Cavitation of Fruit and Vegetable Pomace at Low Temperature

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BREE 495 Engineering Design 3
Bioresource Engineering
McGill University, Macdonald Campus
December 4th, 2019

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ABSTRACT

Oasis, a large fruit and vegetable juice company, has long had a problem dealing with their organic waste. When squeezing their juices, they are left with enormous amounts of leftover fruit residue such as pulp, peel, stem and seeds. Now, Oasis would like to look into ways in which they can reuse this by-product, also known as pomace, and turn the waste into a resource. If the fruit and vegetable residue is able to be given a smooth and attractive texture, it can be resold as a powdered nutrient supplement. This paper will discuss the process which led to the design of a pomace cavitation machine for Oasis. This machine will be used to reduce the residue from cranberries, apples, blueberries, and carrots to a smooth paste that can be dried and sold as a powder. The machine was designed to work at low temperatures in order to not break the phytochemicals present in fruits and vegetables. The design process also took into consideration health and safety requirements as well as social, economic and environmental impact of the design.

1.0 Introduction

During the juice-making process, many fruits and vegetables are pressed, leaving behind a thick pulp-like substance known as pomace. In the past, this pulp was oftentimes seen as an inconvenient by-product of the juice-making process. In fact, our client Oasis' practice is to send this pulp to swine farms to be used as feed for the animals. In order to increase profits, the Oasis juice company wants to turn this pulp into a dry powder which can then be sold for cooking and baking. By doing so, the company would be able to sell it as a product for use in baking, smoothies, etc. Therefore, turning a waste of their juice making process into another marketable product. This could bring a new, and very valuable, revenue stream into their business model.

To turn the pulp into a powder, Oasis wants to use a cavitation unit. Cavitation is a process by which quick changes in pressure forms voids in a liquid (Brennen, 1995). This process will break down the cell walls of the pomace, making the liquid more viscous, and allowing for it to later be dried into a powder. Usually, cavitation is an unwanted by-product of other activities, such as the rotation of a boat propeller or water making a sharp turn in a pipe, that can damage equipment (Evans, 2011). However, with this design, we are endeavouring to use the cavitation to our advantage. While large grinders or blenders would leave little pieces of skins and seeds behind, a cavitation unit would allow for a more homogenous product as a result. By using cavitation, we will also be able to break down the skins and seeds of the fruits by breaking down the cellulose and hemicellulose that they are composed of.

One of the important needs of Oasis is to not destroy the phytochemicals found within the fruits and vegetables. This means that we must make sure the contents in our machine do not get too hot. In order to ensure that we do not destroy the phytochemicals, our machine will not exceed 70°C (V. Orsat, personal communication, September 25th, 2019), which is difficult as heat will be produced while being pumped continuously throughout the system. Maintaining this heated temperature for an extended period of time will also pasteurize the product, ensuring proper food safety. The term “phytochemical” is used to refer to many different compounds derived from plants, many of which have therapeutic properties. Phytochemicals can have many different effects, such as anti-inflammatory, anticarcinogenic and antioxidant properties (McGuire, 2011). Phytochemicals are an important part of healthy diets, making them very valuable to Oasis as they can market their final product around them. Blueberries are popular due to their high antioxidant power, which mainly comes from their many phytochemicals, such as anthocyanins, catechins, quercetin, kaempferol and other flavonoids, as well as ellagitannins and ellagic acid and pterostilbene and resveratrol (AICR). Similarly, cranberries contain catechins, triterpenoids, quinic acid, hippuric acid, anthocyanins. Finally, apples contain health-benefiting phytochemicals such as quercetin, catechin, phloridzin and chlorogenic acid (Boyer, 2004).

In addition to not breaking apart the phytochemicals, Oasis requires that the cavitation unit must be able to run with several different fruits including blueberries, apples, cranberries, and carrots. This brings several complications as the seeds of the cranberries, the cellulose in the skins, and the fibrous carrots can be hard to break down. These different complications mean that the machine must be able to accommodate different sizes of produce. Therefore, the cavitation orifice must be able to adjust based on what is being processed so that big pieces do not block the system.

Although they are uncommon, we have found cavitation units already being used in food processing. One system that we are looking at closely for reference is the Tekmash TEK-SM, which is a cavitation unit used to turn soya, wheat, peas, and barley into animal feed (TEKMASH, 2019). While this system is similar to what our project needs, there are some differences, which we will have to focus on while redesigning the system. Mainly, our unit will deal with larger and less homogeneous substances, which will be much harder to break apart. Our system will also need to be able to account for the harder chunks of produce that might damage the system such as the cranberry seeds.

Another goal of the project is to improve the sustainability of the juice-making process. By turning the by-products of the initial process into a resource, we can reduce the amount of waste being produced. It also creates another healthy product that people can use to fulfill their dietary wants and needs. By doing so, Oasis is increasing its sustainability economically, environmentally and socially, covering the three pillars of sustainability.

2.0 Pomace Cavitation Machine with Cone Orifice

An important phenomenon of physics for our project is the principle of cavitation. When the pressure in a liquid drops dramatically in a very short period of time, voids are created within the liquid. These voids then implode and send shock waves through the system (Physics.org, n.d.). Usually, engineers try to avoid cavitation as it can cause damage to machines and systems that are not meant to produce it, for instance, boat propellers which push the water fast enough to create cavitation. These voids are formed because the pressure drops to its vapour pressure at a certain temperature, turning the water into water vapour, and creating cavities in the liquid (Brennen, 1995).

By controlling the amount of cavitation, our machine will be able to pulverize the fruits and vegetable pomace and turn it into a homogeneous mixture. If we were to just use a more typical method of grinding, such as a blender, this would not be able to make the liquid completely homogeneous as it would not be able to break down the cellulose and hemicellulose. The cavitation voids, however, are able to rip apart these polymers as the liquid is pushed through the cavitation unit over and over again with increasing pressure. (V. Orsat, personal communication, February 22nd, 2019).

It is an interesting project to work on, as cavitation has barely been used in the food engineering industry. Even though it is uncommon, there does exist a few machines, like the Tekmash TEK-SM, which have been used, but on products with less biological constraints, such as soybeans (TEKMASH, 2019). These foods have softer skins and lack large and hard seeds, unlike the ones found in cranberries. Our system has to be able to adapt to the constraints of a variety of fruits. In order to do so, the cavitation orifice should be able to change in diameter in order to be able to accommodate different sized fruits, as well as to be able to increase the cavitation pressure as the cycles go on and the pomace particles get smaller. This is important, especially when using the machine with carrots and cranberries, for the first few minutes of running the system, when there may still be large unground pieces of fruits and vegetables. Another constraint of our design is that it needs to function at a temperature of around 70°C. This is because the mixture must remain at a temperature that preserves the phytochemicals in the pomace, as they offer nutritional benefits that we want in the processed powder, but the mixture must rise to 70°C so that the pomace is pasteurized. A cavitation unit with an orifice that changes diameter to accommodate the type of fruit and the pomace's changing consistency throughout the process has never been used before in food engineering, and we believe it will provide a much more suitable system for our client.

2.1 Pomace Cavitation Machine

Figure 1 below is an AutoCAD rendering of our design. The design consists of an inlet and outlet for the product, the high shear pump with a built-in motor (see APPENDIX 2 and 5 for specifications), and the cavitation unit. For safety, there are four pressure gauges, four thermometers, and a depressurization valve installed in order to monitor pressure and temperature changes before and after each process throughout the design (further explained in the economic assessment: section 4.0)

