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Paper

AN INVESTIGATION OF METHODS TO HOMOGENEOUSLY ENTRAIN AND SUSPEND ABRASIVE PARTICLES IN A LOW PRESSURE DENTAL WATER JET

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ABSTRACT

Water jet systems have been utilized at a wide range of different pressures. Previous research performed at Brigham Young University has shown that low pressure water jets (200-500 psi) have the ability to cut human teeth and remove dental caries. Experiments have revealed that when abrasive particles are added to the water jet stream, a greater amount of tooth material can be removed in a shorter period of time. BYU researchers have attempted a variety of ways to insert abrasive particles into a low pressure water jet stream for dental applications. As with high pressure systems, challenges have included metering the desired mixture of abrasive into the stream and preventing settling and clogging of the abrasive. These challenges are more pronounced in low pressure systems.

A list of methods and concepts to suspend abrasives in a desired low pressure dental system has been generated. Product design principles were applied to screen, score, and rank these various concepts for entraining abrasives in a water jet stream for dental applications. Magnetic stirring, polymer (xanthan) suspension, and ultrasonic vibrations were chosen as the three leading concepts. Experimental initial results are summerized.

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1. INTRODUCTION

The American Dental Association Survey Reports that there are over 155 million filling procedures performed annually in the United States alone (American Dental Association, Survey Center 1990). It has only been in the last few decades that noteworthy improvements have been made to dental tool handpieces.

Currently, the majority of tooth decay is removed by high-speed dental drills. In the 1990's a third wave of accepted technology introduced alternative techniques for removing dental caries. Though the drill has been effective in removing tooth material, it has several weaknesses that until recently have had no alternative design. Two of the most current alternative dental handpieces are the laser and air abrasion handpiece tools.

An alternative method that may be used as a dental handpiece for removing caries is a low pressure abrasive water jet. Industrial water jets have been a growing machine cutting tool for several decades. The drill, laser, and air abrasion tools each have their inherent advantages and disadvantages. It is believed that a low pressure abrasive jet has the capability to overcome many of the weaknesses of the dental tools currently used. Research performed at Brigham Young University (BYU) has shown that a low pressure water jet has the ability to cut tooth enamel. Continued research for an abrasive jet for a dental application is currently pending on discovering a method to successfully entrain and suspend aluminum oxide particles in a low pressure water jet system.

2. CURRENT HANDPIECE DESIGNS

2.1 The Dental Drill Handpiece

The drill remains a very popular choice among dentist for several reasons: It is the fastest cutting tool, it is inexpensive, and it has been on the market for many years. New hand tools are surging because the dental bur (drill) handpiece has several undesirable characteristics. Since the drill bur comes in direct contact with the tooth, friction occurs, which may cause pain. Drill vibration may also result in dentin micro fracture.

A notable drawback of the traditional hand drill is that the minimal amount of cutting is limited to the diameter of the drill tip. Even the smaller tips are often too large to cut away just the decayed enamel, which results in excessive healthy enamel and dentin being removed from the tooth. Due to the nature of traditional drilling, anesthesia is often required to minimize the pain and/or discomfort to the patient. Most modern drills are pneumatically driven and generate a distinct shrill and whine sound.

2.2 The Laser Handpiece

The laser was initially approved for gum surgery in 1995. One of the most prominent deterring factors for investing in the laser as a standard dental handpiece is the relatively high cost of the unit. Also, experience has shown that the laser takes more time than the conventional mechanical drill method of removing caries.

2.3 The Air Abrasion Dental Handpiece

Air abrasion is based off of the well-known sand-blasting principle, but with a focusing tip suited for dental applications. The decayed tooth material is removed by brittle fracture erosion. The process has slower cutting rates when compared to the dental drill. The standard air abrasion handpiece can also create a cloud of dust covering the cutting area and even outside of the mouth.

2.4 Considerations for an Alternative Method

It is believed that an alternative dental handpiece that overcomes the weaknesses of the drill, laser, and air abrasion handpieces would be successful in the dental community. The cost of the tool and operation needs to stay competitive with the traditional drill. The process needs to be virtually pain free for common dental caries removal (no anesthesia required). The stigmatism of a whining drill must be avoided and it needs to be quick and also cleaner than air abrasion. The performance should match or exceed the handpieces currently employed. It is anticipated that a low pressure abrasive water jet has the potential to meet all of this criteria.

