Design of an Abrasive / Erosive Wear Test Machine

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Executive Summary

The primary goal of this ME470 senior design project was to design and build an abrasive/erosive wear test machine which is capable of providing variable media velocity and flow rate as well as variable angle for the test material. Dry sand and different crops such as rice and corn will be used as the abrasive media. The test materials will be various metal samples with a maximum weight of 600g. The main purpose of this machine is to analyze and study impact wear so that better simulation software can be written. To ensure accuracy of the simulation, the machine needs to include a load cell to measure the impact force of the media on the test material and a video recorder which will be mounted as an external part.

To meet the variable speed and flow rate requirements, gravity will be used to move the media from the hopper into a tube leading to the test specimen. In addition to gravity, an air compressor will be introduced to the system to accelerate the media. This method is called gas-blast or gas-stream impingement method. The ASTM G 76 [1] gives the standardized guide for testing wear/erosion using the method of jet-stream or gas blast. However, the standard [1] specifically states that only using one method of testing is not sufficient. Therefore, we decided to incorporate both gravity and gas-stream into our machine.

To change the angle of the test sample, we will be implementing an easy-to-use set screw mechanism and a protractor to measure the angle of impact. In order to contain all the dust within the machine an all clear viewing area was also included in the design. The viewing area has a fiberglass grating base to allow the abrasive material to flow through at the bottom and a 5 inch diameter hole at the top to allow the media from the hopper to enter. Below the viewing area, we have included a waste collecting container to collect and dispose the used abrasive material.

This machine is fully capable of varying mass flow rate, speed of the media, and impact angle. It also includes a manual centering mechanism for the test samples, a load cell to record the impact force, and transparent hopper, tubing and viewing area.

The total budget allotted for this project was $1000. Our team was able to produce a working machine within this budget. However, it was not as aesthetically pleasing so our sponsor, John Deere, was generous to provide us with extra funding to make the system more aesthetically pleasing as well as make it a superior model. Therefore, our final figure is approximately $2500 which includes the price of a new transparent hopper as well as a load cell and related data acquisition equipment.

As promised, our machine was completed on time and has been delivered to John Deere as of May 6, 2011.

Introduction

As a manufacturer of industrial equipment, John Deere has a desire to model the wear and abrasion seen by their equipment. To this end, John Deere requires tribology equipment which will be used to calibrate simulation software as well as provide other qualitative and quantitative wear data. Specifically, John Deere requested the design and construction of a clear-sided machine which is capable of spraying different granular media with different flow rates at a test sample which must be capable of varying in angle relative to the granular flow. By being transparent, the erosion tests performed by the granular spray can be recorded on video for use in software calibration. This calibration can further be validated by the use of impact force data which was to be recorded by a load cell attached to the test sample.

As part of the creation of this machine, research was performed with respect to existing solutions both on the market and following standardized guidelines. These findings were then utilized to develop design proposals which were presented to our sponsor to determine an optimal solution. From discussions with our sponsor, the initial project statement of including a corrosive spray in the machine was discarded as the addition of a corrosive spray was deemed an add-on feature which could be added by the sponsor after the completion of the assembly.

The selected design features a vertically oriented machine with a hopper seated at the top. Media flows from this hopper through tubing towards a test sample which is mounted on a load cell and test stand capable of pivoting the test sample's incident angle to the media flow. The media flow rate varies due to a compressor attachment. The used media exits the testing area and into a waste removal container.

Upon determining this solution, research and selection of materials and parts for the assembly was performed. This included but was not limited to the selection of transparent Plexiglas for the containment of the testing, selection of a load cell, finalized design of the test stand, selection of shelving on which to house the assembly as well as the selection of a hopper to feed the granular media into the testing area. This process took the largest amount of time and also went through several iterations. Namely, a hopper was initially purchased and implemented into the assembly but was ultimately replaced with a more aesthetically pleasing and integrated model after additional funding was granted by our sponsor. Similarly, the connection between the media tubing and compressed air piping was changed from initial designs of either a Y or a W connector to a T connector due to ease of assembly and quality of available parts.

The final assembly is quite similar to the initial design in terms of components, setup and function. It meets the requirements set forth in the proposal and was delivered to our sponsor on time.

Recommendations for further modifications to the test machine are included in this report so as to provide the sponsor with sufficient background to make informed changes.

Final Design and Assembly

The final product is a rigid, fully functional machine that meets the sponsor's requirements as can be seen in Appendix 1, Figure 1A. It features a hopper with an integrated sliding valve which sits above a Plexiglas viewing area that contains the testing apparatuses. This viewing area features two front-opening doors to allow for entrance to the testing area. The hopper and sliding valve feed the granular media through acrylic tubing into the testing area. The sliding valve was determined to be an optimal solution as it does not clog-a feature which is not true of ball joint valves and other tested solutions.

At the final exit from the acrylic tubing, a connection is made through a T-valve to a compressed air source which is fed into the viewing area via a one inch diameter hole in the left wall. Below the final exit from the junction between the acrylic tubing and the T-valve, the test sample is screwed into a load cell which itself is screwed into the test stand. The test stand is an aluminum fixture featuring a test plate mounted on an axis. It is on this test plate that the load cell and test sample are mounted. The axis is free to rotate within a test base until locked at a specific angle through a set screw mechanism.

After the media strikes the test sample, it becomes waste. To remove this waste from the viewing area, fiberglass grating was inserted at the bottom of the viewing area. As the viewing area was seated upon shelving, a hole was cut in this shelving to allow for such drainage. The granular media then would flow into a waste container which could be easily pulled out from the assembly to allow for final disposal of the waste media.

Hopper Assembly

The selection of a hopper to hold the granular media before testing went through several iterations before a final selection was made. Initially, a Tranpak bottom discharge hopper (Appendix 1, Figure 1B) was selected as it is designed specifically for granular media. However, a quote was obtained from Tranpak and, at over $1000, this model was deemed too expensive to be used in our project.

After this setback, Bob Coverdill who is the Director of Engineering and Technical Services at the University of Illinois at Urbana-Champaign, was consulted to determine an option that would be viable both in terms of time and cost. He suggested a hopper that is typically used to hold wall and ceiling spray. Per his recommendation, a $70 model was found and purchased from Home Depot (Appendix 1,

Figure 1C). This model was then connected to a ball joint valve and seated above a funnel which connected to acrylic tubing.

This model met our needs as it sufficiently held granular media and was capable of indicating media levels due to its translucence. However, on April 19, our sponsor visited to observe our progress and the hopper was discussed. It was determined that despite its functionality, aesthetics were of concern. Our team proposed that we could redesign the hopper to be both more aesthetically pleasing and integrated as well as more functional if we could receive more funding to have a model of our design built. This was approved and our team consulted Illini Plastics for the construction of a new hopper. This model can be seen in Appendix 1, Figure 1D.

Supported by acrylic legs attached to a plate, it is rigid and easily supports the weight of the heaviest granular media proposed for use. It holds a sufficient volume to run testing for several minutes. Further attachments can be made above the hopper to allow for expansion of containment volume. Similarly, the hopper can be overfilled to result in the same expansion of containment volume. Due to these add-ons and the variety of flow times for different granular medias, no specific hopper emptying time was determined.

The sliding valve (Appendix 1, Figure 1E) is an improvement over the previous ball joint valve. The ball joint valve trapped the granular media in its moving parts causing wear and preventing movement. The sliding valve avoids these issues and is simple to use, cheap to make and easy to replace. The valve made by Illini Plastics for our hopper has the downside of being a very tight fit. However, this was addressed by our team by filing away at the sliding mechanism. We are also recommending that John Deere obtains other sliding mechanisms when they purchase other tubing and add-ons (Recommendations).

Attached on an interchangeable assembly that contains the sliding valve is the half-inch inner diameter acrylic tubing. This tubing was selected from preliminary testing (Appendix 2) as it provided an optimal flow for smaller sized granular media. Should John Deere wish to test larger granular media such as rice or corn, larger tubing affixed to an acrylic plate can easily replace the present tubing by undoing the bolt assembly as seen in Appendix 1, Figure 1E. This is further addressed in the discussion section of this report.