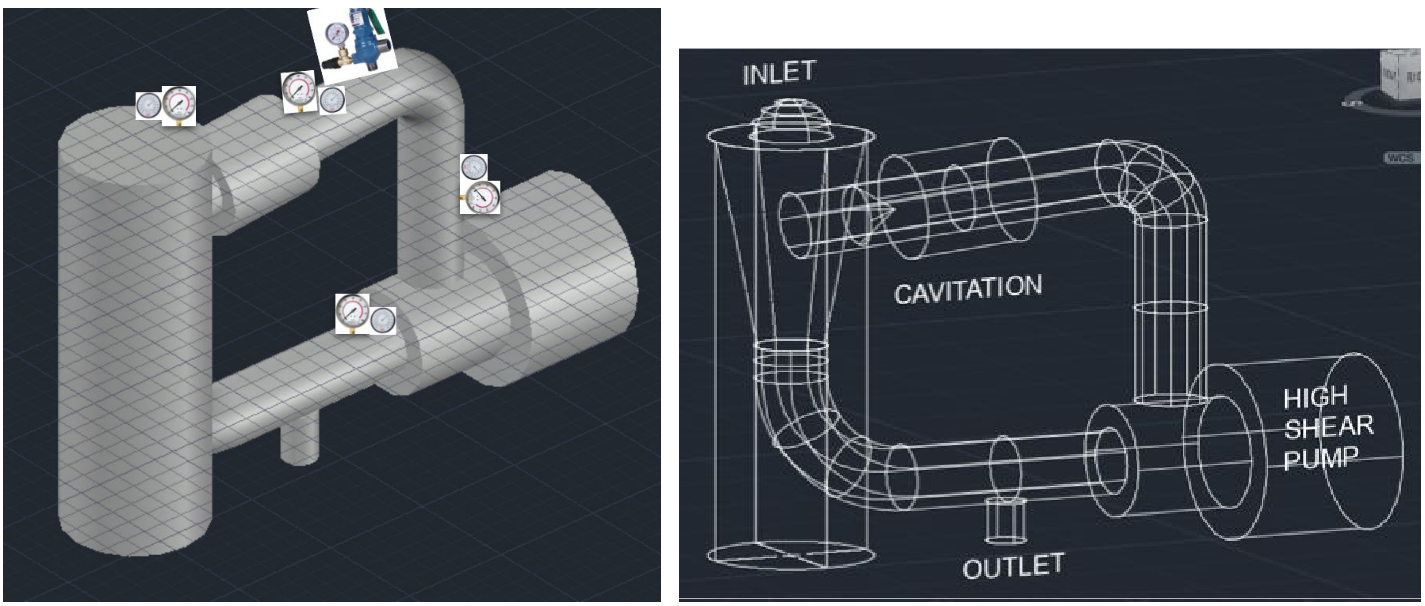


Figure 1 - 3D rendering of pomace cavitation machine

The processing flow goes as follows: 100 kg of pomace is inserted at the inlet. The inlet is then sealed to create a pressurized closed system. The high shear pump will break down the pomace particle size as well as pump the pomace mixture to the cavitation unit with an output pressure of 500 kPa. The cavitation unit will create cavities in the pomace thus breaking down the cellulose and hemicellulose. This cycle will repeat 300 times in the span of an hour, and then the finished mixture will be removed via the outlet and sent for drying. Along the course of the processing, the cavitation orifice will decrease in size thus increasing the pressure during cavitation as the mixture becomes smoother. The pressure gauges and thermometers are located before and after the high shear pump and cavitation unit will ensure the process is functioning under the right conditions, and the depressurization valve, located before the cavitation unit, will release if the pressure in the system starts to approach potentially dangerous levels. Some other important aspects of the design are that the corners of the piping all have an angle of less than

90° to minimize drag. Lastly, all the piping will be made of grade 304 stainless steel because it is a food-grade metal that is typically used in the food industry (OptiMIM, 2019).

2.2 Cavitation Unit Cone Design

Inside the cavitation unit of our design, we designed a cone-shaped obstruction. As the fluid enters the unit, it is forced around the cone and must pass through the space between the perimeter of the cone and the wall of the pipe (see Figure 2). This is where the fluid would be under maximum pressure. The area right after the cone is where the fluid would be under the lowest pressure. The rapid shift from high pressure to low pressure is what allows cavitation to occur (Physics.org, n.d.).

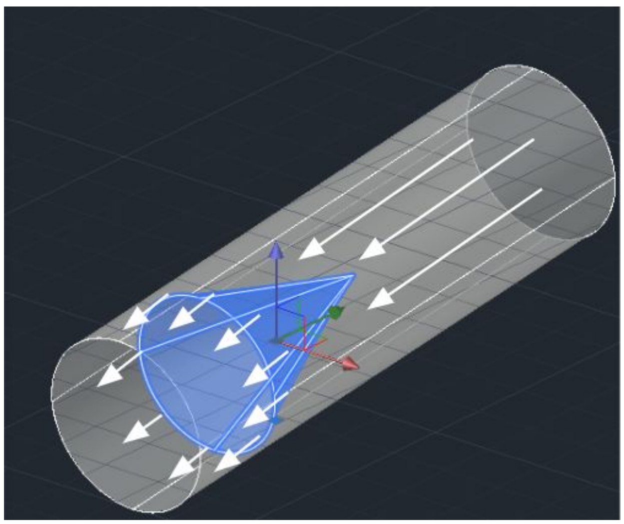


Figure 2 - AutoCAD rendering of pomace flow around cavitation cone

This cone would be able to vary the diameter of its base by wrapping and unwrapping in on itself. It would start with a small diameter in order to have a large gap between the cone and the pipe wall because the pomace would still have a large particle size. Throughout the cavitation cycles, and as the particle size of our pomace decreases, the diameter of the base of the cone will grow, making the gap between the pipe wall smaller and increasing the pressure before cavitation occurs. This progressive increase in pressure will allow this machine to break down the cellulose and hemicellulose in the pomace and create a mixture that can be dried into a very fine powder. The starting size of the diameter can be changed depending on the type of pomace being processed. For instance, carrot pomace might start out with larger chunks than blueberry pomace, so the cone would be set to start with a smaller diameter for carrots so that there is enough space between the cone and the pipe wall for the pomace to flow without causing an obstruction in the machine.

2.3 Assumptions and Calculations

To begin the project, our team made several assumptions that would help in the design phase. Firstly, we assumed that we could add water to the original pomace in order to make it viscous enough to have it flow through the machine. We were looking to achieve close to the same viscosity as apple sauce, which is 1000 cP (centiPoise) (Saravacos, 1970). Secondly, we assumed that since the carrots would be the most fibrous, and therefore the hardest produce to break down, if we designed our machine to work on carrots, it would work with all the other fruits and vegetables. Thirdly, we want our machine to be able to handle a minimum of 100 kg of pomace at once and the total process to not last more than an hour so that it can keep up with the industrial amounts of pomace being produced by Oasis.

Since a machine like this has never been made with these types of produce, it was hard to determine at which pressure cavitation would occur, without building the machine first and producing some experimental data. However, by studying the patent of Tekmash TEK-SM (Osipenko et al., 2009) we were able to assume that the pressure before the cavitation (which is also the pump output pressure) orifice would need to be 500 kPa and that the pomace would have to cycle 300 times through the system during the hour of processing.

In order to be able to find a high shear pump that is suited to our specific needs, we needed to provide the company with a few parameters, such as flow rate, viscosity, and discharge pressure. The only value missing was the flow rate that had to be calculated. The mass flow rate in kilograms per second ($\dot{m}$) can be calculated by dividing the mass of pomace that passes through the tubing each hour by the number of seconds in an hour.

$$\dot{m} = \frac{100\ kg \times 300\ cycles}{3600\ s} = 8.333\ kg/s$$

Mass flow rate can be converted to volumetric flow rate in m^3/s (V) by dividing by the density of the fluid (Eq. 1). As the densities of the produce in question are all either right above or right below 1000 kg/m^3 (Bifani et al., 1994), we have decided to assume that the pomace has a density of 1000 kg/m^3.

$$V = \dot{m} / \rho = \frac{8.333\ kg/s}{1000\ kg/m3} = 0.008333\ m^3/s \qquad (1)$$

Lastly, in order to be able to calculate the diameter needed for the pipes, we had to assume the length of the pipes at 1 meter each, for a total distance travelled by the pomace per cycle of 4 meters.

We can calculate the cross-sectional area of the pipes using the fluid mechanics' equation (Eq. 2):

$$\dot{m} = \rho A v \qquad (2)$$

Where $\dot{m}$ is the mass flow rate, ρ is the fluid density, A is the cross-sectional area of the pipe and v is the velocity of the fluid. Our only missing variable is the velocity (v) which can be calculated with this equation (Eq. 3):

$$v = d / t = \frac{4m \times 300\ cycles}{3600\ s} = 0.333\ m/s \qquad (3)$$

The cross sectional area can then be calculated by rearranging Eq. 2:

$$A = \dot{m} / (\rho \times v) = \frac{8.333\ m3/s}{1000\ kg/m3 \times 0.333\ m/s} = 0.025024\ m^2$$

By rearranging the equation for the area of a circle (Eq. 4) we can find the pipe diameter.

$$A = \pi (d^2 / 4) \qquad (4)$$

$$d = \sqrt{4A / \pi} = \sqrt{4 \times 0.025024\ m^2 / \pi} = 0.1785\ m$$

3.0 Alternative Solutions

3.1 Machine Designs

Before deciding on the final design of this machine, alternative solutions were considered. The first alternative considered was some sort of bladed system, such as a blender or a food processor. However, according to our mentor blending does not break down the food skin cell, but rather just chops them up into small parts while leaving the cellulose and hemicellulose intact (V. Orsat, personal communication, February 22nd, 2019). Since the product being worked with is mainly fruit skins, a solely bladed system cannot adequately fulfill our need. However, some of the tougher food remnants, such as the ends of carrots, will have to be pre-blended beforehand in order to make them a consistency that can be further processed by the cavitation machine.

