA,1,C11,C12,C13  
TBDATA,7,C22,C12  
TBDATA,12,C11  
TBDATA,16,C44  
TBDATA,19,C44  
TBDATA,21,C66  

! Stress matrix of piezo  
! Baseline values  
D33 = 215e-12  
D31 = -95e-12  
D15 = 330e-12  

! Scaling parameters  
S_D33 = 1.0  ! Scaling applied to piezoelectric constant d33  
S_D31 = 1.0  ! Scaling applied to piezoelectric constant d31  
S_D15 = 1.0  ! Scaling applied to piezoelectric constant d15  

! Stress matrix entries  
E12 = (C11*(S_D31*D31)+C13*(S_D31*D31)+C12*(S_D33*D33))  
E22 = 2*C12*(S_D31*D31)+C22*(S_D33*D33)  
E14 = C44*(S_D15*D15)  

! Define stress matrix  
TB,PIEZ,PZT  
TBDATA,2,E12  ! E13 piezoelectric constant (YX)  
TBDATA,5,E22  ! E33 piezoelectric constant (YY)  
TBDATA,8,E12  ! E23 piezoelectric constant (YZ)  
TBDATA,10,E14  ! E61 piezoelectric constant (XXY)  
TBDATA,15,E14  ! E52 piezoelectric constant (ZYZ)  

!*SILICON!*  
ET,SI,82! Structural element for silicon  

! Material properties  
MP,EX,SI,150E9  ! Young's modulus of Si [Pa]  
MP,PRXY,SI,0.21  ! Major Poisson's ratio of Si  
MP,DENS,SI,2330  ! Bulk density of Si [kg/m3]  
MP,DAMP,SI,6E-9  ! Damping coefficient of Si  

!*NITRIDE!*  
ET,NI,82 ! Structural element for nitride  

! Material properties  
MP,EX,NI,250E9  ! Young's modulus of nitride [Pa]
MP,PRXY,NI,0.24  ! Major Poisson's ratio of nitride
MP,DENS,NI,3100  ! Bulk density of nitride [kg/m3]
MP,DAMP,NI,6E-9   ! Damping coefficient of nitride

!*FLUID*!
ET,F_INT,29       ! Fluid element for acoustic analysis (interface)

! Material properties
MP,DENS,F_INT,1000 ! Density of fluid [kg/m3]
MP,SONC,F_INT,1500 ! Speed of sound of fluid [m/s]
MP,VISC,F_INT,1E-3 ! Viscosity of fluid [kg/m-s]
MP,MU,F_INT,0     ! Absorption coefficient of solid at interface

ET,F_BULK,29,,1   ! Fluid element for acoustic analysis (bulk)

! Material properties
MP,DENS,F_BULK,1000 ! Density of fluid [kg/m3]
MP,SONC,F_BULK,1500 ! Speed of sound of fluid [m/s]
MP,VISC,F_BULK,1E-3 ! Viscosity of fluid [kg/m-s]

!***GEOMETRIC PARAMETERS***!

H_FLUID = T_PIEZO + T_SPACE  ! Height of the fluid from base
H_SIL = H_FLUID + T_SIL      ! Height of the silicon from base
H_NIT = H_SIL + T_NIT        ! Height of the nitride from base
W_EDGE = (W_PIEZO - PITCH*(N_NOZ - 1) - W_BASE)/2  ! Width of silicon at edge of array

Y_MEM = H_SIL
X_MEM = T_SIL/1.4144
X_NOZ = (W_BASE - W_NOZ)/2

!***CREATE GEOMETRY***!

!*KEY POINTS*!
K,1,0,0,0
K,2,W_PIEZO,0,0
K,3,0,T_PIEZO,0
K,4,W_SPACE,T_PIEZO,0
K,5,W_PIEZO/2,T_PIEZO,0
K,6,W_PIEZO - W_SPACE,T_PIEZO,0
K,7,W_PIEZO,T_PIEZO,0
K,8,W_SPACE + 5*T_INT,T_PIEZO + 5*T_INT,0
K,9,W_PIEZO/2,T_PIEZO + 5*T_INT,0