Viewing Area

The viewing area is a Plexiglas container which houses the test stand. Its base measures 2'x2' and it is 3' tall. It can be seen in Appendix 1, Figure 1F. Its two front doors are secured shut via turning spring locks. There is a 5'' diameter hole on the top of the viewing area to allow for the entrance of the media from the hopper. On its left wall there is a 1'' diameter hole to allow for piping from a compressed air source. At its bottom is 1'' spaced square fiberglass grating which allows for the media to exit after use. The viewing area was manufactured by Illini Plastics.

Test Stand

The test stand is an aluminum fixture made for us by the UIUC machine shop. As can be seen in Appendix 1, Figure 1G, it features a C-shaped base. This base is itself made of C-shaped, 1'' by 1'' piping welded together. The vertical portion of the test stand is made of 1'' square piping. This piece has nine 1'' diameter holes to provide variation in test stand height. The axis on which the test plate is mounted can be inserted into any of these holes. The axis which goes into these holes has a shoulder on it to allow for limited insertion into the vertical stand. In doing so, a washer and set screw are able to be used on the exiting end of the axis to lock the axis at a certain angle. Between the axis and the vertical stand is a protractor with 10° markings (Appendix 1, Figure 1H). It can be aligned with the vertical stand via a scribe line that runs the length of the vertical stand. Similarly, the angle of the plate can be measured via a scribe line along the axis.

At the end of the 15'' solid aluminum axis, a 5'' by 5'' plate is permanently affixed. This plate has a hole in its center which allows for the load cell to be attached through a screw. On the other end of the load cell, another 5'' by 5'' plate is attached via a screw through a hole in its center (Appendix 1, Figure 1I). The test sample is then secured to the test plate via a clamp.

The test plate to which the test sample is clamped features grid markings at 5 mm increments. This was done to allow for the machine operator to center the test sample. While it was desired that this test plate feature a mechanism which would self-center the test specimen, after consultation with Bob Coverdill and the UIUC machine shop, this was found to be costly and prone to failure as either a reverse threaded screw mechanism or opposing spring mechanisms would not stand up very well to the testing environment. Consequently, a test plate with gridlines was considered sufficient to center the specimen.

Compressor Piping and T-Valve Connection

The John Deere facility in Moline, IL has a preexisting compressed air source rated to 150 psi. Consequently, our design featured piping with a male quick-connect fitting to allow for integration into John Deere's preexisting architecture. The selected piping is rated at 200 psi and is fed into the viewing area through the aforementioned 1 inch diameter hole on the side of the assembly. The piping then screws into the T-valve which connects to the acrylic media flow tube (Appendix 1, Figure 1J).

The T-valve was selected over other designs due to a variety of reasons. Conceptually, it is similar to the ringer design suggested by our sponsor (Appendix 3). However, the ringer design would be very expensive to produce. Initially a W-valve was selected for use. In this design, the acrylic media flow tube would point directly downwards and two tubes from the compressed air source would feed in from the sides of the "W." This design was jettisoned due to both a lack of parts availability as well as the inherent difficulty of evenly splitting the airflow from the compressor. A Y-valve was then attempted. Similar to the W-valve in concept, the Y-valve would feature the granular media flowing in one side of the Y-valve and mixing with compressed air from the other side thus forcing the mixture out the bottom. However, this design was prone to clogging due to the change in angle of the flow of granular media as well as backflow wherein the compressed air forced the granular media to flow backwards.

The T-valve has none of the aforementioned drawbacks. The compressed air flows in from the side and is forced downwards, parallel to the granular flow. It is forced downwards as there is a rubber stopper between the acrylic tubing and the copper T-valve which prevents the compressed air from escaping out of the top of the T-valve (Appendix 4). This rubber stopper is also what makes this assembly rigid. This assembly also has the benefit of being easy to assemble and disassemble as the acrylic tube, rubber stopper and T-valve all slide into place and are easily adjustable. Any torqueing on this assembly from the weight of the compressed air piping can be relieved through the repositioning of the piping through hanging of the piping onto wall hooks which attach to the viewing area via suction cups.

Load Cell and Force Display

We were recommended by our advisor, Dr. Polycarpou, that the load cell that would best fit in our budget and work well for impact testing of granular flow would be a single-axis strain gauge based load cell. There are many providers that offer this type of load cell including Transducer Techniques, a major load cell provider with several models and capacities to choose from. A compact and precision load cell for the ease of calibration and implementation that met the testing requirements as found in our preliminary testing (Appendix 2) was needed. The MDB series from Transducer Techniques, as shown in Appendix 1, Figure 1K was found to meet our preferences. The available capacities are 2.5, 5, 10, etc. up to 100 lbs. The 5 lb. sensor was selected due to the results of the preliminary tests.

The load cell also comes with a compatible force display, DPM-3 from Transducer Techniques as shown in Appendix 1, Figure 1L. The force display can sample 60 readings per second (50 for 50 Hz operation) for fast control response, true peak reading capability, and an analog output (optional) that accurately tracks the signal input. It can be scaled to a full five digits from 0 to 99,999 to read directly in engineering units such as grams, ounces, pounds, inch pounds, etc.

Shelving and Waste Removal Container

The viewing area and hopper assembly sit upon industrial shelving. Industrial shelving was chosen as each shelf is weight-rated and since the heights at which the shelves occur is entirely decided by the user. We chose Whalen's Step Beam Black Wrinkle shelving due to its aesthetic appeal as well as availability from local vendors (Appendix 1, Figure 1M). At only 4' wide and 2' deep, this model allowed for us to meet our sponsor requirement of fitting the machine within a 5' by 5' test area. To allow for the exiting flow of used granular media, an 18'' by 18'' hole was cut within the shelf on which the viewing area is seated. Seated below this shelf is a waste removal container which easily slides out from the bottom shelf.

Results

After the assembly of our machine was complete, experimentation was performed to determine the behavior of the assembly. The first result of this testing was that the machine is capable of achieving variable flow rates by changing the exit size at the bottom of the hopper. This is performed by partial opening and closing of the sliding valve and works for smaller abrasive media such as sand. This method was found to not work for bigger abrasive material such as rice as it causes clogging. However, one can vary the mass flow rate for bigger materials by changing the attachment funnel and tubing as aforementioned in the discussion of the hopper as well as in the following recommendations section.

The second result obtained from testing was the verification that the machine is capable of varying the speed of the abrasive material by changing the pressure of the air compressor.

Third, the angle changing mechanism and test stand were found to perform as desired. The set screw mechanism requires the use of an allen wrench to secure its position as located by the user through the use of the protractor.

Fourth, the viewing area sufficiently contained all dust created by the abrasive materials during testing. All leakages of granular media were found to be due to repositioning of the viewing area or poor test setup. Poor test setup is when the test plate is angled such that the reflection of granular flow is aimed directly at the two front doors.

Fifth, the T-valve was found to cause no backflow.

This working assembly cost approximately $2500 to complete

Discussion

Through various meetings with our sponsor, it was determined that very low mass flow rates within the machine are necessary so that the impact of the grains could be easily analyzed. From preliminary testing (Appendix 2), the optimal diameter of .5 inches for small granular medias was determined. Due to its low cost, ease of obtainability, comparatively high density and strong abrasive characteristics, our machine was optimized for testing with sand. Its design featured a length-to-inner diameter ratio of 28:1 which is bigger than the minimum ASTM recommendation of 24:1 [1]. As the testing demonstrated, the machine works ideally while using sand. However, as mentioned in the results section, the 0.5" inner diameter tubing is prone to clogging when using bigger abrasive material such as rice. This happens because these larger sized materials tend to stack in the tubing in such a way that it prevents its own flow. This complicated issue which is a function of many parameters could be resolved by having a larger hopper exit diameter which can be achieved through changing the attachment funnel as seen in Appendix 1, Figure 1E. In the preliminary testing (Appendix 2), an optimal inner diameter for media such as rice and corn was found to be .75''. Consequently, the exit diameter of the funnel at the entrance of the sliding valve assembly was made to this diameter. It is quite likely that, should these sized media be tested, instead of replacing the funnel assembly section of the hopper, only the acrylic tubing and bottom portion of the sliding valve mechanism would need to be changed. This assumption is affirmed by testing performed without the bottom portion of the sliding valve assembly. This testing showed that larger sized granular media easily flowed through the hopper and funnel assembly.