3.0 PREVIOUS RESEARCH

The purpose of industrial high pressure water jets (HPWJ) is to provide an effective method for cutting a wide range of materials. High pressure industrial water jets carry extreme amounts of momentum energy due to the high velocity of the exiting water stream.

High pressure water jets can be harmful and destructive to softer materials such as human tissue. Research has shown that low pressure water jets (LPWJ) could be effective in dental applications (Hansen 2000, Memmott 2003). To obtain lower water jet pressures that still cut tooth enamel, abrasives have been introduced into the water jet stream. Adding abrasive material allows the cutting pressure to be decreased sufficiently to merit further investigation. However, entraining abrasives into any water jet system presents difficult challenges, particularly in lower pressure water jet systems.

Preliminary studies by Hansen and Memmott at BYU have demonstrated the potential of using LPWJ's for cutting teeth. Both studies found that the addition of abrasives significantly improved cutting ability and cutting rates on teeth and ceramics with similar material characteristics. However, difficulties of entraining abrasives into the water jet stream to achieve homogenous slurry, and therefore, predictable cutting rates proved to be complicated. The abrasive particles consistently settled and clogged the test apparatus. Memmott states:

"This [entraining abrasives] is critical to the success of [low pressure] abrasive jets. Many of the problems of adding abrasive involves the ability to pump fluid with abrasive entrained and then controlling the flow of the fluid with the entrained abrasive. These challenges will have to be addressed in order to take this technology to market (2003)."

There is no known research dealing with methods to entrain and suspend abrasives in a low pressure abrasive jet for a dental application.

The objectives of this research were as follows:

- Investigate the advantages and disadvantages of several possible methods of mixing and suspending abrasive particles homogeneously in a low pressure water jet intended for a dental system.
- Investigate the feasibility of employing the suggested methods into a low pressure water jet system using good product design and development practices.
- Recommend one or more of the possible methods to entrain and suspend abrasives continuously and homogeneously in a low pressure water jet stream.
- Test and validate the entrainment and suspension concepts of the suggested method(s) to determine whether it is a viable solution for a LPWJ for a dental system.

The work previously performed by Hansen and Memmott at BYU has provided the parameters for the intended low pressure water jet, which helped to guide this research.

- The abrasive jet will have a working pressure range of 0-3.40 MPa.
- The nozzle orifice will be between 1.02-2.03E-4 meters.
- It is anticipated that a range of 5-17% Al_2O_3-H_20 (by weight) slurry concentration will be used.
- The Aluminum Oxide will have a diameter range of 1.27-6.86E-7.
- The pressure supply of gas to pressurize the water jet system will likely be a compressed air or nitrogen tank since it is commonly found in dental offices. This approach will eliminate the need of a pump.
- An approximate cavity volume of 2.57E-3 mm^3, a pressure of 3.4 MPa, and an exit orifice diameter of 1.52E-4 meters would require a slurry volume of 6.60E-5 m^3 at a jet velocity of about 80 m/s.

3.1 The Problem at a Macro Level

It is typically easier to narrow down the search for a solution when the macro view is understood, beyond the specific task at hand. For this application, the low pressure dental abrasive jet would be used in a professional environment and is anticipated to be used on human patients ranging in age from young children to mature adults. The function of the system must be safe and user friendly.

Also, just as other dental handpieces are designed to meet the dentist's needs, this water jet system is likely, but not necessarily, to have a similar set-up as shown in Figure 6.1. As such, it is proposed that a batch size set-up similar to Figure 6.2 would be most successful for this application. This approach will avoid the need to mix and suspend the abrasive particles continuously in the region between the main power unit and the exiting handpiece.

3.2 Generated Concepts

The next step in the design process was to generate concepts that may solve the entrainment problem keeping in mind the parameters, delimitations, and functional specifications. The following is a list with a few of the methods that were generated. Some of these concepts and their designed method of particle entrainment are described briefly here, but are presented in more detail in a research thesis by Michael S. Grygla (2007).

The following is a list of several concepts with their proposed advantages and disadvantages. The list begins with those methods that are already being used for industrial jet systems. Thereafter, the list contains possible alternative methods that are from analogous devices and also those that may be considered new or unique.