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K,10,W_PIEZO - W_SPACE - 5*T_INT,T_PIEZO + 5*T_INT,0
K,11,W_SPACE + 5*T_INT,H_FLUID - 5*T_INT,0
K,12,W_EDGE + T_INT,H_FLUID - T_INT,0
K,13,W_PIEZO - W_EDGE - T_INT,H_FLUID - T_INT,0
K,14,W_PIEZO - W_SPACE - 5*T_INT,H_FLUID - 5*T_INT,0
K,15,0,H_FLUID,0
K,16,W_SPACE,H_FLUID,0
K,17,W_EDGE,H_FLUID,0
K,18,W_PIEZO - W_EDGE,H_FLUID,0
K,19,W_PIEZO - W_SPACE,H_FLUID,0
K,20,W_PIEZO,H_FLUID,0
K,21,W_EDGE + X_MEM + T_INT/5,Y_MEM - T_INT/5,0
K,22,W_EDGE + X_NOZ + T_INT/5,Y_MEM - T_INT/5,0
K,23,W_PIEZO - W_EDGE - X_NOZ - T_INT/5,Y_MEM - T_INT/5,0
K,24,W_PIEZO - W_EDGE - X_MEM - T_INT/5,Y_MEM - T_INT/5,0
K,25,0,Y_MEM,0
K,26,W_EDGE + X_MEM,Y_MEM,0
K,27,W_EDGE + X_NOZ,Y_MEM,0
K,28,W_PIEZO - W_EDGE - X_NOZ,Y_MEM,0
K,29,W_PIEZO - W_EDGE - X_MEM,Y_MEM,0
K,30,W_PIEZO,Y_MEM,0
K,31,0,H_NIT,0
K,32,W_EDGE + X_MEM,H_NIT,0
K,33,W_EDGE + X_NOZ,H_NIT,0
K,34,W_EDGE + X_NOZ + T_INT/5,H_NIT,0
K,35,W_PIEZO - W_EDGE - X_NOZ - T_INT/5,H_NIT,0
K,36,W_PIEZO - W_EDGE - X_NOZ,H_NIT,0
K,37,W_PIEZO - W_EDGE - X_MEM,H_NIT,0
K,38,W_PIEZO,H_NIT,0

*IF,N_NOZ,GT,1,THEN
*DO,N,1,N_NOZ - 1,1
K,39 + 18*(N-1),W_EDGE + (N-1)*PITCH + X_NOZ + W_NOZ - T_INT/5,H_NIT,0
K,40 + 18*(N-1),W_EDGE + (N-1)*PITCH + X_NOZ + W_NOZ - T_INT/5,Y_MEM - T_INT/5,0
K,41 + 18*(N-1),W_EDGE + (N-1)*PITCH + W_BASE - X_MEM - T_INT/5,Y_MEM - T_INT/5,0
K,42 + 18*(N-1),W_EDGE + (N-1)*PITCH + W_BASE - T_INT,H_FLUID - T_INT,0
K,43 + 18*(N-1),W_EDGE + N*PITCH + T_INT,H_FLUID - T_INT,0
K,44 + 18*(N-1),W_EDGE + N*PITCH + X_MEM + T_INT/5,Y_MEM - T_INT/5,0
K,45 + 18*(N-1),W_EDGE + N*PITCH + X_NOZ + T_INT/5,Y_MEM - T_INT/5,0
K,46 + 18*(N-1),W_EDGE + N*PITCH + X_NOZ + T_INT/5,H_NIT,0
K,47 + 18*(N-1),W_EDGE + N*PITCH + X_NOZ,H_NIT,0
K,48 + 18*(N-1),W_EDGE + N*PITCH + X_NOZ,Y_MEM,0
K,49 + 18*(N-1),W_EDGE + N*PITCH + X_MEM,Y_MEM,0
K,50 + 18*(N-1),W_EDGE + N*PITCH,H_FLUID,0
K,51 + 18*(N-1),W_EDGE + (N-1)*PITCH + W_BASE,H_FLUID,0
K,52 + 18*(N-1),W_EDGE + (N-1)*PITCH + W_BASE - X_MEM,Y_MEM,0
K,53 + 18*(N-1),W_EDGE + (N-1)*PITCH + X_NOZ + W_NOZ,Y_MEM,0
K,54 + 18*(N-1),W_EDGE + (N-1)*PITCH + X_NOZ + W_NOZ,H_NIT,0
K,55 + 18*(N-1),W_EDGE + (N-1)*PITCH + W_BASE - X_MEM,H_NIT,0
K,56 + 18*(N-1),W_EDGE + N*PITCH + X_MEM,H_NIT,0
*ENDDO
*ENDIF

!*AREAS*!