The second alternative solution was a cavitation machine with pressure built up by an infinite screw (see Figure 3). In this design, the pomace is dropped into the input where it then falls down and is pushed forward by an infinite screw. The infinite screw then fills a sealed chamber with the pomace allowing pressure to build up. Once the pressure is high enough, the valve would open, quickly releasing the pomace through the cone, thus creating cavitation (similar to the design in section 2.2). The mixture could then be collected at the output and sent for drying.

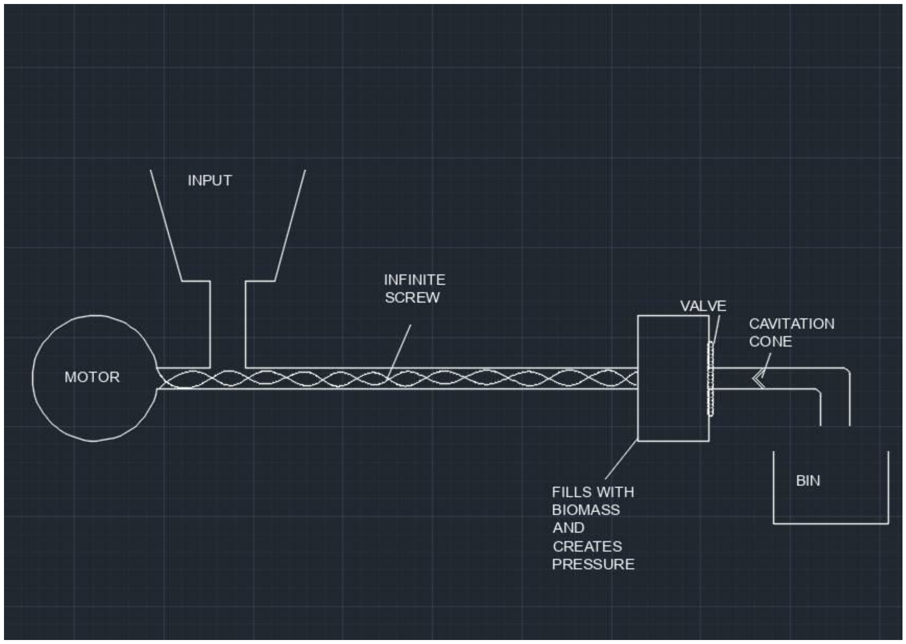


Figure 3 - AutoCAD rendering of infinite screw cavitation machine

There were many problems with this design; in order for cavitation to adequately break down down the pomace in one cycle, the pressure needed to be very high, therefore producing temperatures far too high to preserve the phytochemicals. Furthermore, there was no safe release for the backpressure, therefore the pressure that built up in the chamber would have overloaded the motor while trying to turn the infinite screw.

Table 1 below shows the Pugh Chart comparing the two machine design possibilities. The justifications for the given ratings are outlined below the table.

Machine Designs			**Alternatives**			
	Weight	**Baseline**	**Infinite Screw Cavitation Machine**		**High Shear Pump Cavitation Machine**	
Criteria			**Rating**	**Weighted**	**Rating**	**Weighted**
Output quality	5	0	-1	-5	1	5
Versatility	5	0	1	5	1	5
Cost to build	5	0	0	0	-1	-5
Environmental performance	2	0	1	2	1	2
Longevity	2	0	-1	-2	0	0
Ease of maintenance	2	0	-1	-2	0	0
Profit	5	0	-1	-5	1	5
Total	26	0		**-7**		**12**

Table 1 - Pugh Chart of Machine Designs

The infinite screw design was made under the assumption that we could not add water to the pomace (which is around 50% moisture) (V. Orsat, personal communication, February 22nd, 2019), therefore a pump would be inoperable. We were later informed by our client that we are able to add water to the mixture. This opened up more possibilities of design ideas, which ultimately led to the design analyzed in this report.

Rating Justifications:

Output quality: The Infinite Screw Cavitation Machine (ISCM) receives a negative rating for output quality because it would be unable to turn the pomace into a powder with its single pass through the cavitation orifice. The High Shear Pump Cavitation Machine (HSPCM) receives a positive rating because it's multiple cycles through the cavitation orifice should be able to turn the pomace into the desired powder.

Versatility: Both these designs receive a positive rating because they both include a cavitation orifice that can change its diameter to accommodate different types of fruit.

Cost to build: The ISCM receives a neutral rating, while it is not particularly cheap to build, it is not exceedingly expensive either with its most costly part being the motor. The HSPCM receives a negative rating because of the enormous cost of the high shear pump.

Environmental Performance: Both these designs receive a positive rating because they are both built using local materials and parts.

Longevity: The ISCM receives a negative rating because due to the backpressure having nowhere to go the machine's motor would most likely burn out after one use. The HSPCM receives a neutral score because due to the fragility of the variable diameter cavitation orifice and the high pressures it is subjected to, the orifice might be damaged after several uses and would need to be replaced.

Ease of maintenance: The ISCM receives a negative rating because it would be very difficult to clean the infinite screw without dismantling the machine. The HSPCM receives a neutral rating because, while it is easy to clean, maintenance might need to be done on the variable diameter cavitation orifice if it is damaged.

Profit: Since the ISCM would be unable to produce a powder and would most likely break after one use it is not a profitable design and receives a negative rating. The HSPCM receives a positive rating because it would be able to produce the powder end product, which can then be sold for profit.

The high shear pump design received a final score of 12/26 while the infinite screw design received a final score of -7/26. Therefore, it was decided that we would go with the High Shear Pump Cavitation Machine design.

3.2 Cavitation Orifices

Before deciding on the cone design, discussed in section 2.2, we designed another alternative first, the aperture shaped design (represented in Figure 4).

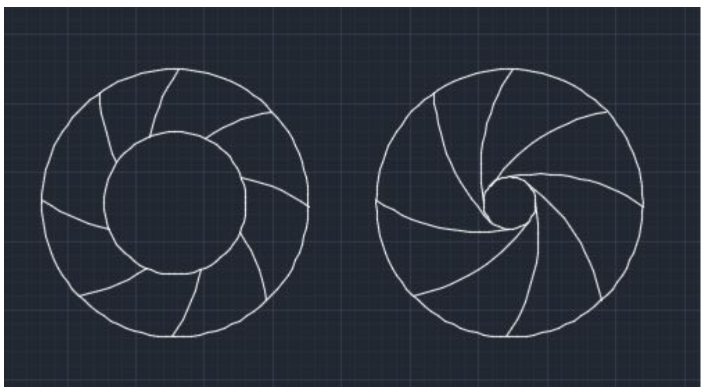


Figure 4 - AutoCAD rendering of aperture cavitation orifice

Each of the designs came with its own advantages and disadvantages. The cone shape design is aerodynamic and would minimize the build-up of pomace. However, in order for the metal to be flexible enough to change in diameter, it would have to be very thin, which could cause problems considering the cone would be subjected to high pressures. Our alternative aperture shaped design works like a camera lens focusing and unfocusing. It could be built with thicker metals to make it more sturdy and it would be easier to design and build. However, it would create much more turbulence and friction in the flow as it creates a flat surface for the pomace to crash into. Furthermore, there is an increased possibility with this design of the pomace getting stuck around the edges of the aperture, which could lead to health and hygiene concerns.

Table 2 below shows the Pugh Chart comparing the two orifice design possibilities.

Cavitation Orifices			Alternatives			
	Weight	Baseline	Cone Shaped		Aperture Shaped	
Criteria			Rating	Weighted	Rating	Weighted
Minimal interuption of flow	2	0	**1**	**2**	**-1**	**-2**
Hygienic	3	0	1	3	-1	-3
Resilance to pressure	3	0	-1	-3	1	3
Simplicity	1	0	-1	-1	1	3
Cavitation efficiency	4	0	1	4	0	0
Total	13	0		**5**		**1**

Table 2 - Pugh Chart of Cavitation Orifices

The cone-shaped design received a final score of 5/13 while the aperture shaped design received a final score of 1/13. Therefore we decided to go with the cone-shaped design.

4.0 Economic Assessment

4.1 Cost of Materials

The main material costs that will have to be incurred to build this machine come from, the metal piping, the high shear pump/motor, the pressure gauges, thermometers, and the depressurization valve.

Firstly, each machine will have 4 meters of piping. This piping will all be food-grade 304 stainless steel and will have a diameter of 178.5mm (7 inches). However, this diameter could not be found in the market so we will be using the closest available diameter of 161.46mm (6.357 inches) with a thickness of 3.4 mm (0.134 inches) (MetalsDepot, 2019). A pipe of 4 ft (1.2 meters) costs around 342.48CAD (MetalsDepot, 2019). Each unit needs almost four times that much piping, which would cost 1369.92CAD. However, it is cheaper to buy 20 ft (6.096 meters) of piping for 1197.00CAD, even though we end up with 2 extra meters of piping (MetalsDepot, 2019).