Table 1 Summary table of the possible advantages and disadvantages of the generated concepts

Concept	Advantages	Disadvantages
Post-Orifice Entrainment (Hashish 1982, 84, 91, 97)	• Adds abrasives after the water jet exits the orifice • Avoids pump and internal system wear	• Low pressure velocities too slow to create sufficient low pressure zone to pull in abrasive particles • Method also entrains air
Traditional DIAjet System (Bypass Principle) (Fairhurst *et al* 1982, 86)	• Does not require a secondary external force to entrain and suspend particles (in high pressure systems) • The design and experience is available and has been improved upon for years (since early 1980's) • Appears to be safe	• Requires higher velocities and slow rates to create the slurry and suspend it sufficiently • Requires several valves and regulators to keep system at the proper pressures • Miniaturization may be difficult
Indirect Jet Method With Polymer (Brandt & Louis 1999)	• Avoids passing abrasives through the pump • Polymer suspends the slurry homogeneously and consistently • Can be easily miniaturized and pre-manufactured in a disposable cartridge	• Must use a separator or a cartridge to prevent water or air from mixing with the slurry • Polymer obscures worksite for dentist • Tested xanthan may decrease cutting ability (unknown)
Abrasive Ice Cube	• Particles pre-entrained and homogeneously mixed • Likely to not create a noise issue	• Requires elaborate design • Heating element may not be safe • Extreme temperatures may cause patient discomfort
Ultrasonic's: Cavitation, Streaming, and Levitation	• High frequency sound waves create strong stirring and mixing reactions and generate a homogeneous slurry • Waves are above audible region • Cavitation breaks up individual particles	• Produced waves are not audible but the piezoelectric motors produce high pitched shrills • Cavitation may destroy particles

Magnetic Stirrer	• Design and principle is simple • Lower costs in comparison to other generated concepts • Can be miniaturized • No mechanical component passing through the pressure vessel	• Requires secondary energy source • Magnetic forces will interact with any ferrous metal present • If abrasives settle compactly together around the stirring rod, the rod may become stuck

3.3 Screening and Scoring as a Means of Process Selection

Both a screening and a scoring process, or *Pugh concept selection*, were applied to quickly narrow down the number of concepts considered (Ulrich 2000). The matrices were prepared by creating a table and listing the concepts across the top and the selection criteria along the left side, as illustrated in Table 1. Recall that the selection criteria are based on the functional specifications hereto outlined. The concepts were scored and ranked. The score given to each of the selection criteria is determined by knowledge acquired from this research and engineering judgment.

According to the specification criteria and the weighted scores, the magnetic stirring ranked first as a method which may be the most viable to entrain and suspend abrasive particles in a low pressure abrasive dental jet. Polymer suspension, ultrasonic propagation, and recirculation methods rank second, third, and fourth respectively.

4.0 CONCEPT VALIDATION AND INITIAL TESTING RESULTS

It is the opinion of the author that the concepts that ranked first and second will be the most promising methods to entrain and suspend abrasive particles. However, the concept of using ultrasonic mixing was considered late in the research. The concept may or may not merit more consideration; therefore, several experiments were also performed using this method to provide further information.

4.1 Polymer Suspension, Xanthan

A previous comparative performance study on xanthan determined which concentration levels may provide the desired characteristics for a high pressure water jet system (Chacko *et al* 2003). The study concluded that xanthan concentrations of around 1.0% by weight offered the best cutting and suspension results when garnet particles were used. For this research, Al_2O_3 particles with a diameter of 6.35E-07 microns were used. These particles are much smaller than garnet, which is often used in high pressure industrial water jet systems. It was assumed that a lower concentration of xanthan would provide better suspension results for the smaller abrasive particles in this experiment.

To obtain a general idea of a solution viscosity with 1.0% concentration of xanthan, an intermediate test was conducted. A small clear 75-ml container was filled with water, 1.0% by weight of xanthan, 11.0% by weight of aluminum oxide material, and the rest was water. The slurry was allowed to sit for 24 hours and then remixed to ensure that the polymer was completely homogeneous and saturated with the water. The intermediate test showed that the 1.0% xanthan viscosity was more than adequate to suspend the particles for this application. The slurry appeared to be very “thick” and kept the abrasive particles completely suspended. These results provided the upper limit of xanthan polymer concentration for the subsequent experiments.

