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BUBBLE ELIMINATION ON THE SURFACE OF A CONTACT LENS SUBMERGED IN DE-IONIZED WATER

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ABSTRACT

A formal research and development process was used to investigate methods for the removal of bubbles found on the surface of a contact lens submerged in de-ionized water. After extensive testing, it was determined that ultrasound can remove well over 99% of the bubbles from a contact lens. The process involves sending ultrasonic pressure waves through the degassed and de-ionized water that holds the contact lens. This method proved to be very reliable, will easily integrate into the existing manufacturing process, and meets all the requirements specified by the costumer, Bausch and Lomb.

INTRODUCTION

Bausch and Lomb is currently developing a fully automated Vision Inspection system that takes an image of a contact lens and has a software algorithm analyze the image for cosmetic defects. However, the algorithm cannot always distinguish between a dark circular air bubble and a dark circular cosmetic defect that it founds on a contact lens. Due to the current manufacturing process, over 90% of the lenses produced have bubbles attached to the surface and the algorithm rejects more than 50% of the lenses. Manual inspection suggests that roughly 20% of the lenses currently produced have true defectives on them. Therefore about 30% of the lenses are falsely discarded due to the presence of bubbles.

A team of students from the Multidisciplinary Senior Design course at RIT was asked to develop a process that would eliminate the air bubbles from the water cell, thereby improving the accuracy of the Wet Vision Inspection system. The water cell is the container that holds the contact lens and the water in the FreeDial production machine, which is where the Wet Vision Inspection system resides. However, the actual manufacturing machine where the vision inspection system resides was not available for testing, so the team designed and built its own semi-automatic test fixture to use for experimentation. The test fixture was attached to a scaled down stand-alone wet vision inspection system provided to the team by Bausch and Lomb. The stand-alone, or One-up, simulates the vision inspection process on the manufacturing machine and was originally built for Wet Vision Inspection development.

NOMENCLATURE

FreeDial – Current automated cosmetic inspection machine
One-up – Stand-alone test station provided by Bausch & Lomb to simulate production version wet vision inspection system
SVS – Single Vision Spherical contact lens
Toric – contact lens made for astigmatism
Water Cell – Glass container that holds the contact lens and the water
P_g - pressure inside of an air bubble (Pa)
P_l - pressure outside of an air bubble (Pa)
σ - surface tension of water (N/m)
R_o - mean radius of an air bubble (m)
P_o - absolute water pressure (Pa)
k - polytropic constant (unit-less)
ρ - density (kg/m^3)
P_b - pressure of undisturbed water (Pa)
P_m - induced amplitude pressure wave (Pa)
I - intensity of a pressure wave (kg/s^3)
Z - acoustic impedance (kg/(m^{2}s))
P – power (W)

PROTECTION OF INTELLECTUAL PROPERTY

To maintain confidentiality with Bausch and Lomb, some aspects of this research and development project cannot be disclosed in this document. Full details are presented in the report prepared for Bausch and Lomb.

DEVELOPMENT PROCESS

Multidisciplinary Senior Design at RIT has traditionally been focused on product development and the techniques used to develop new products. For this project, the sponsor has asked the team research, develop, and prove a viable method for removing bubbles while working within certain constrains. Although the focus seems different, the problem solving methodologies used for product development are applied here in the same way. The only major difference is in the final product. For this project the product will be integrated into a mass production line, as apposed to being mass produced on its own.

The solution to the problem was approached in two stages. The first stage was qualitative testing, where the team conducted research and small scale testing on ten potential technologies. The purpose was simply to see what method could eliminate bubbles from the water cell. The results of this qualitative testing were evaluated for feasibility, from which three candidate technologies were considered for further testing. The second stage was quantitative analysis where the team measured the effectiveness of the chosen methods and quantitatively evaluated the results.

PROJECT REQUIREMENTS AND CONSTRAINTS

The senior design team and Bausch & Lomb established design objectives to produce the most viable bubble elimination method that can be integrated into Bausch and Lomb's existing manufacturing line. The primary design objectives are as follows:

- Method must have the capability of being integrated into the existing manufacturing process and dimensional constraints.
- Method must reduce at least 50% of bubbles within the water cell.
- Method can't induce any damage to the contact lens.
- Method must be reliable, repeatable, and safe to use.
- Method has to meet machine cycle time of 4 seconds.
- The lens must resume in concave up position after application of the method.
- The lens must settle to the bottom of the water cell within 12 seconds.