The speed of the granular material found to be a function of the air compressor settings. Since, as shown in Appendix 3, granular materials act differently than liquids or solids, a numerical speed value was not determined. Nonetheless, this can be determined by using a high speed camera.

As aforementioned, the test stand allows for infinite differentiability of the angle between the impinging media and the test sample. Due to the offset of the test plate to the axis, as the angle changes, the media would not be hitting the sample in the center. As the machine utilizes a one axis strain gauge load cell, it is important that the granular media strikes the test sample in the center of the load cell. The technician in charge of testing must take appropriate caution to ensure that this occurs. This can easily be performed by visually locating the exit of the acrylic tubing and aligning it with the test specimen. The technician must also remember to multiply the force data acquired by the load cell by the cosine of the incident angle used for any given test to achieve normalized results.

To verify the high functionality of the T-valve selection over competitive options, theoretical calculations were performed as can be seen in Appendix 4. From these results, the final design was changed to the setup which can be seen in Figure A-II-8 in Appendix A-II. Though this design could have featured the end of the acrylic tube only slightly lower than the entrance of the compressed air through the T-valve and still avoided back flow, it was decided to not have any mixed flow inside the T-valve. This was selected since the mixture granular material and air flow together can lead to one of the cases depicted in Figure A-II-7 could happen. By keeping the end of the acrylic tube at the same height as the end of the T-valve, this cannot occur.

The allotted budget for this project was $1000. However, our team spent more than twice that amount. At first glance, it appears as though our budget was exceeded; however, this is not the case. We had developed a functioning model for just under the allotted budget of $1000 using the spray hopper previously discussed. This assembly was discussed with our sponsor as aforementioned. This led to our sponsor generously providing extra funding to design and purchase a more professional hopper system. The $2500 figure also includes the price of the load cell and corresponding equipment that our sponsor bought separately. The cost of this equipment was approximately $500. A more detailed analysis of the budget is given in Appendix 5.

Conclusions

We have accomplished the objectives of this project which were to design and build an abrasive wear test machine that can be used to test wear from several types of granular media. The machine has the capability of varying the media flow rate and incident angle to provide a variety of testing conditions. The hopper is transparent which will allow operators to indicate the remaining amount of material at any given point of testing. The viewing area encloses the testing and is also transparent to allow John Deere to video record the interaction between the media and the test sample. The machine also features a load cell of our selection for measuring the force exerted on the test sample by the impinging media. A fiberglass grating and a waste container are used for media removal. The final assembly does not incorporate a corrosive fluid delivery system as initially stated in the project guidelines. This was determined to be an add-on feature and will be addressed by the sponsor at a later time.

Our original design was to have a translucent hopper with a ball joint valve and a less precision load cells. This original design was selected so as to remain within budget. After receiving more funding from our sponsor, we were able to modify our design and purchase a custom made transparent hopper and a high precision load cell. These contributing factors allowed us to further meet project goals in a professional and timely manner.

Overall, our machine is rugged, fully functional, easy and ready to use. There are only a few components and most of them were custom built by the UIUC machine shop and Illini Plastics for concerns of safety, longevity and aesthetics.

Recommendations

Two issues were not addressed in our testing due to time constraints. First, it was observed that as the distance between the exit of the media from the tube and the test sample increases, scatter also increases in a linear fashion. It is recommended that John Deere researches the effect of scatter with respect to the recorded force data on the specimen. Similarly, media accumulation on the test plate varies depending on the test plate angle and compressor setting. Research into these phenomena is also recommended.

The second issue not addressed in our testing is hopper hang-up. Hang-up is when media inside the hopper adheres to the sides of the hopper and creates a funnel of media within the funnel of the hopper. For the different granular media we tested, no hang-up occurred. In addition to visually checking for hang-up, the phenomena can be observed by measuring force versus time and observing if there is a decay in force as time goes on. Due to the delay in acquiring the load cell, our team was not able to acquire this data. However, if this issue is found to exist in our hopper, one way of resolving this it would be to use products like Primasonics® Acoustic Cleaners [2]. The Primasonics machine takes compressed air as an input and outputs sound waves to vibrate the hopper. This shaking prevents the adherence of the granular media to the hopper and resolves hopper hang-up.

Appendix 1-Assembly Parts

Figure 1A: Final Assembly

Figure 1B: Tranpak Bottom Discharge Hopper [3]

Figure 1C: Home Depot Spray Hopper [4]