It was decided that several concentration samples ranging from 0.10%-0.90% of xanthan by weight would be tested. This range of concentrations would allow us to find the best interval of concentrations that may work for the low pressure abrasive jet. For example, if 0.30% xanthan proved to be sufficiently viscous to suspend particles and 0.10% xanthan allowed particles to settle, then the optimal xanthan concentration would then lie somewhere in between these two concentration limits.

The test results demonstrated the viscous suspension ability of the xanthan slurry at different concentrations. There was a very obvious increase in suspension ability from 0.10% to 0.30% concentrations. The 0.30% xanthan (second from the right in Figure 6.3) appears to be suspending the Al_2O_3 particles well; however, upon close inspection of the bottom of the container, there is obvious settling of the particles within 24 hours. The 0.50% xanthan slurry had virtually no settling effects. Therefore, it is deduced that the optimal suspension characteristics for the low pressure abrasive dental jet may be between 0.30-0.50% xanthan by weight with a concentration of 11.0% Al_2O_3.

To increase the confidence level of the experiment, a second series of tests was performed. With the new concentration limits defined, five more slurry samples were prepared: 0.10%, 0.20%, 0.30%, 0.40%, and 0.50% of xanthan, each with 11.0% aluminum oxide by weight. The second test would provide a comparison of the concentrations (0.10%, 0.30%, and 0.50%) against test 1, which would confirm or confute the previous conclusions. Also, testing the center points of 0.20% and 0.40% concentration would help narrow down the optimal concentration levels of xanthan.

The 0.10%-0.90% xanthan concentration slurries were allowed to sit in a refrigerator for 2 more weeks. It was apparent that the abrasives had continued to settle in the lower concentration slurries. Previously, it was believed that 0.40% xanthan might be a candidate for the slurry concentration; however, after 2 weeks of sitting it was obvious that come of the abrasive particles for this concentration had settled. Providentially, the 0.50% has continued to show no signs of settling and will continue to be considered as the best concentration level candidate.

4.1.1 Xanthan Slurry Water Jet Test

It is shown in Figure 6.3 that the suspended-particle xanthan slurry solutions are not transparent. Since the xanthan polymer continually suspends the abrasive material even after being jetted out of the exit nozzle, it could leave a layer of obscure slurry, which would block the operator's vision of the target workpiece (tooth). The consequence may be similar to that of the film left on the inside walls of the test containers.

In order to determine the functionality and capabilities of the xanthan polymer suspension method, a series of low pressure water jet tests were performed. Batch sizes of 400-gram slurry solution with 0.30%, 0.40%, and 0.5% xanthan concentration were prepared. The nozzle sizes available were 1.02 and 2.03E-4 meters in diameter. The basic schematic of the water jet system is in Figure 6.4.

The purpose of the tests was strictly for observation. The goals of the experiment were to determine whether or not the polymer slurry would effectively exit the orifice nozzle while maintaining the abrasive particles homogeneously suspended. Also, it was important to determine whether or not the slurry would leave an obscure covering around the work area similar to that of the baking soda experiments performed by Hansen of BYU.

4.1.2 Xanthan Test Results

All of the test runs were performed to some extent; however, most of them were inconclusive. From the beginning of the experiment, there were random orifice-clogging interruptions, just as previous researchers found. It is strongly believed that the polymer slurry was suspending the abrasive particles as expected and that there was a secondary and unanticipated factor that had not been previously considered, which was plugging the exit orifice. The clogging seemed to be random, but it was found to be more prominent with the smaller diameter nozzles and occurred more often when the pressure was initially applied (no particular pressure value). However, it sometimes randomly occurred toward the middle or end of the test run. Fortunately, some of the tests were completed and performed well with both orifice sizes. This allowed general conclusions to be made about the performance of the xanthan concept.

If the xanthan slurry suspension method is considered further for use in the anticipated low pressure dental jet, more tests will need to be performed in order to determine whether the xanthan polymer increases or decreases the water jet stream cutting performance. This can only be accomplished if the factors causing the nozzle orifice to clog are determined and solved.

4.2 Magnetic Stirring

The concept of creating a magnetic mixing action is elementary. A rotating magnet or electromagnetic field is placed outside a water-abrasive filled container. Inside the container is another magnet or ferrous metal rod. As the magnetic field rotates, it forces the ferrous bar inside the container to respond. If the bar is placed in the center of the rotating field, it will also begin to rotate.