! Piezo
A,1,3,4,5,6,7,2

! Spacer
A,3,15,16,4
A,7,20,19,6

! Bulk silicon
A,15,25,26,17,16
A,20,30,29,18,19

! Bulk nitride
A,25,31,32,33,27,26
A,30,38,37,36,28,29

! Bulk chamber fluid interface
A,5,4,16,17,26,27,33,34,22,21,12,11,8,9
A,5,6,19,18,29,28,36,35,23,24,13,14,10,9

! Bulk chamber fluid
A,9,8,11,12,13,14,10

! Nozzle areas
*IF,N_NOZ,EQ,1,THEN
   ! Fluid pyramid
   A,12,21,22,34,35,23,24,13
   AADD,10,11

*ELSEIF,N_NOZ,EQ,2
   ! Fluid-structure interface
   A,54,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53

   ! Inverted silicon pyramid
   A,52,51,50,49

   ! Nitride layer
   A,54,53,52,49,48,47,56,55

   ! Fluid pyramids
   A,12,21,22,34,39,40,41,42
   A,43,44,45,46,35,23,24,13

   ! Add fluid pyramids to bulk fluid chamber
   ASEL,S,AREA,,10
   ASEL,A,AREA,,11,12
   AADD,ALL

*ELSE
   *DO,M,1,N_NOZ - 1,1
       DMY = 18*(M-1)

       ! Fluid-structure interfaces
       A,54 + DMY,39 + DMY,40 + DMY,41 + DMY,42 + DMY,43 + DMY,44
       + DMY,45 + DMY,46 + DMY,47 + DMY,48 + DMY,49 + DMY,50 + DMY,51 + DMY,
       52 + DMY, 53 + DMY

       ! Inverted silicon pyramid
       A,52 + DMY,51 + DMY,50 + DMY,49 + DMY

       ! Nitride layer
       A,54 + DMY,53 + DMY,52 + DMY,49 + DMY,48 + DMY,47 + DMY,56
       + DMY,55 + DMY

   *ENDDO

   ! Fluid pyramids
   A,12,21,22,34,39,40,41,42
   A,43 + 18*(N_NOZ-2),44 + 18*(N_NOZ-2),45 + 18*(N_NOZ-2),46 +
   18*(N_NOZ-2),35,23,24,13
*DO,L,2,N_NOZ-1,1
   A,43 + 18*(L-2),44 + 18*(L-2),45 + 18*(L-2),46 + 18*(L-2),39 + 18*(L-1),40 + 18*(L-1),41 + 18*(L-1),42 + 18*(L-1)
*ENDDO

! Add fluid pyramids to bulk fluid chamber
ASEL,S,AREA,,10

*DO,J,1,N_NOZ,1
   ASEL,A,AREA,,10 + 3*(N_NOZ-1) + J
*ENDDO

AADD,ALL

*ENDIF

ALLSEL

!***DISPLAY RESULTING GEOMETRY***!

APLOT
/REPLOT
LPLOT

!***MESHING***!

!*SIZE LINES*!
! Bottom of piezo
LSEL,S,LINE,,7
LESIZE,ALL,,,150,-0.5

! Sides of piezo
LSEL,S,LINE,,1,6,5
LESIZE,ALL,,,10

! Top and bottom of spacer
LSEL,S,LINE,,2,5,3
LSEL,A,LINE,,9,12,3
LESIZE,ALL,,,10

! Lines defining the top of piezo and adjoining fluid layer
LSEL,S,LINE,,3
LSEL,A,LINE,,38,46,8
LESIZE,ALL,,,70,0.5
LSEL,S,LINE,,4
LESIZE,ALL,,70,2

! Lines defining sides of spacer and silicon and adjoining fluid layer
LSEL,S,LINE,,8,10,2
LSEL,A,LINE,,11,13,2
LSEL,A,line,,14,18,4
LSEL,A,LINE,,37,45,8
LESIZE,ALL,,10

! Lines on top of silicon and nitride defining area with no nozzles
LSEL,S,LINE,,15,19,4
LSEL,A,LINE,,23,28,5
LESIZE,ALL,,250,0.015

! Lines defining the height of nitride membranes in area with no nozzles and the height of the fluid-structure interface above the piezo
LSEL,S,LINE,,22
LSEL,A,LINE,,27,39,12
LESIZE,ALL,,2