THEORETICAL ANALYSIS OF BEHAVIOR AND SIZE OF BUBBLES

After extensive testing it was determined that ultrasound is the most effective method for removing bubbles from the surface of the contact lens. For this reason, the theoretical analysis on the behavior of air bubbles is discussed during the presence of an ultrasonic pressure wave. Ultrasound takes a different approach at eliminating bubbles than Rotary Motion or Recirculation. However, the underlying principles are all the same. Research conducted by others has demonstrated that ultrasound is very effective at creating cavitation or air bubbles in water. For this reason, the team investigated the effects of ultrasound on air bubbles and then developed a way to use it to eliminate the bubbles instead of creating them.

Bubble Composition and Behavior

When a gas saturated liquid is subjected to a sinusoidal pressure field, the liquid experiences alternating compression and expansion pressure cycles. If during the expansion portion of the cycle the tensile stress exceeds the tensile strength of the fluid, bubbles will form in what are known as a nucleation sites [5]. These sites are generally thought of as microscopic air bubbles trapped within the liquid, whose formation is governed by the Nucleation Theory [7]. Once formed, these bubbles can do one of three things. (1) They can dissolve back into the liquid, (2) grow to a resonant size and fluctuate about their size, or (3) grow to a critical size at which the surface tension forces of the liquid cause it to collapse on to itself [5]. These bubbles will expand and contract, as dissolved air in the water will flow in and out of the air bubble through diffusion. When the bubble experiences positive pressure from the induced pressure wave, the air bubble compresses and the air diffuses out of the bubble. Vise versa for the negative pressure wave, where the bubble expands and the air diffuses from the water into the bubble.

During these alternating pressure waves, air bubbles will actually grow in size through a process known as Rectified Diffusion. There are two properties to rectified diffusion, the "area" effect and the "shell" effect [2]. The "area" effect occurs when the bubble grows in size and its outer surface is much larger when it's expanded than when it's compressed. Therefore, a greater amount of air will diffuse in the bubble during expansion cycle than will during its compression cycle. The "shell" effect pertains to the liquid layer surrounding the air bubble. As the bubble expands, the liquid layer gets thinner and diffusion rate of the air increases into the bubble. When the bubble shrinks, the shell gets thicker and gas diffusion rate decreases. Figure 1 demonstrates now rectified diffusion works.

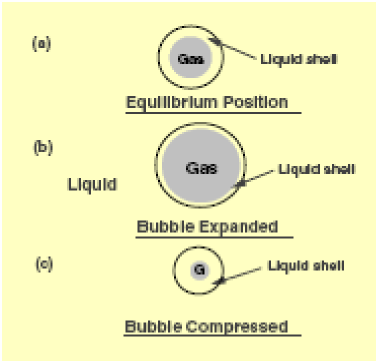


Figure 1: Schematic of rectified diffusion [2]

The combination of these two effects means that a bubble subjected to a sinusoidal pressure wave will continuously gain more dissolved air from the liquid and subsequently grows in volume until it reaches a threshold limit. This limit is the critical pressure amplitude and frequency that will cause the bubble to grow in size and ultimately collapse. A bubble subjected to frequency or pressure wave outside that threshold limit will have no effect on the size of the bubble. The threshold frequency and pressure has also been determined by previous researchers to be very sensitive to dissolved gas concentration of the surrounding liquid and will play a crucial role in making this method successful [1].

Advanced fluid dynamics equations can be derived to model the rectified diffusion process and can be used to fairly accurately determine the necessary conditions to increase or reduce the size of the bubbles [2]. However, the equations are quite complex and require numerical solutions to solve them. For the purpose of understanding the basic principles behind bubble formation and their behavior, simplified equations can be used.

The micro-bubbles in air saturated water are held there by the surface tension between the air in the bubbles and the water surrounding them. This tension holds the higher pressure inside the bubble than that of the immediate liquid surrounding it, and relates to surface tension through the Laplace pressure equation [2].

$$P_g - P_l = 2\sigma/R_o \qquad (1)$$

Here P_g is the pressure inside the bubble, P_l is the pressure of the surrounding water, σ is the surface tension, and R is the radius of the bubble. This equation is simply the summation of all forces acting in the same direction along the interface or liquid membrane of the bubble. Surface tension is constant for air/water at 20ºC and is equal to 7.27E-2 N/m. This means that the pressure difference between the inside and outside of the gas, P_g and P_l, will determine the size of the bubble.