4.2.1 Validation and Test Results for the Magnetic Stirrer

In order to validate the magnetic stirrer as a possible abrasive particle suspension method, a simple test was performed. A magnetic stirring table (hot plate) apparatus, shown in Figure 6.5 was used to simulate the desired mixing characteristics. The table has a small motor underneath a non-ferrous plate that rotates a magnetic bar. The same 80-ml container used in previous experiments was filled with aluminum oxide and water. A second magnetic bar was inserted and situated at the bottom of the container. The magnetic stirring table has a variable control knob to change the rotations per minute of the motor (some unknown value).

The first test utilized the desired slurry proportions that produce optimal cutting rates as suggested by the research of Hansen, which was 11.0% aluminum oxide and 89.0% water by weight. The magnetic table was turned on and its magnetic bar began to rotate. The bar inside the container homogeneously entrained and suspended the particles within seconds. Provided that the motor and magnetic bar continued to rotate the ferrous bar, the slurry stayed well mixed. As soon as the motor was turned off, rotation stopped, and the particles quickly began to settle.

The tests concluded that the most critical consequence of adding more abrasive material was its hindrance on the magnetic bar's ability to "start-up." If too much abrasive was added, the stirrer was not capable of initiating the rotation of the ferrous bar inside the container.

The ability of the magnetic bar to produce a homogeneous slurry, even with excessive amounts of abrasive material, demonstrates the potential of the magnetic stirrer as an entrainment and suspension method for this low volume application. One of the greatest benefits of this method is the fact that no mechanical device is required to pass through the pressure vessel. This reduces the complexity of the design significantly. The magnetic slurry method was not tested while under pressure; however, it is presumed that it's suspension capabilities would be unaffected under these conditions. These tests were performed to gain a perspective for future work. If this concept is pursued for future research, the optimal combination of factors will need to be determined.

4.3 Ultrasonic Cavitation

In order to determine whether ultrasonic sound waves have the ability to entrain and suspend aluminum oxide particles in water, a sonicating apparatus was setup as demonstrated in Figure 6.6. Though this system is large and generates far more power than is needed for this research application, the concepts and principles as set by to the low pressure water jet are anticipated to still apply.

This system is designed as a sonic dismembrator, model 550 by Fisher Scientific. It is intended to breakup cells and bacteria. It is a standard unit that works at a constant 20 KHz. This system uses a 3.2E-3 meter diameter micro-tip. The amplitude of the tip ranges (semi-linearly) from 0 to 6.1E-06 meters ranging from a setting from 0-5.

4.3.1 Validation of Ultrasonic Cavitation

There were two main objectives to accomplish. The first was to determine whether the transient streaming caused by the wave propagation and cavitation would be strong enough to mix and suspend the abrasive particles. Second, since cavitation produces extreme amounts of heat, a simple test would be performed to determine the rate of temperature increase for a given volume of water. It must be determined if the heat generated would produce an unsafe slurry. It was anticipated that these experiments would provide useful foresight and a starting place for the research that is expected to follow.

A sample of 50 ml slurry, with 11.0% Al_2O_3 particles by weight and 6.35E-07 meters in diameter was prepared. The horn was lowered into the solution and the sonicating dismembrator system was turned on with the amplitude set to ZERO. Next, the amplitude knob was slowly increased until noticeable streaming was visible. This occurred at a setting of about 1. As the amplitude was increased to a setting of 1.5-2.0, the cavitation and mixing became stronger which suspended about 75% of the abrasive particles. The amplitude was then increased to a setting of 3, which mixed and suspended all of the abrasive particles. It became apparent that this type of cavitation had capability to stir the solution into the desired homogeneous slurry.

Cavitation produces extreme amounts of heat and pressure as each bubble collapses. It was necessary to perform several experiments to determine the increase in temperature of the slurry mixture during cavitation. The same 50 ml volume amount of water was used, which is in the volume range that may be used for the handpiece. The tests were performed at amplitude settings 3 and 5 without the addition of abrasive material. These points were chosen because setting 3 seemed to efficiently suspend particles and setting 5 would provide information for the extreme upper limit.