The largest material cost is the high shear pump and motor. We were able to find a supplier in St-Hyacinthe, a city only half an hour away from the Oasis juicing factory in Rougemont. The price estimate they provided us was based on a variety of our design parameters such as; flow rate, discharge pressure, absolute viscosity of the fluid, and processing temperature (see APPENDIX 1 for values). The high shear pump they provide has its own motor built-in so we will not have to purchase it separately. The model most suited for our purpose is Fristam Pumps' FSI3542 with 40 HP motor (see APPENDIX 2 for specifications). The price estimate given was 18900CAD, and is where the bulk of the machine's cost comes from (M. Fortin, personal communication, March 28th, 2019). However, during the summer, our client found another supplier for the high shear pump and received an estimate of 44040CAD (see

APPENDIX 5 for specifications). In deference to our clients, we will be using the 44040CAD estimate for our price calculations.

The unit will also require four pressure gauges, one before and after the pump and one before and after the cavitation unit. The price of pressure gauges with a large enough pressure range cost around 10CAD each, for a total of 40CAD (Baker Instruments, 2019a).

Accompanying each pressure gauge will be a thermometer to ensure the system is functioning within our temperature range of 20°C to 70°C. The price of an industry-grade stainless steel thermometer with a temperature range of -20°C to 120°C is 35CAD. Since we would require 4 of them, the total price would be 140CAD (Baker Instruments, 2019b).

The last thing needed is a pressure release valve in case some obstruction causes pressure buildup in the machine. It will be placed right before the cavitation unit as that is where the highest pressures will be. The cost of a pressure release valve with a large enough pressure range is around 13.24CAD (Acklands Grainger, 2019).

Therefore the total material costs for this system equates to:

1197.00CAD+44,040.00CAD+40CAD+140CAD+13.24CAD
=**45,430.24CAD**

4.2 Cost to Build

Oasis wants two of these units built, one for cranberries, blueberries and apples, and one for carrots. As this design is not going to be mass-produced, the cost of building cannot be estimated by comparison to building costs of existing products. Since only two of these machines need to be built, it is more likely that they will be built by hand than with a mechanized system. Therefore, these two machines will cost more per unit because of the requisite cost of labour. The median wage of a Heavy Duty Mechanic is 32.29CAD per hour (Payscale, 2019). Therefore, if it takes one month to build one of these units, assuming a 5 day work weeks and 8 hours of work per day (160 hours total), the cost of building one unit is 5,166.40CAD (two machines equalling 10,332.80CAD). Note that one month to build each unit is a worst-case overestimate.

4.3 Cost to Buy

The breakeven selling cost of one of these units, not counting transportation costs, is the sum of the material costs and building costs at:

45,430.24CAD+5,166.40CAD
=50,596.64CAD

If the fabricator wanted to turn any kind of profit, they would have to charge more than this. If Oasis wanted to purchase two of these machines, the lowest cost to buy them would be **101,193.28CAD.**

4.4 Cost of Electricity

We will assume that this machine will be used in Quebec, using Hydro-Quebec's Rate D structure (Hydro-Quebec, 2019). According to this structure, the fixed price per day is 40.64¢/day. The variable cost of electricity is 5.91¢/kWh up to the use of 36 kWh. After consumption of 36 kWh, the price per kilowatt-hour becomes 9.12¢/kWh (Hydro-Quebec, 2019).

TEKMASH's TEK-2SM model has the same capacity that we are aiming for in our design (100kg/cycle), albeit for soy. Therefore we will assume that our power consumption will be similar to theirs at 15kW (TEKMASH, 2019). If we assume that our machine is being used the minimum amount of times per day for them to still be profitable, it would run for 2 hours a day (1 hour cycle for cavitation of 100 kg of pomace and 1 hour required cleaning cycle at the end of the day). This would mean that our machine uses 30kWh (15kW x 2h) each day.

The fixed cost equals 40.64¢ or 0.4064CAD. Since we are under 36kWh, the variable costs equal, 30kWh x 5.91¢/kWh=177.3¢=1.773CAD. So the total cost of electricity per day, assuming 2 hours of work per day, is 2.18CAD/day.

However, it is far more likely that the machine will be used continuously during working hours. If we assume it will only be run for 8 hours a day, the unit would use 120kWh (15kW x 8h) each day. Since 120kWh surpasses the first tier calculations of 36 kWh.

The fixed cost remains the same at 0.4064CAD. The first 36kWh of the 120kWh costs 36kWh x 5.91¢/kWh=212.76¢=2.1276CAD. The remaining 84 kWh costs:

84kWh x 9.12¢/kWh = 766.08¢ = **7.6608CAD**

As a result, the total cost of electricity per day, assuming 8 hours of work per day, is **10.20CAD/day**.

4.5 Profit

In order to know how much profit Oasis would be making by selling their powdered nutrient product, it is necessary to know how much they are making or losing by giving the pomace to farms as swine feed. Unfortunately, we do not have access to this data as Oasis keeps them confidential. However, we can make some educated guesses. The pomace that is produced by the factory is a production residue that must be disposed of regularly in order for juice production to continue. The first possible solution, Oasis must pay to have the pomace transported to a landfill. The second possible solution, and the one that Oasis is currently utilising, is that the pomace is used as swine feed and the swine producers pay for the transportation costs (V. Orsat, personal communication, October 31st, 2019). The final solution, and the one that we are suggesting in this report, is to process the pomace into a new product. In order to find the profit that would be accrued by selling the pomace as a nutrient supplement, we must calculate the net difference in what they are making using their current method versus the suggested method.

By using their pomace as swine feed for which transportation costs will be covered by the swine industry, Oasis is neither losing or making money. Instead of using their pomace as swine feed, Oasis would like to sell it as a powdered nutrient supplement. Similar producers tend to charge 0.112 CAD per gram on average (Lucky Vitamin, 2019) (Amazing Grass, 2019) (Purely Inspired, 2019). This is equivalent to a staggering 112022 CAD per tonne (1000 kg), over 180 times the cost per tonne of using the pomace as animal feed. Since the powder will not contain any colouring or flavouring additives it might not be as appealing to consumers. Therefore, we will assume that our product will sell for around 90% of the cost of comparable brands at 100000 CAD per tonne. Furthermore, if we assume a markup of 50% (a common markup for non-competitive products) (Ghosal, 2000), Oasis' actual profit will only be half this amount with the rest being allocated to production, transportation, packaging, paying staff, and other miscellaneous costs.

Assuming that the machine was only used to pulverize pomace once a day to process 100 kg of pomace (the minimum amount), before cleaning, it would take less than 11 days to become profitable per the following:

$$\text{Profit per day} = \frac{\$100000\ x\ 0.5\ x\ 100\ kg}{1000\ kg} = \$5000$$

$$\text{Days to be profitable} = \frac{\$50596.64}{(\$5000 - \$10.20)} = 10.14 \text{ day} \approx 11 \text{ days}$$

Where, $50,596.64 is the cost of the machine and $10.20 is the price of electricity (calculated in section 4.4).

Even with the machine doing the bare minimum, Oasis would still become profitable within 11 days. Assuming that the machine is used seven times a day to process 700 kg of pomace (the minimum amount), before cleaning, it would take less than 2 days to become profitable per the following:

$$\text{Profit per day} = \frac{\$100000\ x\ 0.5\ x\ 700\ kg}{1000\ kg} = \$35000$$

$$\text{Days to be profitable} = \frac{\$50596.64}{(\$35000 - \$10.20)} = 1.45 \text{ day} \approx 2 \text{ days}$$

With an even lower markup, for instance 25%, profits will therefore only be a quarter of the earnings. As a result, the payback period will still be extremely low.

$$\text{Profit per day} = \frac{\$100000\ x\ 0.25\ x\ 100\ kg}{1000\ kg} = \$2500$$

$$\text{Days to be profitable} = \frac{\$50596.64}{(\$2500 - \$10.20)} = 20.32 \text{ days} \approx 21 \text{ days}$$

To compare, we found an article that discusses small bioreactors that produce biogas and compost from waste. The payback period estimated on their report is 4 years, this is due to the fact that they have to take into account many expenses such as site preparation, biogas storage systems, biogas purification equipment, etc. (Baltrėnas & Baltrėnaitė, 2018). Our design is to be implemented into a pre-existing manufacturing plant with multiple processes, therefore, the system is simply an add-on where the waste will be allocated to, instead of being disposed of or sent to farms for swine feed.