! Lines on both sides of ejector plate (edge) defining area with no nozzles and adjoining fluid layer
LSEL,S,LINE,,17,21,4
LSEL,A,LINE,,36,44,8
LESIZE,ALL,,75,10

! Lines defining thickness (horizontal) of fluid-structure interface layer on left of left most nozzle and right of right most nozzle
LSEL,S,LINE,,32,40,8
LESIZE,ALL,,3

! Lines defining vertical portion of nozzles on left of left most nozzle and right of right most nozzle and adjoining fluid layer
LSEL,S,LINE,,25,33,8
LSEL,A,LINE,,30,41,11
LESIZE,ALL,,5

! Lines defining membrane extent on left of left most nozzle and right of right most nozzle and adjoining fluid layer
LSEL,S,LINE,,24,29,5
LESIZE,ALL,,10,0.2
LSEL,S,LINE,,26,31,5
LSEL,A,LINE,,34,42,8
LESIZE,ALL,,10,5
! Lines defining slanted portion of nozzles and adjoining fluid layer on left of left most
nozzle and right of right most nozzle
LSEL,S,LINE,,16,35,19
LSEL,A,LINE,,20,43,23
LESIZE,ALL,,60,10

*IF,N_NOZ,EQ,1,THEN
! Line defining width of top of single nozzle
LSEL,S,LINE,,48
LESIZE,ALL,,5

*ELSE
! Line defining width of top of outer two nozzles
LSEL,S,LINE,,48 + (N_NOZ-1)*20,50 + (N_NOZ-1)*20,2
LESIZE,ALL,,5

*DO,I,1,N_NOZ-1,1
! Lines defining thickness of fluid-structure interface layer on top of
nozzles
LSEL,S,LINE,,48 + (I-1)*20,56 + (I-1)*20,8
LESIZE,ALL,,3

! Lines defining length of upper portion of inner nozzles and adjoining
fluid layer
LSEL,S,LINE,,49 + (I-1)*20,55 + (I-1)*20,6
LSEL,A,LINE,,57 + (I-1)*20,63 + (I-1)*20,6
LESIZE,ALL,,5

! Lines defining membrane extent of inner nozzles and adjoining fluid
layer
LSEL,S,LINE,,50 + (I-1)*20,58 + (I-1)*20,8
LSEL,A,LINE,,65 + (I-1)*20
LESIZE,ALL,,10,5
LSEL,S,LINE,,54 + (I-1)*20,62 + (I-1)*20,8
LSEL,A,LINE,,67 + (I-1)*20
LESIZE,ALL,,10,0,2

! Lines defining slanted part of inner nozzles
LSEL,S,LINE,,51 + (I-1)*20,59 + (I-1)*20,8
LESIZE,ALL,,60,10
LSEL,S,LINE,,53 + (I-1)*20,61 + (I-1)*20,8
LESIZE,ALL,,60,0,1

! Lines defining the area between inner nozzles and adjoining fluid layers
LSEL,S,LINE,,52 + (I-1)*20,60 + (I-1)*20,8
LESIZE,ALL,,5
! Lines between tops of nozzles in silicon and nitride
LSEL,S,LINE,,64 + (I-1)*20,66 + (I-1)*20,2
LESIZE,ALL,,,50,-20
*ENDDO
*ENDIF

*IF,N_NOZ,GT,2,THEN
  *DO,H,1,N_NOZ-2,1
     ! Lines defining the top face of nozzles
     LSEL,S,LINE,,52 + (N_NOZ-1)*20 + 2*(H-1)
     LESIZE,ALL,,,5
  *ENDDO
*ENDIF
*ENDIF

ALLSEL

!*MESH AREAS*!
ASEL,S,AREA,,1! Select the piezo area
AATT,1,,1,0 ! Attach the element and material types to the unmeshed piezo area
MSHAPE,0,2D ! Select element mesh shapes to be quadrilateral
AMESH,1 ! Mesh the piezo area
ALLSEL

ASEL,S,AREA,,2,5 ! Select the silicon spacer and edge areas (silicon)
AATT,2,,2,0 ! Attach the element and material types to the unmeshed silicon areas
MSHAPE,0,2D ! Select element mesh shapes to be quadrilateral
AMESH,2,5 ! Mesh the silicon areas
ALLSEL