Figure 1D: Final Hopper

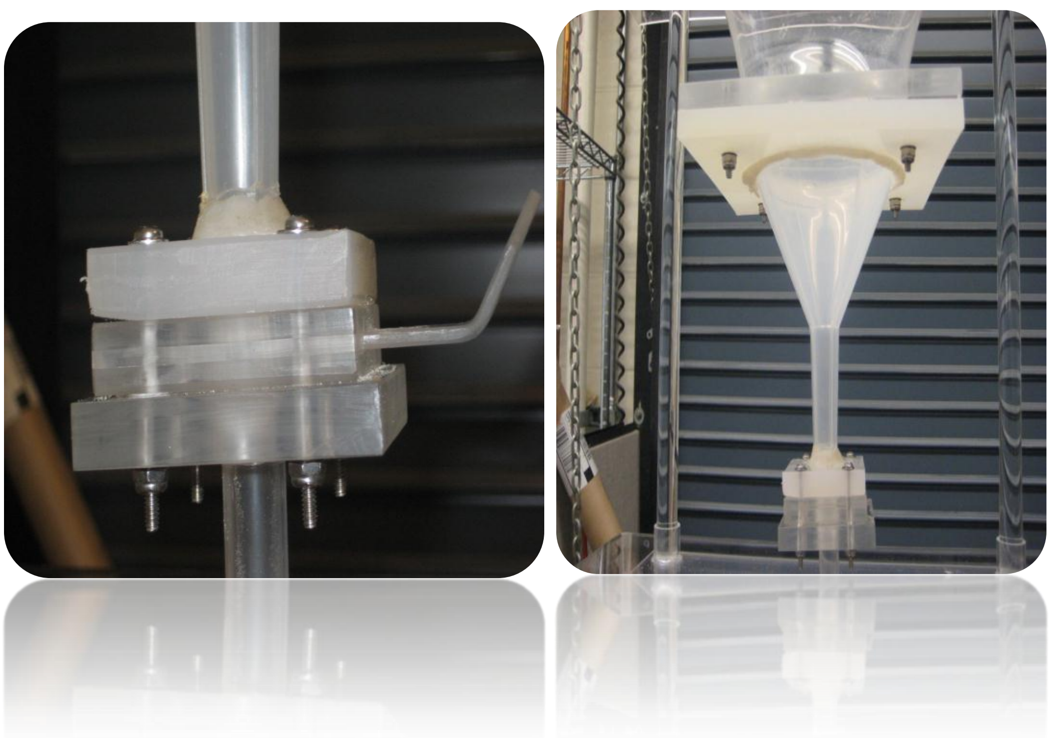

Figure 1E: Left-Sliding Valve Assembly; Right-Funnel Assembly

Figure 1F: Viewing Area

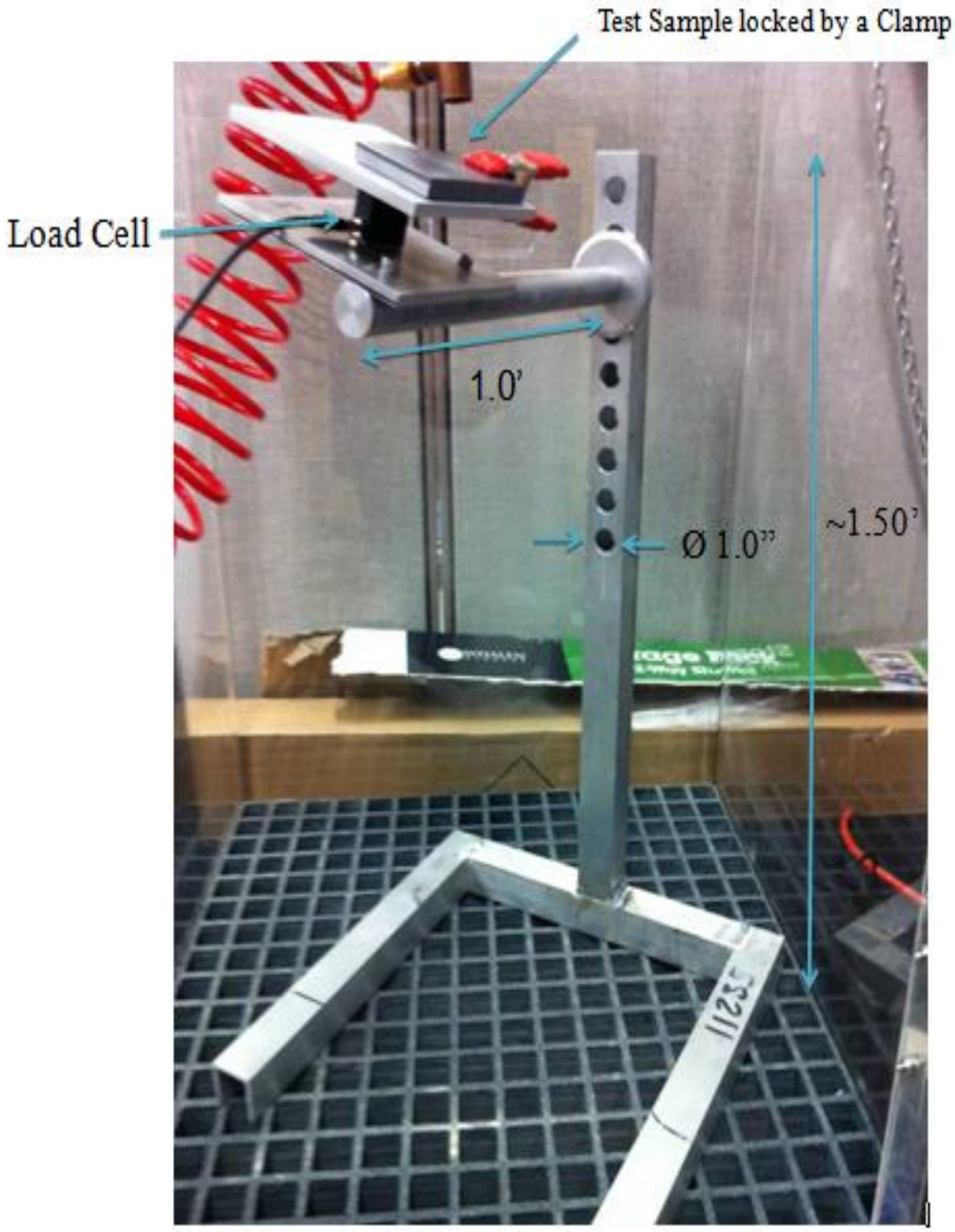

Figure 1G: Test Stand, Seated Within Viewing Area

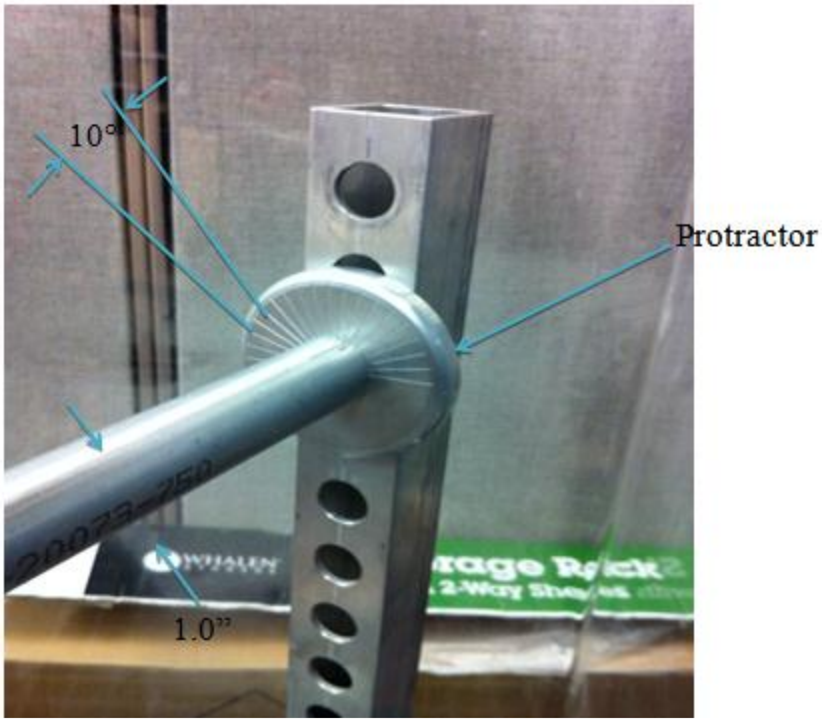

Figure 1H: Protractor Mounted on Test Stand

Figure 1I: Gridded Test Plate Mounted on Load Cell, Other Test Plate and Axis

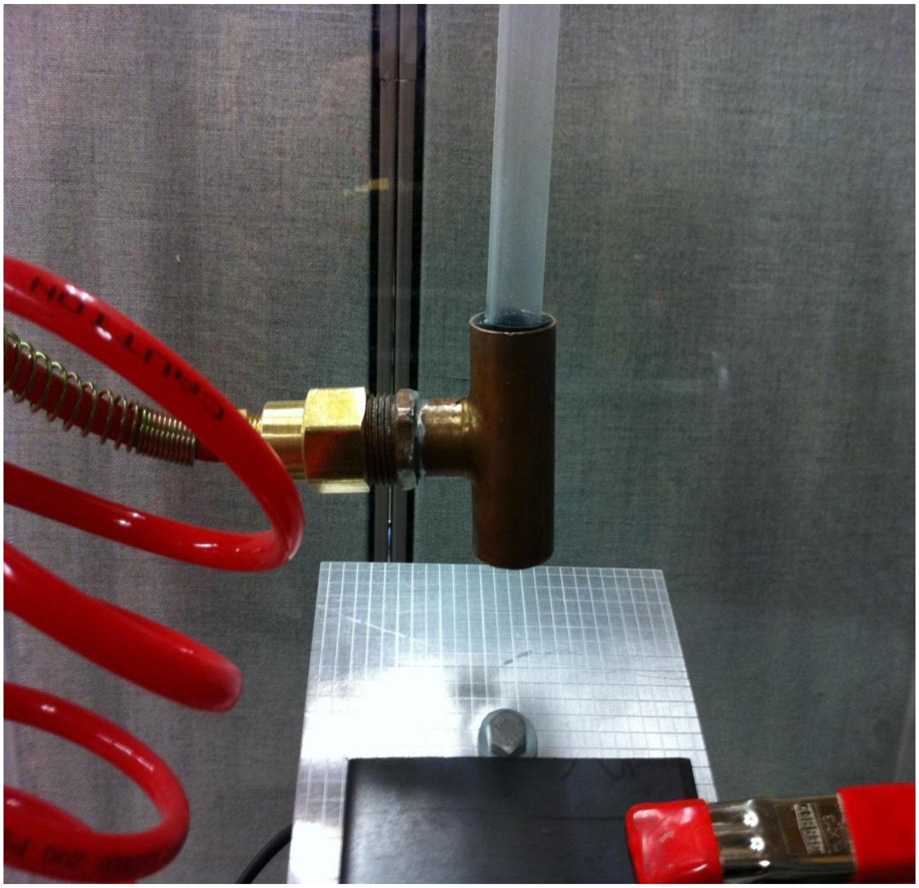

Figure 1J: T-Valve Connector

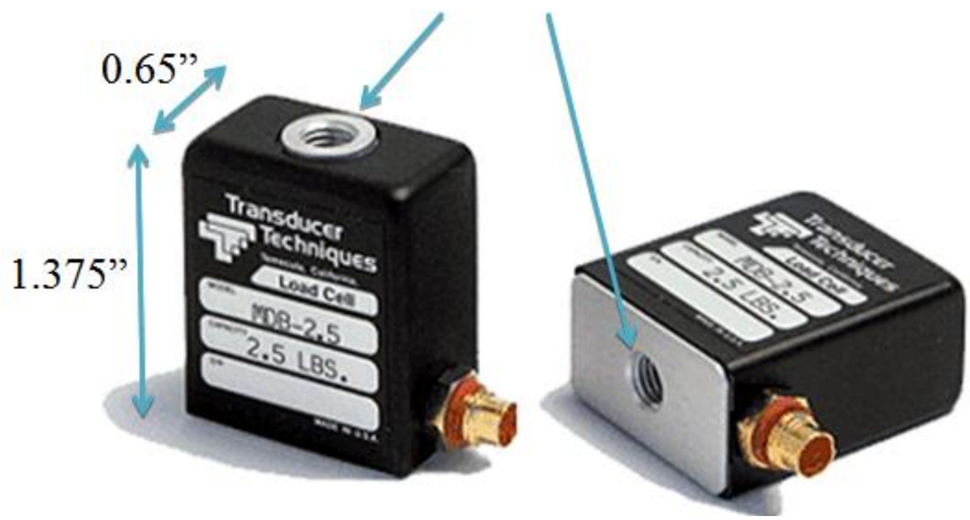

Figure 1K: Load Cell [5]

Figure 1L: Force Display [5]

Figure 1M: Whalen Shelving [6]

Appendix 2-Preliminary Testing

To determine the size and capacity load cell that would be required for our machine, preliminary testing was performed with sand and various diameter piping. The setup can be seen in Figure 2A. Here, one meter long piping was fed with sand which was chosen as it was the densest media stated to be used during testing. This sand exited into a container on a scale. This allowed for the impacting force to be determined. As the maximum impact force was found to be no more than 35 grams. From this result, a load cell was chosen. Another result from this testing was that the optimal diameter for the granular flow of sand and other similarly sized granular media was determined to be .5 inches. Smaller diameter piping restricted the flow too severely while larger diameter piping allowed for torrential flow. Neither of these allowed for flow that would provide John Deere with meaningful granular flow data. Consequently, .5 inch inner diameter piping was chosen. The downside to this selection is that larger sized granular media such as rice require larger diameter piping (testing found an optimal diameter of .75 inches for rice). This was addressed via an interchangeable assembly on our hopper.

Figure 2A: Preliminary Test Setup

Appendix 3-Flow Rate Measurement

Granular flow is behaves as a solid while at rest but as a compressible liquid like characteristic when in motion. This is a new area of research; therefore, there are no unified or standardized equations to calculate the flow rate.