Since the pressure inside is difficult to control, the size of the bubble could theoretically by controlled by changing the immediate pressure applied to the bubbles surface, or $P_{ap} = P_{l.}$ This pressure has been determined to be as low as 0.25 bar and is dependent on the history of the water [6]. This is the threshold pressure mentioned above, and it is higher for air saturated water and lower for degassed water.

Another interesting phenomenon of air bubbles is that they can be modeled as simple spring/mass systems that have their own natural frequency of isolation, or threshold frequency. The air inside the bubble forms the spring and the liquid layer surrounding the bubble forms the mass. Therefore, the natural frequency of a spherical bubble is expressed as

$$Fn = [1/(2\pi*R_o*\text{sqrt}(\rho))]*[\text{sqrt}(3*k*P_o - (2*\sigma/R_o))] \qquad (2)$$

Where P_o is the absolute liquid pressure ($P_o = p_{atm} + \rho gh$), R_o is the mean radius of the bubble, k is the polytropic constant of the gas in bubble, σ is the surface tension, ρ is the density of the liquid surrounding the bubble [3]. The polytropic constant is between $1 \leq k \leq \gamma$, where γ is the specific heat and is 1.4 for air. When the process is isothermal, where heat can transfer in and out of the bubble very rapidly, k = 1 and this is usually the case for small bubbles. Large bubbles tend to behave in an adiabatic manor, transferring very little heat, and have the value of γ. For example, a bubble of 100μm in radius has a natural frequency of about 27.5 kHz. Therefore ultrasonic frequencies are required to burst the bubbles.

<u>Current Applications of Ultrasound</u>

Substantial research exists in the application of ultrasonic waves to create cavitation for the purpose of cleaning materials. Ultrasonic waves are used to increase the diameter of the bubbles until they reach a critical size, where they collapse and produce shock waves with localized high temperature (up to 5000k) and high pressure (up to 1000 atm) [5]. If the bubbles collapse near a material covered in dirt or grime, that energy can be used to clean the material. In industrial applications the frequency is rarely varied and is usually set for a specific application. Lower the frequency the bigger the bubbles will get, and the more energy they will release when they collapse. The intensity of the induced pressure waves is usually used to control the rate of cavitation.

Since this technology is currently used in the cleaning and chemical processing industries, requirements for cavitation have been well established. Cavitation is contributed by several parameters described below [2].

1. The radius of the bubble and the mass of the gas inside it is affected by the pressure amplitude (P_m) of the ultrasonic wave.
2. The mass of the gas inside the bubble is affected by the initial concentration of gas inside the surrounding liquid.
3. Frequency of the induced pressure wave affects the rate of diffusion and therefore the amount of gas inside the bubble.

By reversing some of the necessary requirements for cavitation, ultrasound can instead be used to eliminate the bubbles from the surface of the contact lens and from the water cell itself. The team decided to pursue the second condition and degas the water in the water cell. If the concentration of air in the liquid is decreased, there is the less gas available to diffuse into the bubble during rectified diffusion.

QAULITATIVE FEASIBILITY ASSESSMENT

Before a process for eliminating bubbles could be developed, a method to eliminate bubbles had to be researched. The team began researching for existing methods, but was unable to find any methods that could be applied to this application. After a brainstorming session with Bausch and Lomb engineers a large list of methods was produced. Focus then turned toward theoretical understanding of bubble formation and basic knowledge of mechanics and fluid dynamics, to determine which methods had potential for bubble elimination and which were erroneous. The following is a list of potential ideas was developed.

- Decrease ambient pressure above the water cell to 29 inHg and force the bubbles to dissolve
- Send an ultrasonic pressure waves into the water cell to cause the bubble to burst
- Physically force the bubbles off the lens with tweezers
- Degas the water before it goes into the water cell to force the air inside the bubbles will naturally diffuse out of the bubble
- Subsonic Vibration- vibrate the water in the water cell until the bubbles shake off the lens
- Re-circulate the water in the water cell to create a centripetal force to shear the bubbles off the lens
- Rotary Motion - also create a centripetal force by spinning a Teflon tip submerged in the water cell
- Chang the temperature of the water in the water cell to decrease the surface tension of the bubbles
- Change the water to surfactant in the water cell to decrease the surface tension of the bubbles
- Create an electrical potential difference in the water cell by sending an electric current

To validate the theories and methods developed, crude testing was done for each method on the One-up wet vision inspection system. On average, five B&L Toric contact lenses were used per testing parameter of each method. The parameters were chosen arbitrarily based on what the team felt would contribute to bubble elimination.