ASEL,S,AREA,,6,7 ! Select the edge areas (nitride)
AATT,5,,5,0 ! Attach the element and material types to the unmeshed nitride areas
MSHAPE,1,2D ! Select element mesh shapes to be triangles
AMESH,6,7 ! Mesh the nitride areas
ALLSEL

ASEL,S,AREA,,8,9 ! Select the fluid-structure interfaces next to the edge areas
AATT,3,,3,0 ! Attach the element and material types to these unmeshed areas
MSHAPE,1,2D ! Select element mesh shapes to be triangles
AMESH,8,9 ! Mesh these areas
ALLSEL

ASEL,S,AREA,,11 + (N_NOZ-1)*3 + N_NOZ ! Select the fluid chamber area
AATT,4,,4,0 ! Attach the element and material types to the unmeshed fluid chamber area
MSHAPE,1,2D ! Select the element mesh shapes to be triangles
AMESH,11 + (N_NOZ-1)*3 + N_NOZ ! Mesh the fluid chamber area

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ALLSEL

*IF,N_NOZ,GT,1,THEN
  *DO,F,1,N_NOZ-1,1
    ASEL,S,AREA,,11 + (F-1)*3
    AATT,3,3,0
    MSHAPE,1,2D
    AMESH,11 + (F-1)*3
    ALLSEL
    ASEL,S,AREA,,12 + (F-1)*3
    AATT,2,2,0
    MSHAPE,0,2D
    AMESH,12 + (F-1)*3
    ALLSEL
    ASEL,S,AREA,,13 + (F-1)*3
    AATT,5,5,0
    MSHAPE,0,2D
    AMESH,13 + (F-1)*3
  ALLSEL
  *ENDDO
*ENDIF

***BOUNDARY CONDITIONS***!

!*FLAG FLUID/STRUCTURE INTERFACE*!
LSEL,S,LINE,,3,4
LSEL,A,LINE,,10
LSEL,A,LINE,,13
LSEL,A,LINE,,16,17
LSEL,A,LINE,,20,21
LSEL,A,LINE,,25,26
LSEL,A,LINE,,30,31

*IF,N_NOZ,GT,1,THEN
  *DO,E,1,N_NOZ-1,1
    LSEL,A,LINE,,57 + (E-1)*20,63 + (E-1)*20
  *ENDDO
*ENDIF

SFL,ALL,FSI   ! Issue the fluid-structure interface flag
ALLSEL

!*SET THE ZERO PRESSURE BC AT THE NOZZLE TIP*!
LSEL,S,LINE,,32,40,8

*IF,N_NOZ,EQ,1,THEN
LSEL,A,LINE,,48
*ELSE
LSEL,A,LINE,,48 + (N_NOZ-1)*20,50 + (N_NOZ-1)*20,2

*DO,D,1,N_NOZ-1,1
LSEL,A,LINE,,48 + (D-1)*20,56 + (D-1)*20,8
*ENDDO
*ENDIF

*IF,N_NOZ,GT,2,THEN
*DO,C,1,N_NOZ-2,1
LSEL,A,LINE,,52 + (N_NOZ-1)*20 + 2*(C-1)
*ENDDO
*ENDIF

NSLL,S,1! Select all nodes attached to these lines
D,ALL,PRESS,0 ! Set pressure to a constant value of zero
ALLSEL

!*SET ZERO VERTICAL DISPLACEMENT BC AT THE TOP OF THE SILICON*!
LSEL,S,LINE,,23,28,5

!*IF,N_NOZ,GT,1,THEN
*DO,B,1,N_NOZ-1,1
LSEL,A,LINE,,66 + (B-1)*20
*ENDDO
*ENDIF

DL,ALL,,UY,0 ! Apply the zero vertical displacement boundary condition
ALLSEL

!*SET THE VOLTAGE BCS AT THE TOP AND BOTTOM OF THE PIEZO*!
LSEL,S,LINE,,7! Select the bottom line for the piezo area
DL,ALL,,VOLT,0! Apply the zero voltage boundary condition to the bottom line for the piezo area
ALLSEL

LSEL,S,LINE,,3,4 ! Select the top line for the piezo area
NSLL,S,1! Select nodes attached to the top line for the piezo area
CP,1,VOLT,ALL
D,12,VOLT,10 ! Apply the nonzero voltage boundary condition to the top line for the piezo area
ALLSEL