Room temperature was recorded to be 23.5°C. The same clear plastic container was filled with 50 ml of tap water. A type-k thermocouple was inserted into the water. The test began at time zero and temperatures were recorded each minute for three consecutive minutes on setting 3. The same test was then repeated for setting 5.

The incremental increases appeared to be linear. More notably, the temperature rise on setting 3 increases at exactly 1.2°C/min. It is assumed that this temperature increase would be acceptable since the required batch size would be used within a 5 minutes. However, the results are intended to be useful information for future consideration.

5.0 CONCEPT VALIDATION CONCLUSIONS

This chapter reported on the results obtained from tests performed on the magnetic stirring, polymer suspension, and ultrasonic cavitation concepts. The tests were performed to validate their suspension and entrainment abilities. All three of these methods proved they were able to achieve their objectives.

The xanthan slurry was prepared and tested at different concentrations levels. A method and order for mixing the water, abrasive material, and xanthan polymer was suggested. It was determined that a xanthan concentration of 0.50% provides sufficient viscosity to suspend the aluminum oxide particles. The xanthan slurry was also noted to obscure the cutting point due to its cloudy characteristic.

A magnetic stirring apparatus was set up using a magnetic stirring table. A 50 ml container was filled with water and 11.0% abrasive material by weight. A ferrous rod was placed inside of the container. The container was placed on the table and the rotating magnetic bar inside the table was turned on. The rod inside the container quickly began to rotate, which created a mixing action with the water and abrasives. It appeared that the magnetic mixing concept was able to create the desired homogeneous slurry.

It was suggested that ultrasonic waves could be utilized to produce "streaming" and mix the abrasive particles in the water. A sonicating horn was lowered into a 50 ml container filled with the abrasive material. The machine was turned on and raised to several different intensity levels (0-5). Complete mixing was achieved at a setting of three. The machine demonstrated that ultrasonic cavitation and streaming have the potential to entrain and suspend the abrasive particles as desired by this research.

The purpose of this research was to investigate and suggest several possible methods to entrain and suspend abrasive particles for a low pressure dental water jet. The results from these tests are intended to help validate the chosen method's abilities to suspend and entrain Al_2O_3 particles and to provide stepping stones for future research.