A picture of a lens was taken before and after each application with a digital camera mounted on the One-up. The team later evaluated the captured images to determine the effectiveness of the methods. Assessment of bubble reduction was visually estimated.

Concept Performance

The performance of each test was then compared to each other in a feasibility matrix to find the most viable solution(s). This matrix weighted requirements the team and Bausch and Lomb felt were the most important in finding a solution. Based on the testing outcomes, each working concept received a performance score for each respective requirement. Each respective performance score and requirement weight were multiplied together and summed up for each concept. Total concept scores were then totaled up and compared to each other. The feasibility matrix used is illustrated in Table 1.

Table 1: Qualitative Feasibility Matrix

Criteria	Criteria Weight	Subsonic Vibration	Rotary Motion	Surfactant w/ Vacuum	Ultrasonic Vibration	Recirculation	Vacuum
Testing Ease	2	3	3	2	3	2	2
Process Integration	3	2	2	1	2	1	2
Cost	1	2	2	2	1	2	2
Process Reliability	5	1	3	1	3	2	1
Cycle Time	5	3	3	2	3	3	0
Lens Damage	5	2	2	2	2	3	3
Maintain Lens Position	4	1	1	2	3	1	2
Settling Time	4	2	2	2	3	2	2
Reduction Results	5	2	3	3	3	2	3
Reduction Reliability	5	1	3	2	1	2	2
	Total	19	24	19	24	20	19
	Weighted Total	71	96	75	97	81	73

The matrix showed that ultrasound, rotary motion, and recirculation had the greatest potential for eliminating bubbles while meeting the needs of Bausch and Lomb. As predicted from theoretical analysis and testing during this stage, degassed water aided in bubble reduction in the water cell. The team decided to incorporate degassed water for all tests in the quantitative stage of this research and development process.

THEORY OF ULTRASOUND

The applied pressure wave that is experienced by the bubble can be expressed as

$$P_{ap} = P_b - P_m \mathrm{Sin}(2\pi f t) \tag{3}$$

Here P_b is the pressure of the undisturbed liquid and P_m and f is the amplitude pressure wave and frequency of the imposed pressure wave [2]. The pressure wave amplitude can be also be expressed by the intensity (I) on the wave.

$$I = P_m^{\ 2}/Z \tag{4}$$

Here Z is the acoustic impedance in the water and equals 1.54E5 Pa*s/m [4]. The intensity of the induced pressure wave can be controlled by the power applied to the piezo-electric transducer. The simple relationship is expressed by

$$P = I{*}A \tag{5}$$

The A is the area of the effective wave emission area on the transducer [4]. Based on experimentation and analytical analysis, it is also determined that ramping the power level is essential to effectively remove the bubbles from the water cell. Since most of the bubbles are of different sizes, by ramping the power level the bubbles gradually grow because of rectified diffusion. The gradual growth of the bubbles will cause them to collapse without releasing excessive energy, like during spontaneous collapse of bubbles during cavitation. When they reach a critical radius of about 280μm, otherwise the threshold frequency at 20 kHz, the bubbles collapse. This occurs at approximately 15W when cavitation is just about to start in the water cell. The 20 kHz is a constant frequency set on the ultrasonic homogenizer used during experimentation.

THEORY OF ROTARY MOTION AND RECIRCULATION

The idea behind Rotary Motion and Recirculation is to use circular flows and the momentum of the water to remove the bubbles from the contact lens. The circular flow pattern produced by both methods will create a low pressure around the bubble and a shear force that will either push the bubbles off the lens and out of the camera's field of view or force them to collapse. The process can be described by Euler's equation for differential pressure change normal to a streamline.

$$\frac{\partial p}{\partial n} = \frac{V^2 \rho}{R} \tag{6}$$

Here V is the velocity of a particle along a streamline, ρ in the density of the particle, and R is the radius of curvature for the streamline. From the above equation the pressure in the fluid will decrease in the outward direction from the center of curvature of a streamline. Since the water cell is shaped like a bowl, the water will travel in an arc around the water cell and cause a pressure field [8]. The generated circular cross flow of the water will shear the bubble off the lens and cause them to collapse [9]. Also, the mass of the bubbles is much less than the mass of the contact lens, so a low flow circular pattern might be enough to overcome the surface tension that holds the bubbles to the lens. An added advantage from Rotary Motion is that its Teflon head, discussed later, will help physically shear off the bubbles as it comes in contact with the lens.