!***SOLUTION***!
/SOLU  ! Enter the solution processor  
ANTYPE,HARMIC,NEW  ! Select a new harmonic analysis  
HROPT,FULL  ! Use the full method  
HROUT,ON! Print complex results as real and imaginary parts  
OUTRES,ALL,ALL! Store every substep  
HARFRQ,LFREQ,HFREQ  ! Set the range for the frequency sweep (Hz)  
NSUBST,SUBSTEPS     ! Set the number of substeps between the initial and final frequencies  
KBC,1   ! Specify stepped loading between steps  
/STATUS,SOLU  ! Provide a solution status summary  
SOLVE   ! Solve the problem setup  

Postprocessing commands used most commonly were those such as the following:  

LSEL,S,LINE,,3,4  
NSLL,S,1  
!ESLN,S,0  

*DO,A,1,200,1  
    /POST1  
    SET,1,A,,0  
    /OUTPUT,real_current_0.txt,,APPEND  
    PRNLD,AMPS  
    /OUTPUT  
    FINISH  
*ENDDO  

*DO,A,1,200,1  
    /POST1  
    SET,1,A,,1  
    /OUTPUT,imag_current_0.txt,,APPEND  
    PRNLD,AMPS  
    /OUTPUT  
    FINISH  
*ENDDO  

ALLSEL  

! SELECT ALL LINES AT NOZZLE OPENINGS ON TOP OF EJECTOR PLATE  
LSEL,S,LINE,,32,40,8
*IF, N_NOZ, EQ, 1, THEN
  LSEL, A, LINE,, 48
*ELSE
  LSEL, A, LINE,, 48 + (N_NOZ-1)*20, 50 + (N_NOZ-1)*20, 2
*DO, D, 1, N_NOZ-1, 1
  LSEL, A, LINE,, 48 + (D-1)*20, 56 + (D-1)*20, 8
*ENDDO
*ENDIF

*IF, N_NOZ, GT, 2, THEN
  *DO, C, 1, N_NOZ-2, 1
    LSEL, A, LINE,, 52 + (N_NOZ-1)*20 + 2*(C-1)
  *ENDDO
*ENDIF

NSLL, S, 0
ESLN, S, 0

! OUTPUT THE PRESSURE GRADIENT AT THE NOZZLE TIP TO FILE
/POST1
/FORMAT,,,13

/OUTPUT, pressure_gradient_real, txt,, APPEND
*DO, A, 1, 200, 1
  SET, 1, A,, 0
  PRESOL, SMISC, 2
*ENDDO
/OUTPUT

/OUTPUT, pressure_gradient_imag, txt,, APPEND
*DO, A, 1, 200, 1
  SET, 1, A,, 1
  PRESOL, SMISC, 2
*ENDDO
/OUTPUT

! DEFINE PATHS THROUGH ALL NOZZLES AND OUTPUT PRESSURES ALONG PATHS
ALLSEL

/POST1
/PAGE,,,9999

*CFOPEN, Real_Path_Pressures.txt
*DO, A, 1, SUBSTEPS, 1
SET,1,A,,0
*GET,FREQUENCY,ACTIVE,0,SET,FREQ
*VWRITE,FREQUENCY
%16.8g

! For each nozzle, define a path, map the pressure, and output it
*DO,NOZ,1,N_NOZ,1
   PATH,NOZPATH,2,,99 ! define 100 points along each path
   NOZPATHX = (W_PIEZO-(N_NOZ-1)*PITCH)/2+(NOZ-1)*PITCH
   PPATH,1,,NOZPATHX,T_PIEZO
   PPATH,2,,NOZPATHX,H_SIL
   PDEF,NOZPRES,PRES
   PAGET,PATHINFO,TABLE
   *VWRITE,PATHINFO(1,1),PATHINFO(1,2),PATHINFO(1,3),PATHINFO(1,4),PATHINFO(1,5)
      %16.6g %16.6g %16g %16.6g %16.7g
PATHINFO=
*ENDDO
*ENDDO
*CFCLOSE