According Jose Flore, Guillermo Solovey et al. [3] unlike liquids granular flow does not change with time, but it still changes with the area of the orifice "For liquids the time rate of the discharged through an orifice depends on the column and thus is time dependent."[3]

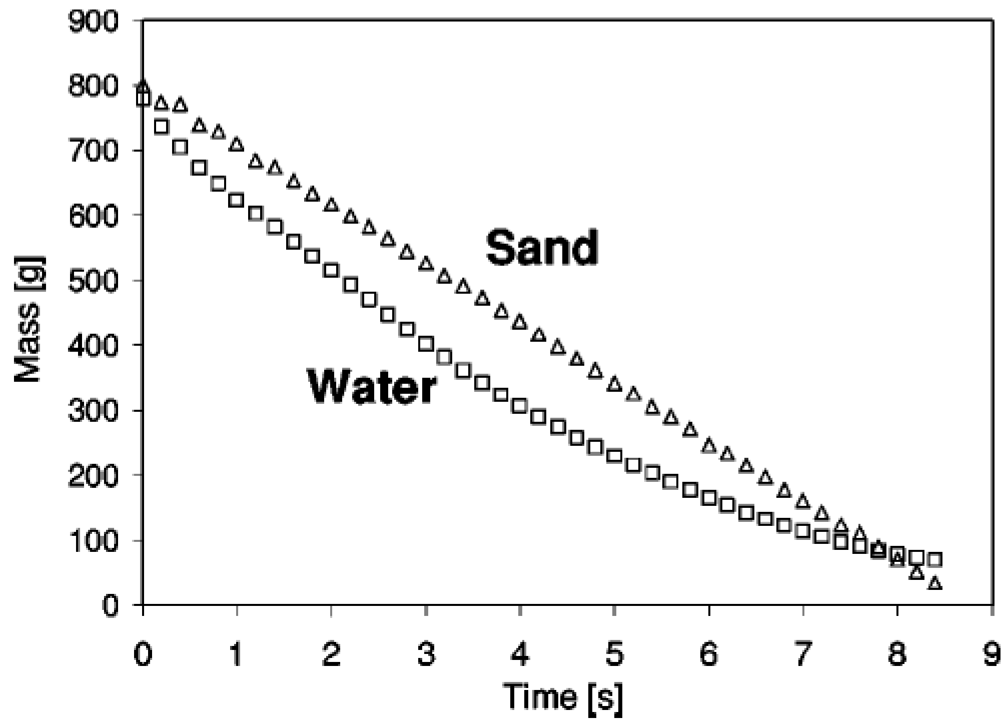

Figure 3A: Comparison of the flow rate of water versus sand. The flow of water, in g/s, clearly decreases with the height of the column, while sand does not.[7]

[7] $\frac{dm}{dt} = k * \rho * \sqrt{g} * A^{\frac{5}{4}}$ (1)

Where k-experimental constant, ρ-density of abrasive media, g-gravitational acceleration, and A-area of orifice

Even though Equation 1 was a good starting point, the paper did not give us any value for the experimental constants; therefore, we were forced to look for more equations.

According to Bervaloo et al. we can calculate the flow rate of a granular flow using Equation 2 given below

[8] $W = C * \rho_b * \sqrt{g} * (Do - k * dp)^{\frac{5}{2}}$ (2)

Where W is the average mass discharge rate through the orifice, C & k are empirical discharge and shape coefficient respectively, ρ_b is apparent density of granular media, g is acceleration of gravity, dp is diameter of granular media, Do is diameter of orifice, and L is height of the siloAccording to [8] if L > 2.5 Do and Do >> Do + 30dp then the flow will be independent of Do.

This equation is also known as the Bevarloo law and is mentioned in most of the papers related to granular flow. Again this paper did not give the values of C and k therefore, we could not use it.

The Bevarloo law is valid [9] only when Do >> dp. Therefore, Zuriguel et al. made some adjustment to Equation 2 and came up with a new equation given by Equation 3 below

$$[8]\ Wb = C' * \left(1 - \frac{1}{2} * e^{-b(R-1)}\right) * (R-1)^{\frac{3}{2}} \qquad (2)$$

Where Wb is flow rate in number of beads, C' and b are fitting parameters which were experimentally found to be 108 and 0.23 respectively, R = Do/dp

Since sand is the densest media we will be using in our project, we used its density for our initial calculation of flow rate. Since dp of sand ranges from 0.065 millimeters (mm) to 2mm and we wanted to see the effect of changing Do on the flow rate we developed a Mathematica based GUI. Figure 3B shows the snap shot of our GUI.