QUANTITATIVE FEASIBILITY ASSESSMENT

The second phase of the development process involves designing and building a test fixture to be used for quantitative testing analysis. This phase involves using only the three best performing methods discussed above.

Experimentation Set-up and Fixture Design

To perform effective quantitative tests for the three chosen methods, a test fixture was designed and constructed. The fixture, shown in Figure 2, was designed to be mechanically robust, versatile, and adjustable to accommodate any changes that could arise during testing.

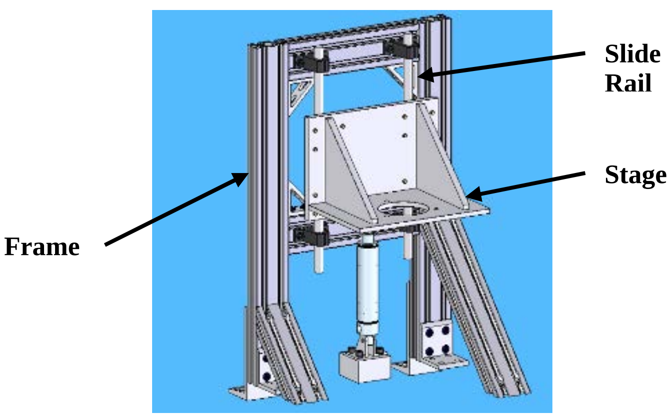


Figure 2: Designed Test Fixture

The test fixture was also designed to attach directly onto the One-up test station as shown in Figure 3. In addition to the camera system, the One-up also has a replica section of the indexing table used in FreeDial, but it's on a lateral slide instead. This section of the indexing table contains the water cell that holds the contact lens in the degassed de-ionized water. The set-up also has all the same dimensions as on the production machine.

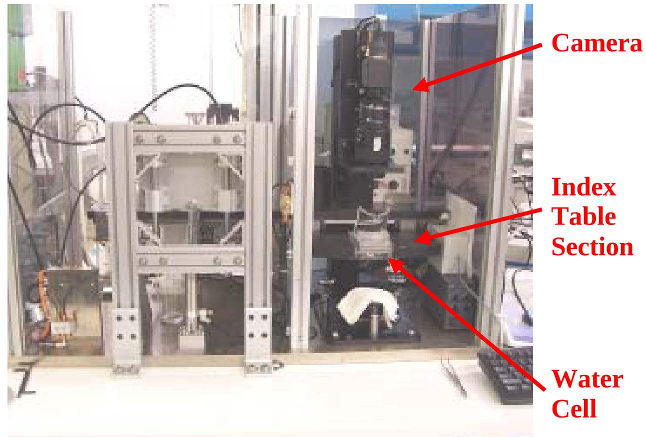
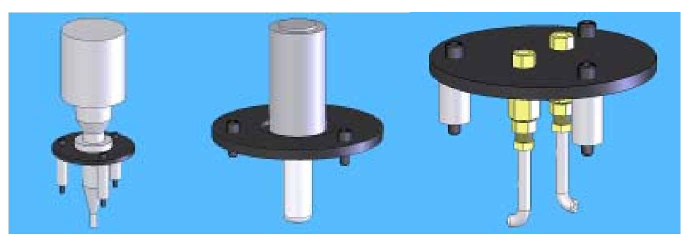


Figure3: Test fixture on the One-op

The new test fixture was designed to fit in the open section to the left of the camera on the One-up. With versatility and functionality as primary design factors, the fixture consists of a frame with a sliding stage that holds all the required hardware for all three methods. The frame was made from 80/20 extruded aluminum and a double acting pneumatic air cylinder was used to move the stage up and down.

The stage was designed out of plate aluminum with a large hole in the center so that various tools ranging from an ultrasonic wand to a pair of circulation tubes could pass thru the stage and reach the water cell. Since the units are all different, three mounting holes were added to the stage, and spacers were utilized to attach the required hardware onto the stage and achieve appropriate depth in the water cell. The individual hardware is shown in Figure 4.



a. Ultrasound b. Rotary Motion c. Recirculation

Figure 4: Hardware used for all three methods

Design of Experiments

A design of experiments was developed for each concept to test the effectiveness of the methods, to quantify their performance, determine their repeatability/reliability to eliminate the bubbles, and establish an operating window. The tests were conducted over several days and 30 SVS lenses were used for each testing parameter or run. Each DOE was conducted with regular and degassed de-ionized water. The data was recorded with before and after images to keep track of the number of bubbles on the lens. The test procedure was also kept constant to minimize outside variables that might affect the results between the methods. The procedure for testing each lens is as follows:

1. Fill the water cell with 13 ml of degassed or regular de-ionized water using the automatic peristaltic pump.
2. Slide the water cell carriage under camera.
3. Insert contact lens containing bubbles into water cell.
4. Take a picture of the lens and save it in the appropriate “Before” folder.
5. Slide the water cell carriage under the test fixture.
6. Initiate the air cylinder and turn on the bubble removal device.
7. When the lens settles into middle of the camera’s view, take another picture of the contact lens and save it in appropriate “After” folder
8. Remove water cell from the carriage and dispose of the lens and the water.
9. Replace the water cell onto the index table and repeat the process.

For the degassed portion of the DOE, de-ionized water was passed through a Liqui-Cel Mini-Module G432 membrane that was attached to a vacuum pump that drew 28 inHg. The air contained in air saturated water at STP can be determined by Henry’s Law to be about 8 ppm. The degassing membrane used in the experiments can remove 90% of air from the water when the flow rate is less than 200ml/min and the vacuum pressure is 28 inHg. The flow rate of the water refilling the water cell was measured to be about 150ml/min. Therefore the water used in the experiments was degassed down to about 0.8 ppm.

Ultrasound

To generate ultrasonic frequencies needed to perform both phases of testing, the team used the BioLogics 150 V/T Homogenizer, shown in Figure 5. It was determined that cavitation in the water cell occurs when the output power level excides about 15W. So the power level was ramped up to 15W and then back down to zero for all runs. Exact power level could not be determined because the unit only had incremental marks.

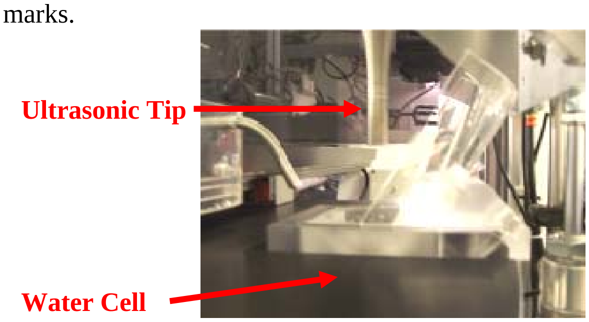


Figure 5: Ultrasonic tip approaching a water cell.

During qualitative testing, it was determined that no other power level removed the bubbles from the lens and that ramping of the power was essential to effectively remove the bubbles. Therefore the varied parameters for ultrasound were the tip immersion depth below the top of the water cell and duration cycle time. All design of experiments were created with Design Expert statistical software to include replications and center points. Table 2 demonstrates the parameters tested with ultrasound.

Table 2: DOE for Ultrasound

Trial #	Depth	Cycle Time
1	5/8"	1 sec
2	5/8"	2 sec
3	5/8"	1 sec
4	1/2"	1 sec
5	11/16"	2 sec
6	1/2"	1 sec
7	1/2"	2 sec
8	5/8"	2 sec
9	11/16"	1 sec
10	11/16"	2 sec
11	1/2"	2 sec
12	5/8"	1 sec
13	11/16"	1 sec
14	5/8"	2 sec

Rotary Motion

For rotary motion a Teflon head was attached to a 12V DC motor and submersed into a water cell below the water line. The Teflon head was then spun at several speeds for different lengths of time to remove the bubbles on the surface of the contact lens. The rotation speeds of the motor were chosen to be 8 volts and 10 volts or 1570 RPM and 1970 RPM. Speeds below 8V had little impact on bubble reduction, and speeds above 10V caused the water to flow out of the water cell. The motor was turned on for 0.5 sec and 1 sec; anything higher than that showed no improvement in bubble reduction in preliminary testing. The submersion depth was kept constant at 13/16” below the top of the water cell, because it also had no impact on bubble reduction in preliminary testing. After the motor was turned off, the Teflon head was held in the water cell for 2 seconds to reduce the time required for the lens to settle to the bottom of the water cell. The DOE used for Rotary Motion Testing is shown in Table 3 and the test set-up with the Teflon head used is shown in Figure 6.