*CFOPEN, Imag_Path_Pressures.txt
*DO,A,1,SUBSTEPS,1

SET,1,A,,1
*GET,FREQUENCY,ACTIVE,0,SET,FREQ
*VWRITE,FREQUENCY
%16.8g

! For each nozzle, define a path, map the pressure, and output it
*DO,NOZ,1,N_NOZ,1
   PATH,NOZPATH,2,,99 ! define 100 points along each path
   NOZPATHX = (W_PIEZO-(N_NOZ-1)*PITCH)/2+(NOZ-1)*PITCH
   PPATH,1,,NOZPATHX,T_PIEZO
   PPATH,2,,NOZPATHX,H_SIL
   PDEF,NOZPRES,PRES
   PAGET,PATHINFO,TABLE
   *VWRITE,PATHINFO(1,1),PATHINFO(1,2),PATHINFO(1,3),PATHINFO(1,4),PATHINFO(1,5)
      %16.6g %16.6g %16g %16.6g %16.7g
PATHINFO=
*ENDDO
*ENDDO
*CFCLOSE
FINISH
APPENDIX C:

FLUIDIC NUMERICAL MODEL

The numerical model of fluid flow within the nozzle was conducted using the CFD program FLUENT (Lebanon, NH) version 6.2.16. The mesh is represented in Figure 43; it contains 24,500 cells. Results were checked against a mesh of half the density to ensure mesh-independent values; error was $O(10^{-2})$. A representative command file is presented here for reference.

```plaintext
(cx-gui-do cx-activate-item "MenuBar*ReadSubMenu*Case...")
(cx-gui-do cx-set-text-entry "Select File*FilterText" "c:\documents and settings\lauren\my documents\fluent\sim\steadyflow\16um\**")
(cx-gui-do cx-activate-item "Select File*Apply")
(cx-gui-do cx-set-text-entry "Select File*Text" "16um.msh")
(cx-gui-do cx-activate-item "Select File*OK")
(cx-gui-do cx-activate-item "MenuBar*GridMenu*Check")
(cx-gui-do cx-activate-item "MenuBar*GridMenu*Smooth/Swap...")
(cx-gui-do cx-activate-item "Smooth/Swap Grid*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "Smooth/Swap Grid*PanelButtons*PushButton1(Swap)")
(cx-gui-do cx-activate-item "Smooth/Swap Grid*PanelButtons*PushButton2(Cancel)")
(cx-gui-do cx-activate-item "MenuBar*GridMenu*Scale...")
(cx-gui-do cx-set-real-entry-list "Scale Grid*Frame1(Scale Factors)*RealEntry1(X)" '((1e-006))
(cx-gui-do cx-set-real-entry-list "Scale Grid*Frame1(Scale Factors)*RealEntry2(Y)" '((1e-006))
(cx-gui-do cx-activate-item "Scale Grid*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "Scale Grid*PanelButtons*PushButton2(Cancel)")
(cx-gui-do cx-activate-item "MenuBar*ModelsSubMenu*Solver...")
(cx-gui-do cx-set-toggle-button "Solver*Table1*Frame5(Space)*ToggleButton5(Space)*Axisymmetric" #f)
(cx-gui-do cx-activate-item "Solver*Table1*Frame5(Space)*ToggleButton5(Space)*Axisymmetric")
(cx-gui-do cx-activate-item "Solver*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "MenuBar*DefineMenu*Materials...")
(cx-gui-do cx-activate-item "Materials*Table1*Frame3*ButtonBox3*PushButton1(Fluent Database)"
```
(cx-gui-do cx-set-list-selections "Database Materials*Table1*Frame1*Frame1*List1(Materials)" '( 548))
(cx-gui-do cx-activate-item "Database Materials*Table1*Frame1*Frame1*List1(Materials)")
(cx-gui-do cx-set-position "Database Materials" '(x 116 y 447))
(cx-gui-do cx-activate-item "Database Materials*PanelButtons*PushButton1(Copy)")
(cx-gui-do cx-activate-item "Database Materials*PanelButtons*PushButton1(Close)")
(cx-gui-do cx-set-text-entry "Materials*Table1*Frame1*Table1*TextEntry1(Name)" "test_10cp")
(cx-gui-do cx-set-text-entry "Materials*Table1*Frame1*Table1*TextEntry2(Chemical Formula)" "")
(cx-gui-do cx-set-real-entry-list "Materials*Frame2(Properties)*Table2(Properties)*Frame10*Frame2*RealEntry3" '( 0.01))
(cx-gui-do cx-activate-item "Materials*PanelButtons*PushButton1(Change/Create)")
(cx-gui-do cx-activate-item "Materials*PanelButtons*PushButton1(Close)")