Therefore, using the pomace as a nutrient supplement instead of swine feed is not only financially feasible, but it’s extremely profitable as well and a very good economic decision.

5.0 Environmental Impact Assessment

Our cavitation unit will increase the sustainability of Oasis' processes and decrease their environmental impacts by reducing the amount of waste they produce. By reusing the pomace and turning it into another usable product, Oasis will further feed more people off the same amount of produce being grown, therefore lowering our environmental footprint.

Since the cavitation unit is made fully of type 304 stainless steel, the machine will be easily recyclable at the end of its lifespan. If the product were made with a variety of different metals the process of recycling would require the separation of the different types of metals, thus complicating the process (Conserve Energy Future, 2016). When finished with the cavitation unit, the metal will be able to be melted down and used as a standard piece of recycled grade 304 stainless steel metal.

Oasis will likely be able to use one machine with many different products, resulting in a lower environmental cost to their project as a whole. Although reusing this machine will likely result in added maintenance, it will reduce the environmental impact by ensuring that Oasis does not need multiple machines for their different juice lines, thus reducing the amount of raw metals being mined and energy being used for the building and use of more machines.

By increasing the amount of food available to consumers, without having to grow anything more than what is already being grown, we are aiding in feeding the world, while not increasing humanity's use of land and its resources. It also offers another plant-based alternative, which is much more sustainable than meat-based diets. The meat industry has affected our climate, air, soil, and water in negative ways in the past, so anything we can do to help shift to a more plant-based society is good for the planet (Westhoek, et al. 2014).

While Oasis does not provide the harvest information of their ingredients, making it impossible to know where their fruits and vegetables come from, we do know that these four fruits and vegetables are able to be grown in Quebec (Reid, 2018). We believe, that Oasis likely buys their produce from farms close to their processing plant as it would decrease their shipping costs. This also brings down their carbon footprint as the transportation of these fruits and vegetables takes place over a short distance. The only downside our product brings into the equation is the fact that the stores in which the powder will be sold in are likely further than the swine farms in which the pomace was sold to before as feed.

Luckily, when designing our machine, we came across a high shear pump that would work with our design, which happens to have a supplier in St-Hyacinthe, a city only 26 km away from the Oasis Factory in Rougemont. This was good news as it meant that the transportation emissions associated with building our machine as well as the emissions associated with part replacement would be reduced. Furthermore, having the pump supplier so nearby will make it easier to have the pump repaired or replace a small part of it if the pump were to malfunction or break. This would reduce the likelihood of Oasis throwing away the pump and buying a new one if something goes wrong, thus reducing their technological consumption. However, the supplier of the high shear pump that our client suggested is located in Waterloo, Ontario. This will undoubtedly make for higher transportation and repair emission. But as this is still a local supplier, the environmental footprint will still be less than with an international supplier.

6.0 Social Assessment

6.1 Health Effects

This project will ultimately result in beneficial effects on human health. The end product will deliver a powdered form of fruits and vegetables which will be available for human consumption. While our cavitation unit will break down the hard skin and seeds, it will keep the phytochemicals, vitamins, and nutrients intact, keeping the many anti-inflammatory, anticarcinogenic and antioxidant attributes related to them (McGuire, 2011). Therefore, this product would likely be a good dietary supplement for those who need more vitamins and nutrients. Because our processing temperature is above 70°C, the homogeneous output mixture will be pasteurized and safe for public consumption.

6.2 Ergonomics

During the design phase, it was important to us that our machine was user-friendly. Users would have to load in the pomace, seal the inlet, and turn the machine on via the control panel. At the end of the repeated cycles (approximately an hour), the user would have to turn the outlet value and unload the homogenous mixture into a container. The simple workings of the machine allow the employees to accomplish other tasks while the machine is running on its own.

The cleaning procedure for the system does not require extensive work, simply adding the appropriate detergents/sanitizing solutions, running a machine cycle, and then properly draining and rinsing them is enough to meet the requirements of the FDA’s regulations. We suggest that this cleaning cycle be done in the last hour of the workday so that the machine is ready to go the next day. Further details regarding the type of solutions and procedures for cleaning are discussed in section 8.1 of this report.

7.0 Hazard Analysis

Since our design is a food processing machine, we will use these two documents to identify and define possible hazards that can occur during the processing of the raw produce. The U.S. Food & Drug Administration (FDA) enforces the Current Good Manufacturing Practices (CGMPs), which are regulations that assure proper design, monitoring, and control of manufacturing processes and facilities (FDA, 2018). The FDA also provides a management system, The Hazard Analysis & Critical Control points (HACCP), which addresses food safety through the analysis and control of biological, chemical, and physical hazards (FDA, 2018). Table 4 in section 7 (Codes and Standards) of this report provides a brief overview of further requirements concerning food safety.

According to the CGMP report, when it comes to food processing, the three main types of food safety hazards are physical, biological and chemical. Physical hazards include foreign objects in food that can be harmful when consumed, for example, glass or metal fragments. Biological hazards include harmful bacteria, viruses or parasites, such as Salmonella spp., or mycotoxins found in raw produce. Lastly, chemical hazards include compounds that can cause illness from short or long-term exposure (Center for Food Safety and Applied Nutrition). These hazards can occur at any of the stages leading up to the final product. These stages include growing and harvesting of raw materials, storage and transport to the factory where the processing of the raw materials will occur, during subsequent storage and transportation to the companies selling the product, and lastly, during storage and preparation by the consumer (Lelieveld et. al, 2003).

In the CGMP report, preventive controls and corrective actions to take for preventing food safety problems, also known as critical control points (CCPs), are identified. Table 3 lists the possible problems and the following actions to take, along with examples that pertain to our design.

Table 3: Preventive controls and corrective actions

Food Safety Problem	**Preventive control/Corrective action**
Contamination during food processing	- Separation of production lines: keeping the raw produce separate from the final product. - Physical detachments and lockouts: Sealed cover at the inlet and outlet. Pump and cavitation unit easily

	removable. - Routine maintenance of equipment: Making sure the shear pump is working efficiently, change the pumps engine or gears if not.
Contamination of raw materials	- Supplier audits - Raw produce testing and verification - Pre-processing treatments: washing the raw produce - Documentation from suppliers certifying safety of materials: making sure the raw produce is FDA approved.
Deficient employee training	- Proper training to use the system - Bilingual training (Quebec) - Providing learning aids: Step-by-step instructions on how to work the machine, videos and/or brochures.
Difficult-to-clean equipment	- Environmental sampling: making sure the air/water quality is up to standards. - Cleaning areas prone to niches: running a cleaning cycle on a regular basis (last work hour each day). - Sanitation standard operating procedures: cleaning and sanitizing food contact surfaces. - Taking equipment apart to clean.

In APPENDIX 4, our risk matrix summarizes the possible risks discussed thus far, as well as other risks that can potentially occur, including pipe bursts and shear pump malfunctions. The table includes its level of risk, causes and methods to mitigate these problems. This information was gathered from codes and standards, and literature review.

According to FDA's "HACCP Principles & Application Guidelines", when conducting a hazard analysis the questions below should be taken into consideration for equipment design and use (questions taken directly from the HACCP report). Answers for our design follow after each question.

1. Will the equipment provide the time-temperature control that is necessary for safe food?

In regard to time-temperature control, our design will be equipped with multiple thermometers, especially after the cavitation unit, where pressure will be at its highest (500 kPa). According to the FDAs “Juice HACCP Regulation”, Temperatures at 70 degrees Celsius (160 degrees Fahrenheit) must be maintained for at least 3 to 6 seconds in order to attain the 5-log reduction in pathogens that might be contained in raw produce, ultimately pasteurizing the liquid.

An example of a possible pathogen that cannot be destroyed from pasteurization is called Patulin, which is a toxic chemical, mostly found in apples that have fallen onto the ground and have been damaged by either insects or birds, or that have been bruised. Patulin is produced from a number of moulds such as Penicillium and Aspergillus. Although apples tend to be the major source, any mouldy or rotten fruit could contain this toxin (Patulin, 2004). According to the FDA, there is an action level of 50 micrograms per kilogram of apple juice, meaning if the apple juice contains more than 50 micrograms of this pathogen then it is necessary for regulatory or remedial action (Office of Regulatory Affairs, 2005). In order to mitigate this hazard for our design we will use the same standard.

2. Is the equipment properly sized for the volume of food that will be processed?

As shown in section 2.3, in order to calculate the required diameter of the pipes, we took into consideration the amount of pomace we will be processing per batch (100 kg), along with other design parameters. Therefore, theoretically, the system is designed for the volume of food we will be processing per batch.

3. Can the equipment be sufficiently controlled so that the variation in performance will be within the tolerances required to produce a safe food?