Table 3: DOE for Rotary Motion

Run	Motor Speed (Volts/RPM)	Cycle Time (sec)
1	8/1570	1
2	10/1970	0.5
3	8/1570	0.5
4	8/1570	1
5	10/1970	1
6	10/1970	0.5
7	8/1570	0.5
8	10/1970	1

a. Teflon head approaching water cell b. Teflon head

Figure 6: Teflon head used in Rotary Motion.

Recirculation

During qualitative testing of the recirculation concept the ends of the tube were held in place manually. For quantitative testing a prototype was made to hold the ends in a fixed position, allowing for accurate and repeatable results. A peristaltic pump was attached to the stainless steel outlet tubes that could be attached to a stage plate through a pair of connection fittings. The ends of the outlet tubes are bent 90° in order to produce the centripetal flow in the water cell. The inlet end of the tube passed through the peristaltic pump and attached to the outlet tube. Recirculation set-up is shown in Figure 7.

Figure 7: Recirculation tubes approaching the water cell.

The original recirculation DOE involved 3 heights, 3 flow amounts, and 3 application times. However, due to the poor performance of recirculation in comparison with Ultrasound and Rotary Motion, only a few tests runs were conducted. Table 4 shows the 5 runs that were tested.

Table 4: DOE for Recirculation

Run Number	Volume (ml)	Depth	Cycle Time (sec)
1	14	Position 1	6
2	7	Position 1	2.5
3	7	Position 2	2.5
4	9.6	Position 1	3
5	14	Position 2	6

DATA ANALYSIS-QUANTITATIVE TESTING

Data analysis consisted of taking the before and after images from the DOE and passing them through the Zenergy/Cognex Wet Vision System algorithm. The captured images were analyzed by the algorithm, which produced a log file containing a variety of information pertaining to each lens. The only data of interest for these experiments was the amount of bubbles per lens and the area of the bubbles in pixels, which is 64 μm^2 per pixel. By knowing the number and area of the bubbles on the lens before and after the experiment, a percent reduction in bubbles could be calculated. Since Recirculation didn't match the performance of Ultrasound and Rotary Motion, it was excluded from data analysis.

From the results, it was observed that the percent reduction in the number of bubbles on the lens coincided with the area reduction of the bubbles averaged within 5%. Therefore, the following data is concerned primarily with the physical number of bubbles on the lens that was acquired by the Wet Vision Inspection System. Figure 8 demonstrates the performance of Ultrasound and Rotary Motion with and without degassed water.

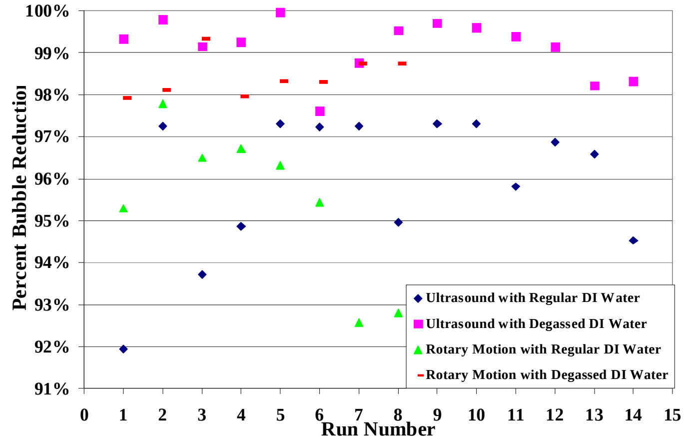


Figure 8: Total Bubble Count Reduction

In the above figure all four scenarios met the expectation set by Bausch and Lomb to reduce at least 50% of the bubbles. However, for the Wet Vision System to operate effectively with the lease number of false rejects, the number of bubbles on the lens should be as close to zero as possible. A summary of the average number of bubbles on the lens after each experiment is shown in Figure 9. For comparison, in current manufacturing the average number of bubbles per lens is between 5 and 20 with a high of 36. Figure 9 also demonstrates the consistency of ultrasound to reduce the number of bubbles, regardless of how many bubbles are on the lens initially. Out of 14 runs for ultrasound, all but 1 had less then 1 bubble per lens.