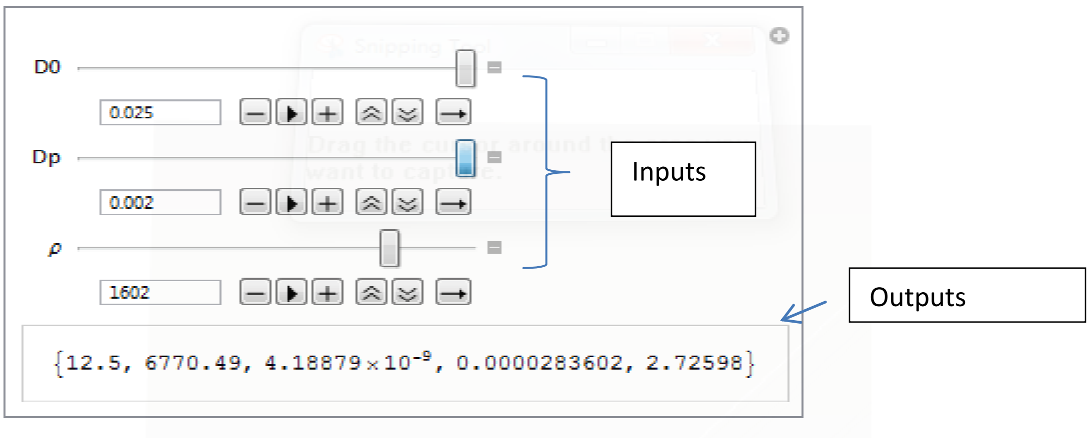

Figure 3B: Mathematica based GUI that inputs Do, Dp, and ρ then outputs R=D0/Dp, Wb-grain flow in grains/second, volume of each grain in m^3, Vdot volumetric flow rate-m^3/Sec, and mdot-mass flow rate which is in kg/min (Left to Right)

As shown in Figure 3B, our GUI predicts 2.7 kg/second of flow rate for the displayed initial conditions. This is a high flow, but decreasing Do by half lowers the flow rate to 0.7 kg/second. Again these calculations were made to see what kind of flow rates we expect to see when we run the completed machine. We care mostly controlling a specific flow rate than knowing what the flow rate value is so we did not try to prove the validity of the equation published in our experiment.

The first design we came up with is what we called the "Ringer Model" which is shown in Figure 3C-E. The dimensions of tube are 24" high, outer diameter of 2.25", inner diameter of 1 inch and the gap between the outer diameter of the inner cylinder and the inner diameter of the outer cylinder is 1 inch.

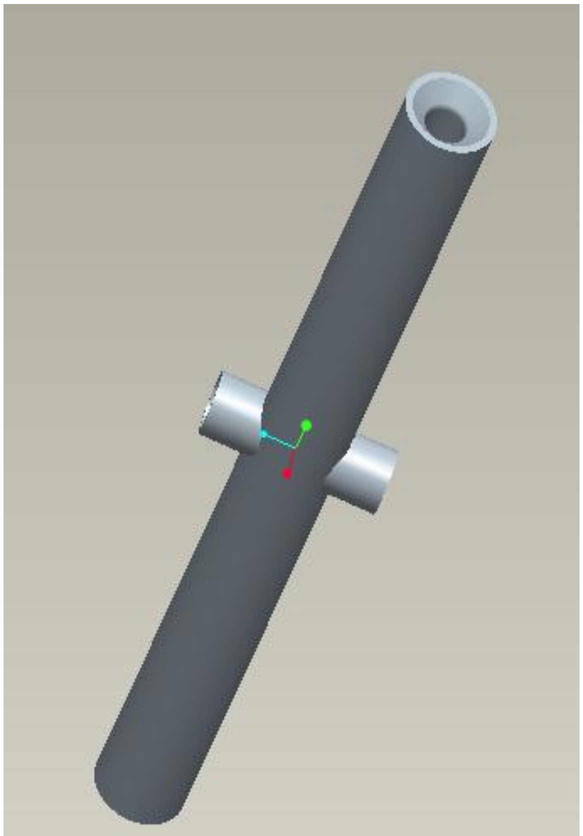

Figure 3C: Isometric shaded view of ringer model

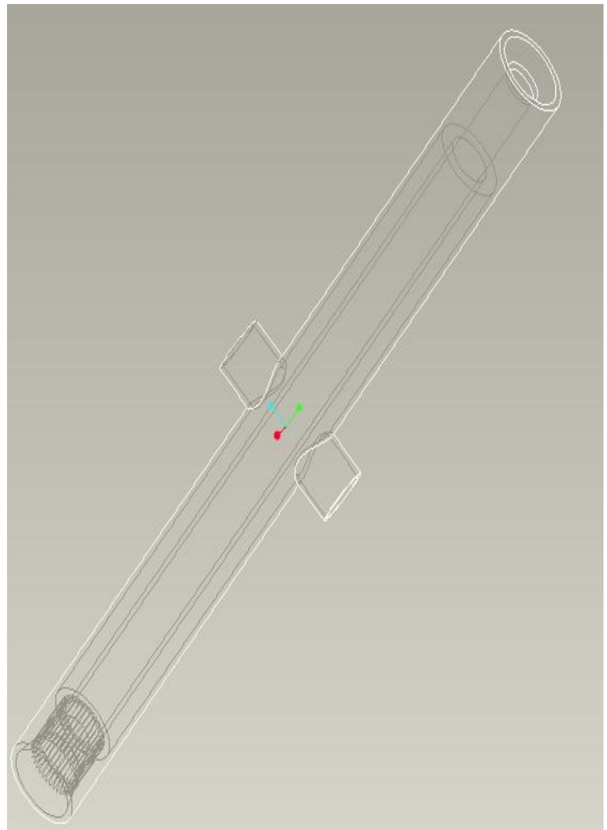

Figure 3D: Isometric view of hidden line view of ringer model

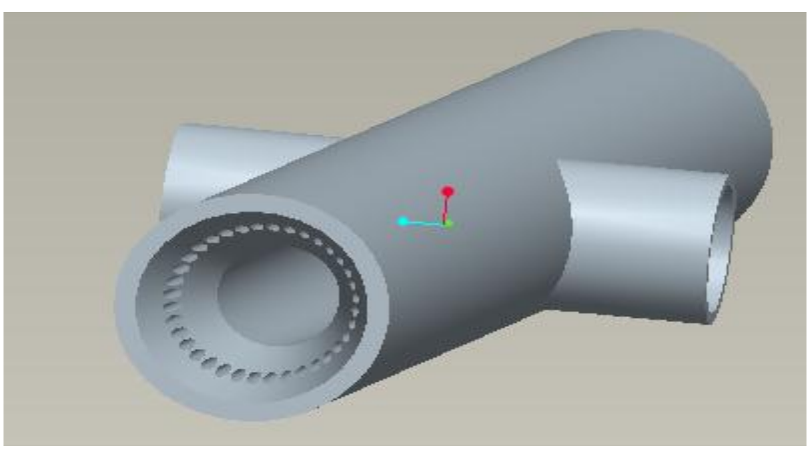

Figure 3E: Bottom Isometric view of the ringer model

In this system, air come in to the volume between the inner and outer cylinder through the two tubes on the side, and exits out through the holes at the bottom (Figure 3E). The media on the other hand gets into the inner cylinder at the top and meets with the air at the bottom. The reason the bottom of the cylinder exit is chamfered is because we want to focus the media. This system looks like it would work great; however, according to our apriori estimation (Figure 3F) it costs about $174 to make it from polycarbonate, which exceeds our budget. The reason why we chose polycarbonate is because we want to the connector tube to be transparent.

Variable Costs	Current (USD)
Material Cost	3.63
Labor	2.30
Direct Overhead	10.67
Amortized Batch Setup	156.69
Logistics	0.00
Other Direct Costs	0.00
Total Variable Costs	173.29
Period Costs	
Period Overhead Allocations	0.00
Margin	
Margin	0.00
Piece Part Cost	173.29
Fixed Costs	
Total Amortized Investments	35,203.86
Fully Burdened Cost	35,377.15
Capital Costs	
Total Capital Investments	35,203.86

Figure 3F: Apriori cost estimation of the ringer model. (Note: definition to what each vocabulary in this Figure could be found in the Apriori user manual.)