Throughout section 2, we discuss mechanisms in our system used for instrumentation and control, including multiple pressure gauges and thermometers, a pressure relief valve and a control box for the high shear pump.

4. Is the equipment reliable or is it prone to frequent breakdowns?

Considering that we are dealing with high pressures, certain parts will experience wear-and-tear (i.e. the pump and the cavitation unit), again, mostly after the cavitation where the pressure is at its highest. However, we are hoping to make those parts easily replaceable or fixable.

5. Is the equipment designed so that it can be easily cleaned and sanitized?

In order to clean the system, we will be running a cleaning cycle on a scheduled basis. We recommend the cleaning cycle be done once at the end of the workday.

6. Is there a chance for product contamination with hazardous substances; e.g., glass?

Due to the fact that we are dealing with raw produce, there is a possibility of microbial contamination, as mentioned at the beginning of this section and in our risk matrix (see APPENDIX 4). Other possible contaminants, ie. physical or chemical, can either come from glass fragments from broken light fixtures, metal fragments broken off from parts of the system (most likely to occur in the shear pump), or possible air and water contaminants.

7. What product safety devices are used to enhance consumer safety?

Instrument and control devices will be implemented into our design in order to ensure that our system produces a safe product for consumers.

8. To what degree will normal equipment wear affect the likely occurrence of a physical hazard (e.g., metal) in the product?

Our design is mainly made of food-grade stainless steel 304L, which consists of 0.8% carbon, 18% chromium, and 8% nickel. The chromium binds oxygen to the surface of the product to protect it from rusting and nickel helps strengthen the corrosion resistance, therefore making the metal safe for food processing.

9. Are allergen protocols needed in using equipment for different products?

Since we are working with a variety of fruits and vegetables (cranberries, apples, blueberries, and carrots), allergen protocols do need to be taken into consideration. However, since we are processing 100% pure raw produce into 100% pure powder with no additives (ie. soy protein), that can potentially cause allergic or allergic-type (food intolerance) reactions, our only potential hazard, in regard to allergens, is mixing fruit together. Therefore, on the product label we would simply put “may contain apples, cranberries, etc”.

8.0 Codes and Standards

Table 4 below is a summary of the requirements found in codes and standards that apply to our design. We have made sure that our machine meets all these requirements.

Table 4: Codes and standards

Code/Standard	Requirements

FDA (U.S. Food & Drug Administration)	- CGMPs;
	  - System designed to facilitate the cleaning of equipment.
	  - Food contact surfaces must be corrosion-resistant and made of nontoxic materials.
	  - Any systems in the machine (i.e. pressure gages, pump controls, etc.) must be controlled and maintained in sanitary conditions.
	
	- HACCP; Procedures for the Safe and Sanitary Processing and Importing of Juice
	  - 5-log reduction performance standard
	    - 160℉ (71℃) for 3-6 seconds

ISO (International Organization for Standardization) - Stainless steel tubes for the food industry.	- Thickness : For tube outside diameter ~ 175.8mm, tube thickness must equal 2.6mm - Austenitic Stainless steel (TS 47, TS 60 or TS 61)

ASME (American Society of Mechanical Engineers)	- 304 Stainless Steel (see APPENDIX 3)
	  - Design pressures: 350-600 psig
	  - Design Temperatures: 100-650 ℉
	  - Pipe Sizing: 1/4 - 12 inch

8.1 Cleaning procedure

In regards of the cleaning and sanitizing of the machine, the FDA is involved in evaluating residues formed from sanitizer-use that could potentially enter the food supply, therefore, any antimicrobial agent used must be approved by them. Sanitizing solutions that have been approved are listed in the Code of Federal Regulation (Sec. 178.1010 Sanitizing Solutions)(FDA, 2019). The list includes the following:

(1) An aqueous solution containing potassium, sodium, or calcium hypochlorite, with or without the bromides of potassium, sodium, or calcium.

(2) An aqueous solution containing dichloroisocyanuric acid, trichloroisocyanuric acid, or sodium or potassium salts of these acids, with or without the bromides of potassium, sodium, or calcium.

(3) An aqueous solution containing potassium iodide, sodium *p*-toluenesulfonchloroamide, and sodium lauryl sulfate.
(FDA, 2019)

It should also be noted that after using the sanitizing solution, it is necessary to adequately rinse and drain the system using hot water before any contact with food (FDA, 2019).

The following is an example of the cleaning procedure:

- Pre-rinse
  - Removes all of the loose soil the surfaces
  - Use warm water (100-120 °F or 37.78-48.89°C)
- Wash
  - Removes carbohydrates, fat, protein and mineral soils
  - Follow SSOPs for cleaning procedure and chemical selection (example of SSOP below)
- Post-rinse
  - Removes detergent and chlorine (if applied)
  - Acid rinse (optional)
  - Removes minerals and prevents mineral deposits
- Sanitize
  - Limits the amount of microorganisms on the surface
  - Sanitizes the food-contact surface
  - Surface must be cleaned before sanitizing step

(Kaylegian, 2019)

*Example of **SSOP** used @ Penn State Berkey Creamery Juice*:

a. *Water rinse*
b. *Water is heated and a chlorinated alkaline detergent is added. The solution is circulated throughout the circuit while valves and agitators are periodically pulsed to aid in soil removal*
c. *The wash cycle is followed by a water rinse which cools down the circuit*
d. *An acid sanitizer is added, circulated throughout the circuit, and allowed to drain to the floor*

*(*Juice HACCP Plan, 2014)

9.0 Making of a Simulation

9.1 COMSOL

Due to the high cost of building materials, the cavitation unit was not able to be built in time for physical testing. As a result, while other options were being discussed, a unanimous decision was made to turn to computer simulations. By doing so, testing would be able to commence before building the machine. Several benefits come with computer testing, including a lower costs, as well as the ability to find unexpected errors or oversights, and change the design before building the unit.

In order to develop an accurate computer simulation, the team chose to use COMSOL as it offered many of the options needed to produce an accurate representation of the design. Firstly, COMSOL offered multiphysics capabilities, meaning that the program allows users to control and test variables in multiple different subcategories of physics. For this project, testing needed to include fluid velocity, pressure and viscosity, as well as the heat transfer within the machine. COMSOL also allows users to create a visual representation through time, which is important for both the design phase, as well as for project presentations. Lastly, COMSOL also allows users to extract data onto other, simpler software such as Excel, which facilitates the processing of the data.

9.2 Objective of Simulation

Over the summer, it was decided that building a cavitation orifice capable of changing its diameter was unfeasible to build because of how much the structural integrity of the orifice would be compromised. If the orifice were made of multiple parts or of metal flexible enough for it to be able to change its diameter, it is unlikely that it would be able to withstand the high-pressure conditions of the machine. This would result in mechanical failure within the machine and thus lead to costly repairs and part replacement. Therefore, the new design's cavitation unit will consist of a continuation of piping that suddenly decreases dramatically in diameter only to suddenly reincrease in diameter, thus causing a rapid increase then decrease in pressure (see Figure 5). This leaves us with the question: what is the ideal diameter for the cavitation orifice?

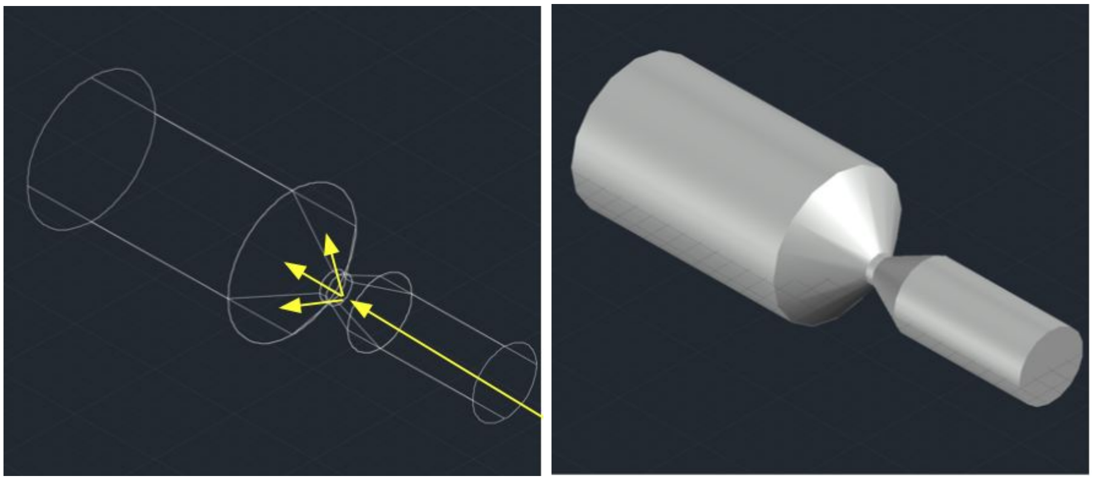


Figure 5 - AutoCAD rendering of new cavitation unit

One of the goals we had while simulating the machine was to create an easy-to-understand visual representation of the fluid flow through the unit. The simulation was also set out to be a functional part of the design process, which we hoped would help in finding the ideal diameter of the cavitation orifice. The original hypothesis was that as the pomace kept being pumped through the machine over and over again, it would simultaneously heat up. This simulation would also give us insight into the thermodynamic properties of the machine, providing us with the number of cycles the pomace has to go through to become both homogeneous, as well as pasteurized, without exceeding a temperature of 70 degrees celsius. Lastly, we were looking to gain insightful knowledge about the viscosity of the pomace, and how it changes throughout the cavitation process.