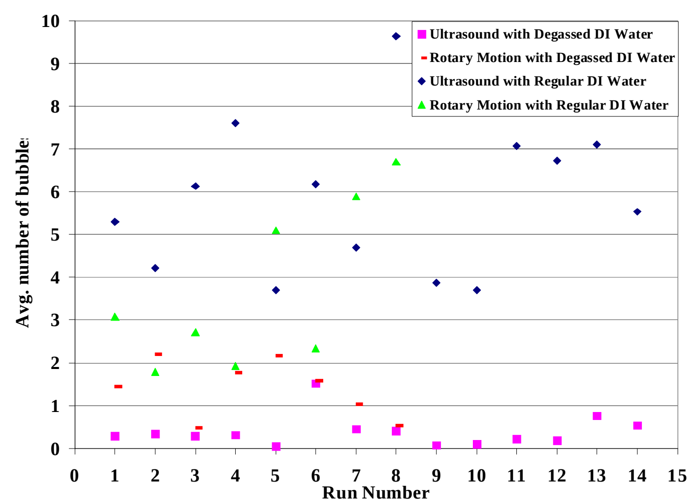


Figure 9: Bubbles remaining on lens after each experiment

It's important to note that because the experiments were not conducted in an FDA approved manufacturing environment, most of the lens had some debris on them. To measure the performance of ultrasound more accurately, four small live runs were performed on the actual production line. Crude parts were fabricated to attach the ultrasonic tip to the FreeDial machine. Table 5 summarizes the results from the live runs on the production line.

Table 5: Live run results with ultrasound

Run Number	Images Processed	Total Bubble Count	Total Bubble Area	Avg Bubble Count
1	299	11	466	0.04
2	298	63	3923	0.22
3	150	25	2467	0.18
4	200	14	805	0.08

The results were not much better than those gathered from the stand-alone systems used in the experiments. This gives a good comparison of the quality of data collected in the experiments and their correlation with line runs on the production line. The data tables in Tables 6,7,8,9, and 10 are the results from each run. This data was used to generate the figures 1 and 2 for Ultrasound and Rotary Motion.

	Avg Bubble Count	Total Bubble Count Reduction	Total Bubble Area Reduction
Minimum:	3.69	91.9%	89.2%
Maximum:	9.63	97.3%	97.9%
Average:	5.82	95.9%	94.1%

Figure 6: Ultrasound with De-ionized Water

	Avg Bubble Count	Total Bubble Count Reduction	Total Bubble Area Reduction
Minimum:	1.79	92.6%	95.1%
Maximum:	6.7	97.8%	98.4%
Average:	3.69	95.4%	96.9%

Figure 7: Rotary Motion with De-ionized Water

	Avg Bubble Count	Total Bubble Count Reduction	Total Bubble Area Reduction
Minimum:	0.04	97.6%	97.4%
Maximum:	1.52	99.96%	99.91%
Average:	0.39	99.3%	99.6%

Figure 8: Ultrasound with De-ionized Degassed Water

	Avg Bubble Count	Total Bubble Count Reduction	Total Bubble Area Reduction
Minimum:	0.48	97.9%	98.1%
Maximum:	2.21	99.3%	99.8%
Average:	1.40	98.4%	98.8%

Figure 9: Rotary Motion with De-ionized Degassed Water

	Avg Bubble Count	Total Bubble Count Reduction	Total Bubble Area Reduction
Minimum:	12.14	16.0%	5.3%
Maximum:	76.93	78.3%	66.6%
Average:	39.81	39.6%	41.4%

Figure 10: Recirculation with De-ionized Degassed Water

FINAL RECOMMENDATIONS

Although two successful methods for eliminating bubbles were developed, ultrasound proved to be more reliable and more repeatable then rotary motion. For the wet vision system to work properly, the contact lens needs to be completely clear of any bubbles. Even though the algorithm can distinguish between a bubble and a cosmetic defect, it only takes one wrong call for perfectly good lens to be rejected. Since lenses are manufactured on a large production scale, there is high probability that lenses will be falsely rejected by the wet vision system if there are any bubbles on the lens. Therefore, the implementation of an ultrasound bubble elimination system is an essential step to improving the current production process.

For optimal performance the team recommends using the ultrasonic homogenizer model VC130VB by Sonics, Inc because it has I/O port that allows the system to be integrated with the PLC logic on FreeDial and has the ability to ramp the power level. It also has a maximum power level of only 130W and a set frequency of 20 kHz. During operation, the tip should be submerged in the water before the power is turned on. Then it should be ramped to 15W/sec and then turned off before retracting from the water. It's also important to keep the tip centered in the water cell to within 2mm and the tip itself has to be about 14mm in diameter to cover the area of the contact lens. The submersion depth for the tip should be about 0.25in below the surface of the water line in the water cell.

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