Since the ringer model was too expensive we decided to have a simpler model as shown in Figure 3G. Here, the abrasive media flows through the middle and air flows from the compressor (which is provided by John Deere) to the system through the two tubes labeled A and B to focus and drive the flow. This is a much cheaper and easier to implement design.

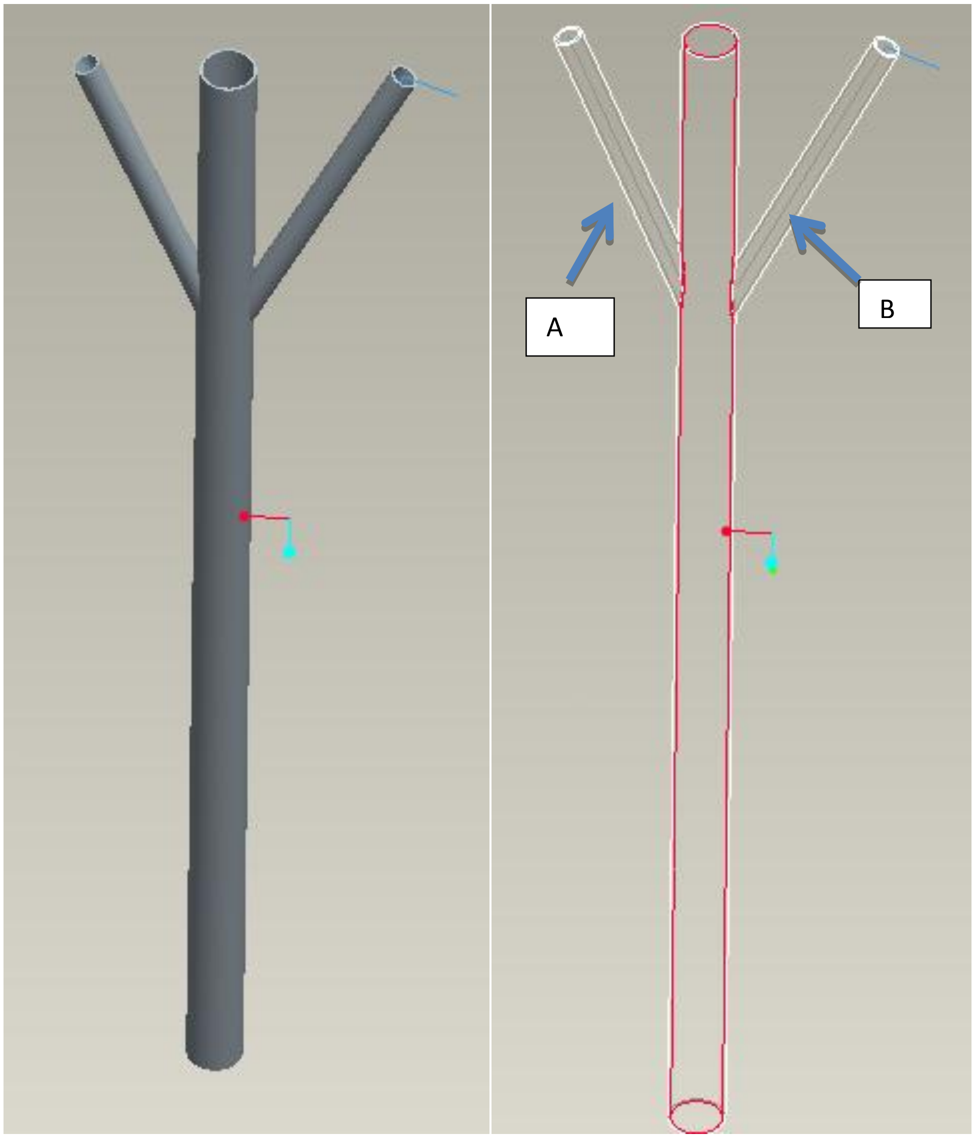

Figure 3G: W-Shaped model of connector tube

However, as shown in Appendix 4 This model could result in a back flow in our system. Therefore, we decided to discard this method and went with our final design, which is shown in Figure 3I.

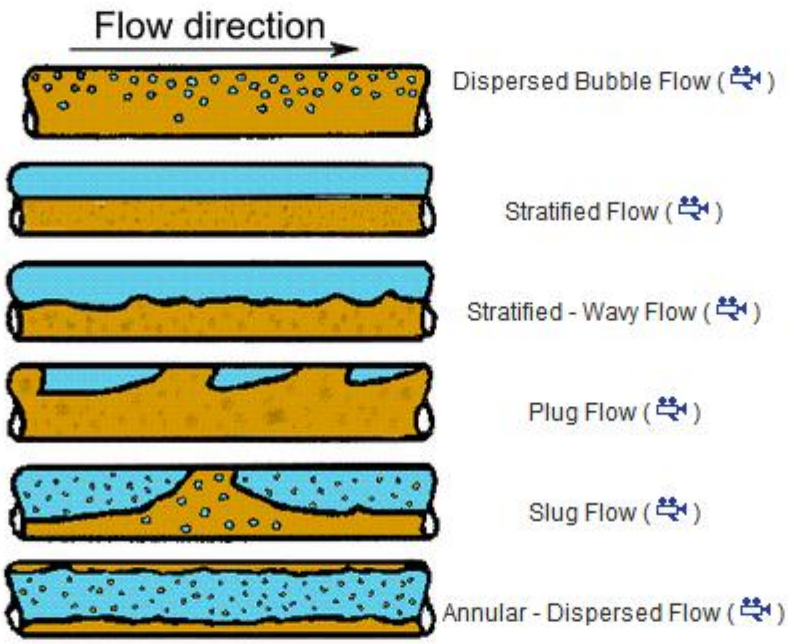

Figure 3H: Flow regimes in gas-liquid pipe flow [10]
These issues were avoided by having the compressed air and the media combined at the very end of the tubing.

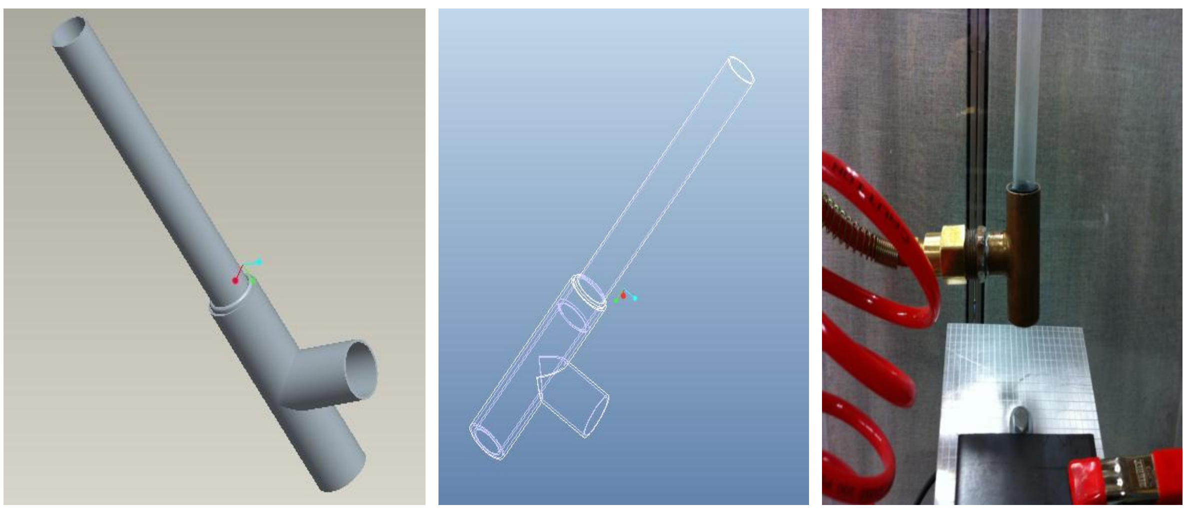

Figure 3I: connecting tube 3d model and actual design snap shot (Left to Right)

Appendix 4-Backflow Calculation

Since one of the purposes of this project was to control the media velocity, an air compressor was to be attached to the machine. We consequently designed a W-shaped connecting tube in order to attach the compressor to the acrylic tubing carrying the media.