9.3 Implications of Design Change

Changing the design so that the cavitation orifice no longer varies its size has several implications for this design. One advantage of the original design was its ability to adapt to whatever fruit or vegetable was put into it and then change its diameter based on how much pressure needs to be exerted during the progress of the cycles. However, having such a flexible orifice would have lowered the structural integrity of the machine and lowered its life expectancy. Therefore, while the versatility of the machine has gone down with this redesign, its longevity has gone up.

Thus, the Pugh Chart becomes:

New Machine Designs			Alternatives			
	Weight	Baseline	Infinite Screw Cavitation Machine		High Shear Pump Cavitation Machine	
Criteria			Rating	Weighted	Rating	Weighted
Output quality	5	0	-1	-5	1	5
Versatility	5	0	1	5	-1	-5
Cost to build	5	0	0	0	-1	-5
Environmental performance	2	0	1	2	1	2
Longevity	2	0	-1	-2	1	2
Ease of maintenance	2	0	-1	-2	0	0
Profit	5	0	-1	-5	1	5
Total	26	0		**-7**		**4**

Table 5 - Updated Pugh Chart with the high shear pump design having negative versatility and positive longevity

As can be seen in Table 5 above, the high shear pump design now received a final score of 4/26 while the infinite screw design maintains its final score of -7/26. Even though the score of the high shear pump design has dropped, it still exceeds that of the infinite screw design, so we will still be pursuing the high shear pump design.

9.4 Simulation Trials

While over ten different simulation trials were done over the course of this semester, here we will discuss the four stages where the simulation's geometry was altered.

Stage 1

The first stage of the trials involved solely the simulation of the process where cavitation will occur. The other parts of the machine, such as the pump and most of the piping, were not represented in this stage. This facilitated the technical drawing of the machine, and allowed us to learn the program more efficiently than if we had tried to simulate everything all together. This simulation was a 2D axisymmetric geometric design since the piping will be symmetric around its central axis. First the top side of the geometry was designed and drawn with COMSOL, and then it was mirrored below. This caused the input pipe (bottom, see Figure 6) and output pipe (top, see Figure 6) to be the same size. Although our design called for the two pipes to be different sizes, the first stage of our simulation ran identical sizes as this was easier to draw and allowed us to start with a simple simulation so we could experiment with COMSOL more efficiently. This would later be changed in future stages.

Unfortunately, at this time, the only version of COMSOL available to us did not offer turbulent flow simulations, which we needed, so we decided to simulate the process using laminar flow. In this stage, we also neglected both heat transfer properties, as well as the cycling of the machine, making the simulation run with steady-state properties. The final results of this stage can be seen below in Figure 6. While the fluid velocity of the simulation behaved as expected, the maximum pressure before the orifice instead of at the orifice where, in theory, it was supposed to be.

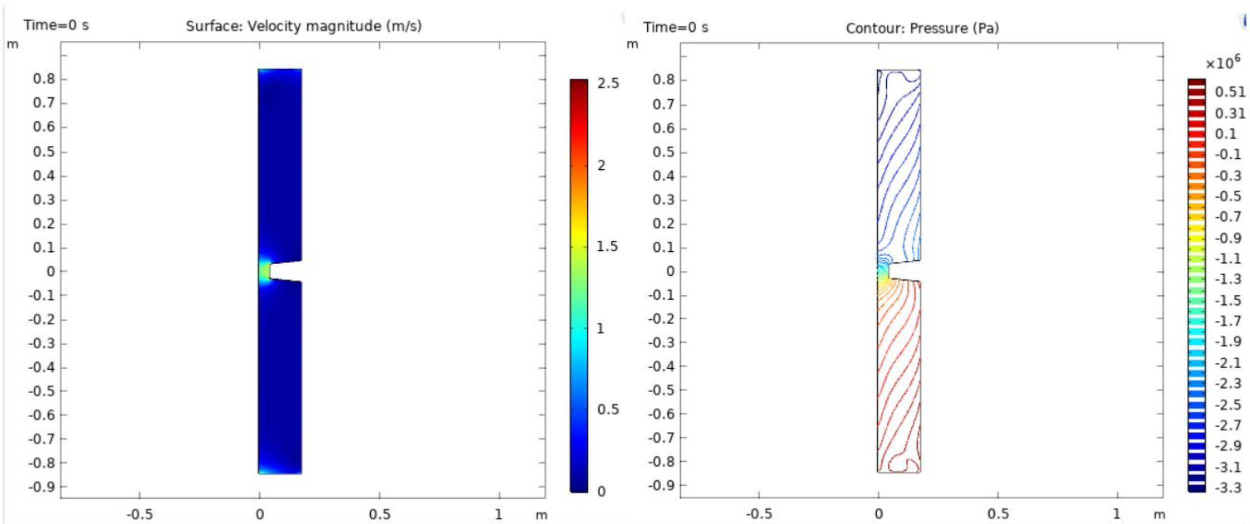


Figure 6 - Stage 1 2D simulation results showing velocity distribution (left) with maximum velocity at orifice and pressure distribution (right) with maximum pressure at inlet (at the bottom)

One hypothesis for why the maximum pressure was at the wrong location was because the input and output pipe were the same size, so maybe the pressure difference wasn't high enough between the input and output. It was also likely that the source of the problem was that we were using laminar flow instead of turbulent flow (as cavitation bubbles cannot form in perfectly laminar flow) (Moholkar & Pandit, 1997), however, since the size of the output pipe would have had to be changed to that of the original design at some point, and since we couldn't do anything about the turbulent flow problem without the Comsol add-ons, we decided to try and see if making the output pipe larger would fix the problem.

Stage 2

In order to be able to make the input and output pipe different diameters, the mirroring function had to be removed. However, this interfered with the parameter definitions that had been set to make the original geometry. Therefore, it was more convenient to create a new simulation from scratch (see Figure 7). After the new simulation was run, the same problem persisted. Maximum pressure was before instead of at the orifice (see Figure 7). The change in input and output diameter did have a positive effect on the fluid velocity, however, which became much more akin to what would have been expected from our machine (see Figure 8).

Another hypothesis for what was causing this problem was the fact that we had been running steady-state simulations and not time-dependent simulations where the pomace circulates back around each cycle. In order to create a time-dependent simulation where the pomace would recirculate through the system, we needed to make the system periodic. However, making a simulation periodic means the input and output would be directly connected together. Therefore, the geometry had to be edited so that the output pipe shrinks back to the size of the input pipe so that they could fit together (see top of Figure 7 and Figure 8).

After this was done, we still received an error. It turns out that making a simulation periodic does not allow you to continuously add energy (as is the case with our high shear pump).