6.0 GRAPHICS AND FIGURES

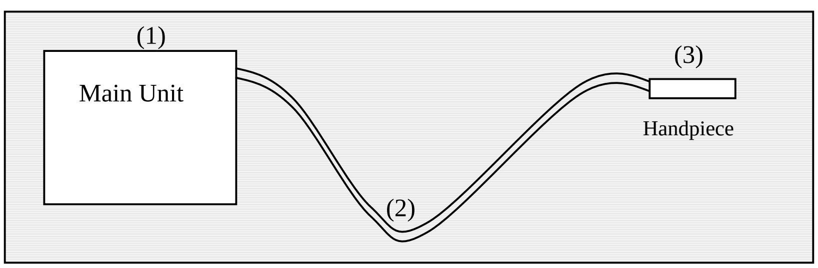

Figure 6.1 Test 2 of xanthan concentrations after 1 week

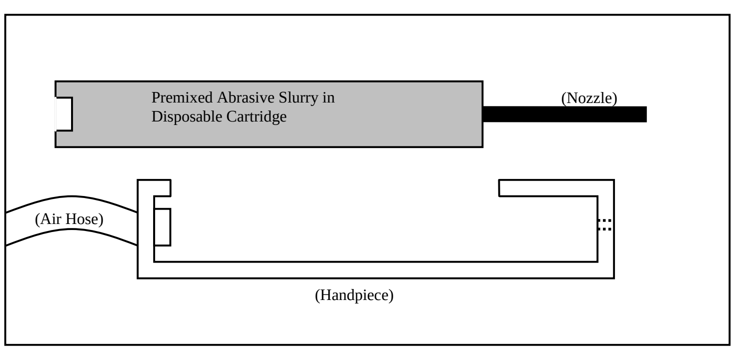

Figure 6.2 Possible batch size handpiece design

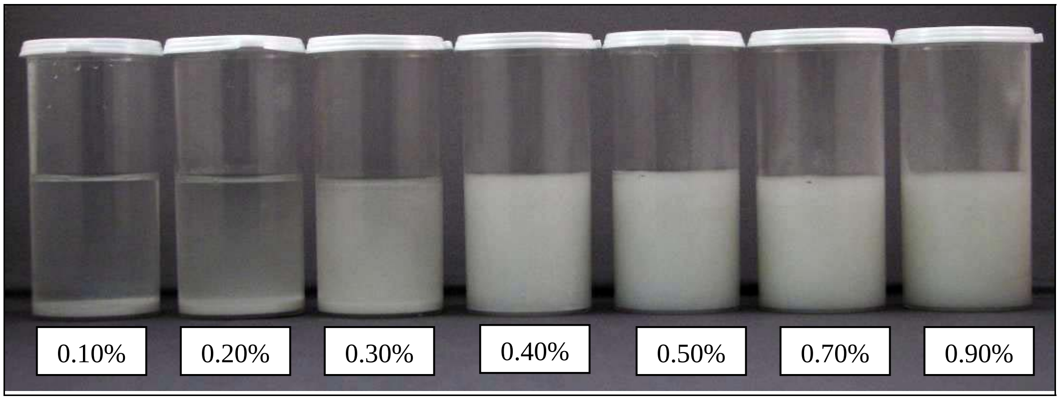

Figure 6.3 Test 2 of xanthan concentrations after 7 days

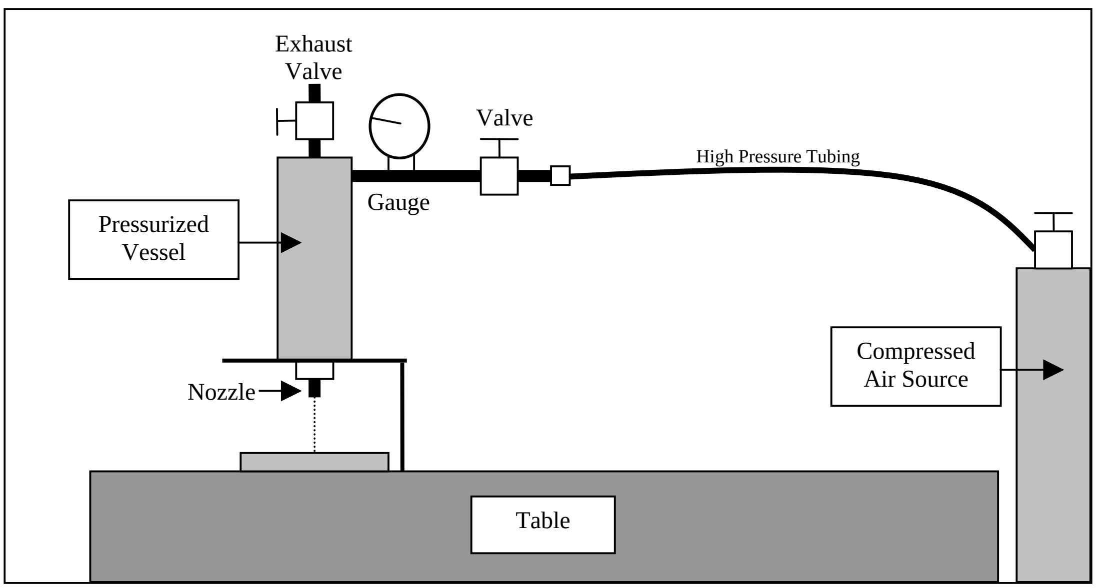

Figure 6.4 Schematic of general water jet set-up

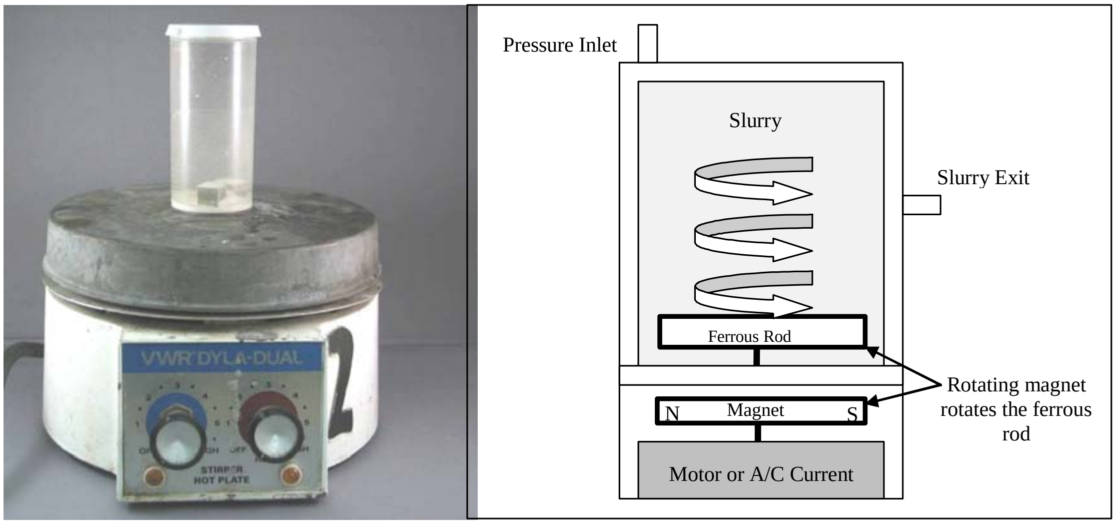

Figure 6.5 Magnetic mixing apparatus and schematic

Figure 6.6 Sonic dismembrator in a 50-ml solution with 11.0% Aluminum Oxide: (left) setting of 1.5 (right) setting of 3

Table 6.1 Screening and Scoring Matrices

Screening Matrix	Generated Concepts										
	A	B	C	D	E	F	G	H	I	J	E
Specification Criteria	**(Reference)** Stirring Mechanism (ex impellor)	Polymer Suspension	Melting Abrasive Ice	Vibration (ultrasonic)	Vibration (magnetic mechanism)	Mixer (Recirculation Mixer/Pump)	Magnetic Stirrer	Pulsing Bladder	Bubble System	Traditional DIAjet System	Rotating Vessel
Overall Functionality	0	0	-1	1	0	1	1	-1	-1	0	-1
Cost	0	1	0	0	1	1	1	-1	1	0	0
Reliability (overall design)	0	1	-1	0	0	0	0	0	0	0	-1
Performance (Homogeneity)	0	1	0	1	0	0	0	0	-1	0	0
Performance (Entrainment)	0	1	1	1	0	0	0	1	-1	0	1
Performance (Water Jet steam)	0	-1	0	1	1	1	1	0	0	0	1
Safety	0	-1	-1	1	1	1	1	0	1	1	0