This design featured the acrylic tubing entering into the center of the W from above. To determine flow rates analytically, airflow in the pipe had to be inspected based on linear momentum equations according to Bruce Munson [11]. Only the y-direction of flow was considered because x-direction of flow will be cancelled due to symmetry.

$$In\ y\ direction:\ (-v_1)\rho(-v_1)cos\theta A + v_2(-v_2)\rho A + v_3\rho v_3 A = 0 \qquad \text{Eqn. 1}$$

$$Conservation\ of\ mass:\ 2Q_1 = Q_2 + Q_3\ \ or\ \ 2v_1A = v_2A + v_2A \qquad \text{Eqn. 2}$$

$$A = \pi\left(\frac{d}{2}\right)^2 \quad where\ \ d = 0.5\ inch\ , \quad v1\ will\ be\ given\ by\ air\ compressor$$

Based on these equations and Figure 4A, it was concluded that airflow within the W-shaped connecting tube would likely cause backflow since v3 is positive as can be seen in Figure 4B.

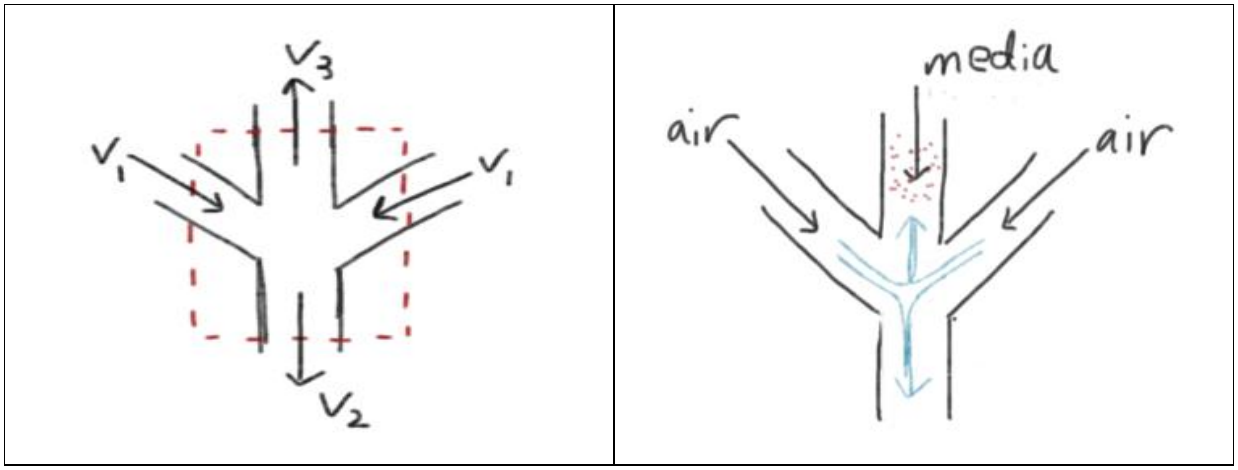

Figure 4A-Free body diagram of W-pipe

```
(* if angle is π/4 and v1 is 20m/s *)
Quit[]

In[1]:= ρ = 1.2 (* Density of air  kg/m^3*);
d = 0.0127 (* diameter of pipe 0.5inch = 0.0127m *);
A = π (d / 2) ^2 (* Area of cross section of pipe in m^2 *);
v1 = 20 (* we assume v1 is 20m/s*);
θ = π / 4 (* angle between compressed air pipe and media pipe *);
v2 = 2 v1 - v3 (* conservation of mass 2Q1=Q2+Q3 *);

In[7]:= LinearEq = (-v1) ρ (-v1) Cos[θ] A + (v2) (-v2) ρ A + v3 * v3 * ρ * A;

In[8]:= Solve[LinearEq == 0, v3]

Out[8]= {{v3 → 16.4645}}

In[9]:=

Quit[]

(* if angle is π/8 and v1=20m/s *)

In[1]:= ρ = 1.2 (* Density of air  kg/m^3*);
d = 0.0127 (* diameter of pipe 0.5inch = 0.0127m *);
A = π (d / 2) ^2 (* Area of cross section of pipe in m^2 *);
v1 = 20 (* we assume v1 is 20m/s*);
θ = π / 8 (* angle between compressed air pipe and media pipe *);

In[6]:= v2 = 2 v1 - v3 (* conservation of mass 2Q1=Q2+Q3 *);

In[7]:= LinearEq = (-v1) ρ (-v1) Cos[θ] A + (v2) (-v2) ρ A + v3 * v3 * ρ * A;

In[8]:= Solve[LinearEq == 0, v3]

Out[8]= {{v3 → 15.3806}}

In[14]:=

(* if angle is π/2 and v1=20m/s *)
Quit[]

In[1]:= ρ = 1.2 (* Density of air  kg/m^3*);
d = 0.0127 (* diameter of pipe 0.5inch = 0.0127m *);
A = π (d / 2) ^2 (* Area of cross section of pipe in m^2 *);
v1 = 20 (* we assume v1 is 20m/s*);
θ = π / 2 (* angle between compressed air pipe and media pipe *);

In[6]:= v2 = 2 v1 - v3 (* conservation of mass 2Q1=Q2+Q3 *);

In[7]:= LinearEq = (-v1) ρ (-v1) Cos[θ] A + (v2) (-v2) ρ A + v3 * v3 * ρ * A;

In[8]:= Solve[LinearEq == 0, v3]

Out[8]= {{v3 → 20.}}
```


Figure 4B-Calculation of airflow in W-pipe by Mathematica

To address the issue of backflow, the connecting tube was redesigned. Figure 4C addressed the above concerns and passes the analytical criteria listed above.

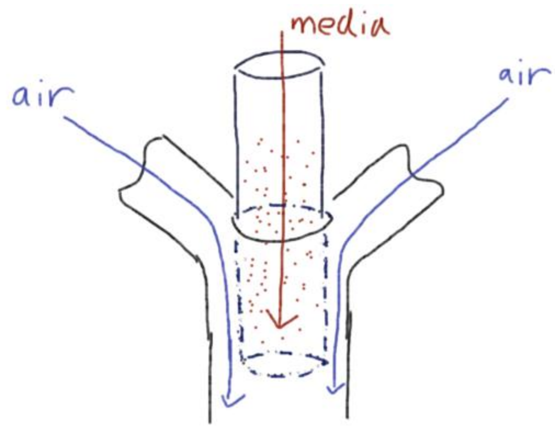

Figure 4C-Free body diagram of new design for piping

This design will prevent clogging in the pipe since airflow and media are going toward in same direction.

Appendix 5-Budget

Our expenses that have been taken out of the $1000 budget consist of a hopper from Home Depot as shown in Appendix 1, Figure 1C which cost $70, a viewing area from Illini Plastics as shown in Appendix 1, Figure 1E which costs $547, $98 shelving, $20 tubing, and $175 test plate and test stand as shown in Appendix 1, Figures 1G-I. By adding up everything, we spent $910 out of the $1000 budget. Other expenses that were paid by our sponsor consist of a load cell, a force display, and cables which cost $945. The total cost of the fully functional machine came out to be $1855.

As aforementioned, our sponsor visited on April 19 to see the progress being made on the machine. After a discussion, it was decided that our team would receive additional funding to design and build a transparent hopper and sliding valve assembly. The hopper that we had custom made by Illini Plastics cost $665. By summing the initial and new expenses, the total cost of the machine is $2520. The summary table of the budget is shown below in Table 5A.

Material	**$/amount**	**Amount**	**Cost ($)**
Hopper	70	1	70
Shelving	98	1	98
Viewing Area	547	1	547
Tubing	4	5	20
Load Cell	445	1	445
Force Display and Cables	500	1	500
Test Stand and Plate	170	1	170
New Hopper	665	1	665
Total			2520

Table 5A: Budget Summary

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