(cx-gui-do cx-activate-item "MenuBar*DefineMenu*Operating Conditions...")
(cx-gui-do cx-set-real-entry-list "Operating Conditions*Table1*Frame1(Pressure)*Table1(Pressure)*Frame3(Reference Pressure Location)*Table3(Reference Pressure Location)*RealEntry1(X)" '( 2.5e-006))
(cx-gui-do cx-set-real-entry-list "Operating Conditions*Table1*Frame1(Pressure)*Table1(Pressure)*Frame3(Reference Pressure Location)*Table3(Reference Pressure Location)*RealEntry2(Y)" '( 8e-006))
(cx-gui-do cx-activate-item "Operating Conditions*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "MenuBar*DefineMenu*Boundary Conditions...")
(cx-gui-do cx-set-list-selections "Boundary Conditions*Table1*Frame1*List1(Zone)" '( 2))
(cx-gui-do cx-activate-item "Boundary Conditions*Table1*Frame1*List1(Zone)")
(cx-gui-do cx-activate-item "Boundary Conditions*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-set-list-selections "fluid-2-1*Table3*Table1*DropDownList1(Material Name)" '( 0))
(cx-gui-do cx-activate-item "fluid-2-1*Table3*Table1*DropDownList1(Material Name)")
(cx-gui-do cx-activate-item "fluid-2-1*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-set-list-selections "Boundary Conditions*Table1*Frame1*List1(Zone)" '( 3))
(cx-gui-do cx-activate-item "Boundary Conditions*Table1*Frame1*List1(Zone)")
(cx-gui-do cx-activate-item "Boundary Conditions*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-set-real-entry-list "pressure-inlet-6-1*Table4*RealEntry9(Gauge Total Pressure)" '( 101325))
(cx-gui-do cx-activate-item "pressure-inlet-6-1*PanelButtons*PushButton1(OK)")
(cx-gui-do cx-activate-item "Boundary Conditions*PanelButtons*PushButton2(Cancel)")
(cx-gui-do cx-activate-item "MenuBar*ControlsSubMenu*Solution..."
(cx-gui-do cx-set-list-selections "Solution Controls*Table2*Frame1(Discretization)*Table1(Discretization)*DropDownList2(Momentum)" ( 1))
(cx-gui-do cx-activate-item "Solution Controls*Table2*Frame1(Discretization)*Table1(Discretization)*DropDownList2(Momentum)"
(cx-gui-do cx-activate-item "Solution Controls*PanelButtons*PushButton1(OK)"
(cx-gui-do cx-activate-item "MenuBar*InitializeSubMenu*Initialize..."
(cx-gui-do cx-activate-item "Solution Initialization*PanelButtons*PushButton1(OK)"
(cx-gui-do cx-activate-item "Solution Initialization*PanelButtons*PushButton2(Cancel)"
(cx-gui-do cx-activate-item "MenuBar*MonitorsSubMenu*Residual...
(cx-gui-do cx-set-toggle-button "Residual Monitors*Table1*Frame1(Options)*CheckBoxBox2(Options)*CheckButton2(Plot)" #f)
(cx-gui-do cx-activate-item "Residual Monitors*Table1*Frame1(Options)*CheckBoxBox1(Options)*CheckButton2(Plot)"
(cx-gui-do cx-set-real-entry-list "Residual Monitors*Table2*RealEntry10" '( 1e-007))
(cx-gui-do cx-set-real-entry-list "Residual Monitors*Table2*RealEntry15" '( 1e-007))
(cx-gui-do cx-set-real-entry-list "Residual Monitors*Table2*RealEntry20" '( 1e-007))
(cx-gui-do cx-activate-item "Residual Monitors*PanelButtons*PushButton1(OK)"
(cx-gui-do cx-activate-item "MenuBar*SolveSubMenu*Iterate...
(cx-gui-do cx-set-integer-entry "Iterate*Table1*Frame2(Iteration)*Table2(Iteration)*IntegerEntry1(Number of Iterations)" 10000)
(cx-gui-do cx-activate-item "Iterate*PanelButtons*PushButton1(Apply)"
(cx-gui-do cx-activate-item "Iterate*PanelButtons*PushButton2(Cancel)"
(cx-gui-do cx-activate-item "MenuBar*WriteSubMenu*Stop Journal")}
REFERENCES


86. "Blending chart for Dow Corning 200 Fluid." Dow Corning.