External Energy	0	1	-1	0	0	0	0	-1	0	0	-1
Manufacturability	0	0	-1	-1	-1	-1	0	-1	1	-1	-1
Location (miniaturization)	0	1	1	0	0	not required	0	-1	1	-1	-1
Visibility for Dentist	0	-1	0	0	0	0	0	0	0	0	0
Noise	0	1	1	-1	-1	0	0	-1	0	1	0
Total	**0**	**4**	**-2**	**3**	**1**	**3**	**4**	**-5**	**1**	**0**	**-3**

Scoring Matrix **Specifications Criteria**		F **(Reference)** Mixer (Recirculation Mixer/Pump)		B Polymer Suspension		G Magnetic Stirrer		G Ultrasonic Cavitation/Streaming	
	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Functionality	10%	**3**	0.3	3	0.3	5	0.5	4	0.4
Performance (Homogeneity)	15%	**3**	0.45	4	0.6	3	0.45	4	0.6
Performance (Entrainment)	15%	**3**	0.45	5	0.75	5	0.75	5	0.75
Performance (Cutting Ability)	15%	5	0.75	**3**	0.45	5	0.75	5	0.75
External Energy	10%	**3**	0.3	5	0.5	4	0.4	3	0.3
Manufacturability	5%	2	0.1	4	0.2	**3**	0.15	3	0.15
Placement (any location)	15%	**3**	0.45	5	0.75	4	0.6	3	0.45
Decrease Cutting Visibility	10%	5	0.5	**3**	0.3	5	0.5	5	0.5
Noise	5%	1	0.05	**3**	0.15	1	0.05	1	0.05
Total Weighted Score		**3.35**		**4.00**		**4.15**		**3.95**	
Rank		**4**		**2**		**1**		**3**	

Relative Performance	Rating
(Reference number in bold)	
Much worse than reference	1
Worse than reference	2
Same as reference	3
Better than reference	4
Much better than reference	5

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