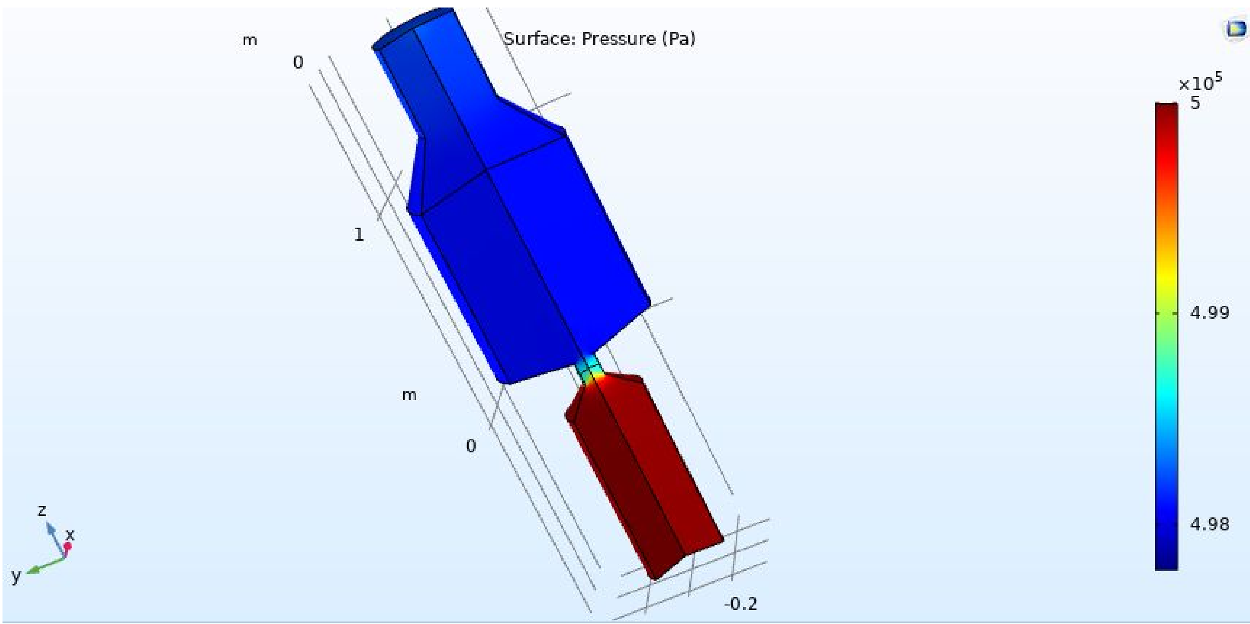


Figure 7 - Stage 2 3D simulation results showing pressure distribution with maximum pressure at the inlet (near the bottom)

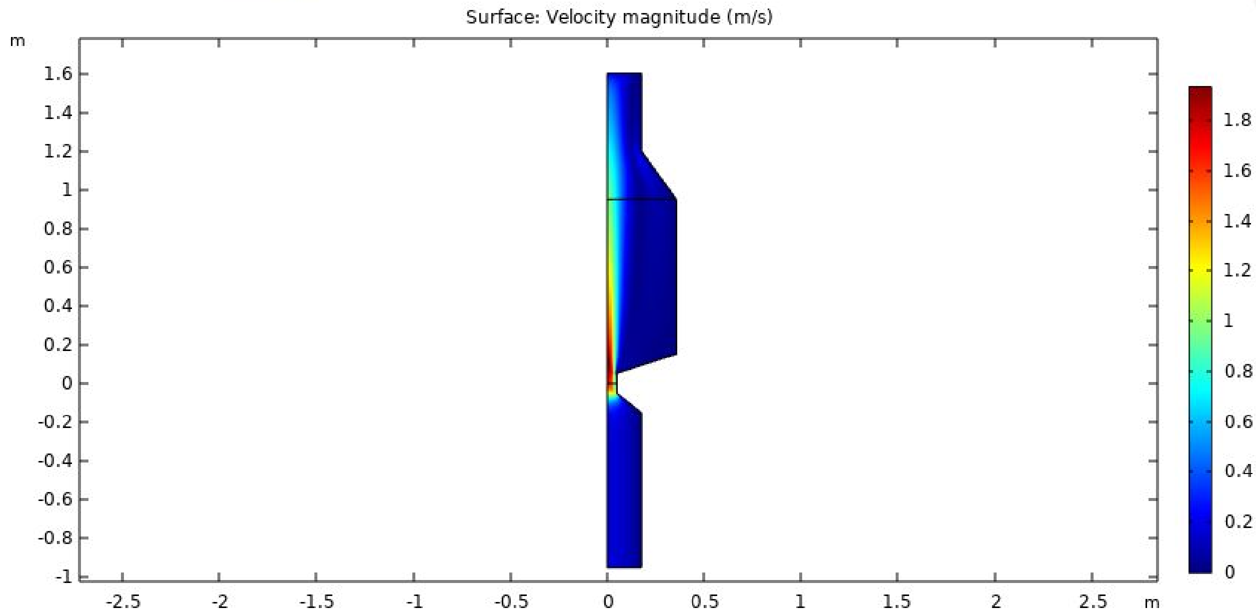


Figure 8 - Stage 2 2D simulation results showing the velocity of the fluid

Stage 3

After consulting with Shahin Eskandari, a TA of Dr. Akbarzadeh Shafaroudi, we decided that the best course of action was to make a new simulation from scratch, again, one that simulated the entirety of the system and not just the cavitation unit. This required recreating an entirely new simulation since it would no longer have 2D axisymmetric geometry but regular 2D geometry.

The new simulation needed the addition of some sort of pump that would ideally simulate the high shear pump, as discussed in section 2.1 of this report. After rigorously attempting to implement the "vacuum pump" function on COMSOL, we concluded that it only works at an input, and since this simulation demonstrates a closed-loop system, there is no input or output. Moving forward, we tried to implement the "interior fan" function. The fan seemed to have worked to a certain extent; the fluid would heat up, starting at the fan and slowly spreading throughout the rest of the system while increasing pressure (see Figure 9). However, the fan did not seem to be moving the fluid. We couldn't determine why there was no fluid flow. Perhaps with further knowledge on COMSOL, we could have troubleshot and figured out a solution, but due to time constraints, we decided to drop the "interior fan" function. Additionally, since we couldn't make the laminar simulation work it wasn't worth attempting to make a turbulent one.

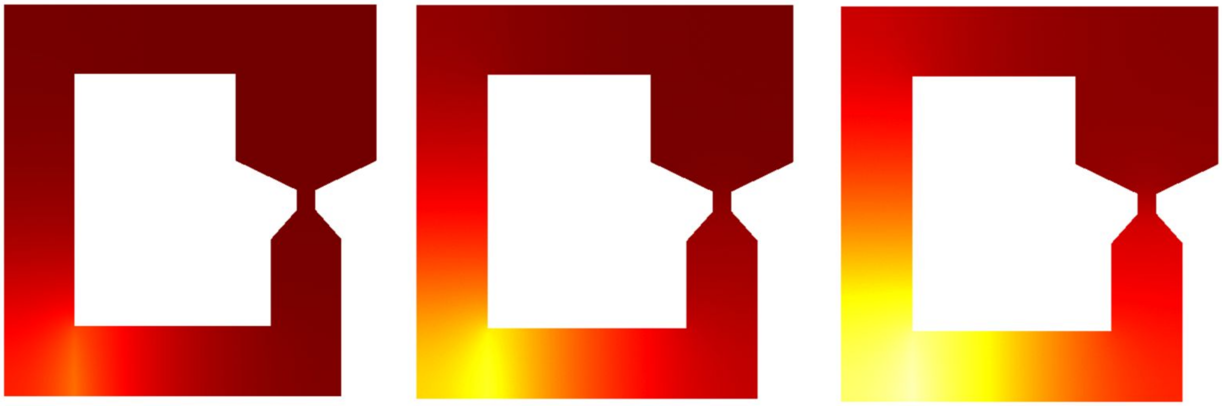


Figure 9 - Stage 3 2D animation frames of temperature radiating out over time from location of "interior fan"

Stage 4

Since the "interior fan" was not moving the fluid, we decided to remove it. Instead of sticking to adhering to the closed system geometry of Stage 3, we decided to create an input and output locations right next to each other at the location of where the pump would have been. We then input the parameters of the inlet and outlet of our pump. By doing so we were able to obtain the visualization of the fluid flow through the whole system (Figure 10) as well as the pressure throughout the machine (Figure 11).

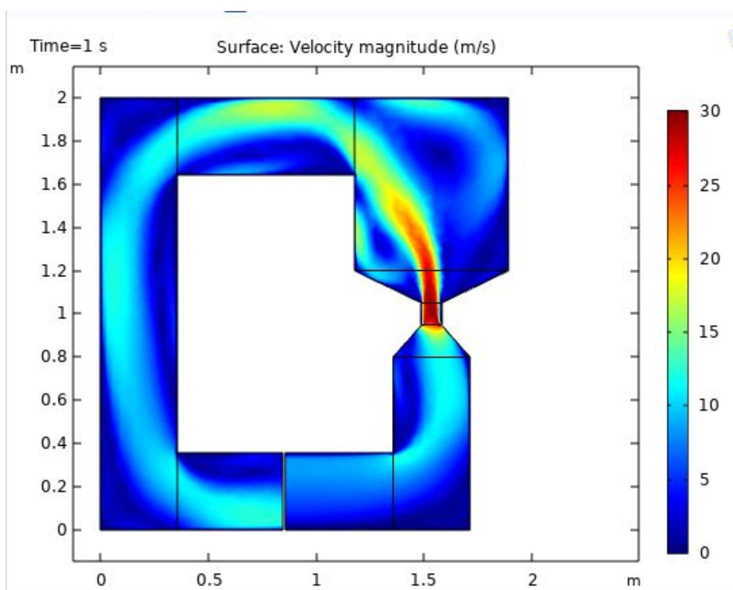


Figure 10 - Stage 4 2D simulation results showing the velocity of the fluid

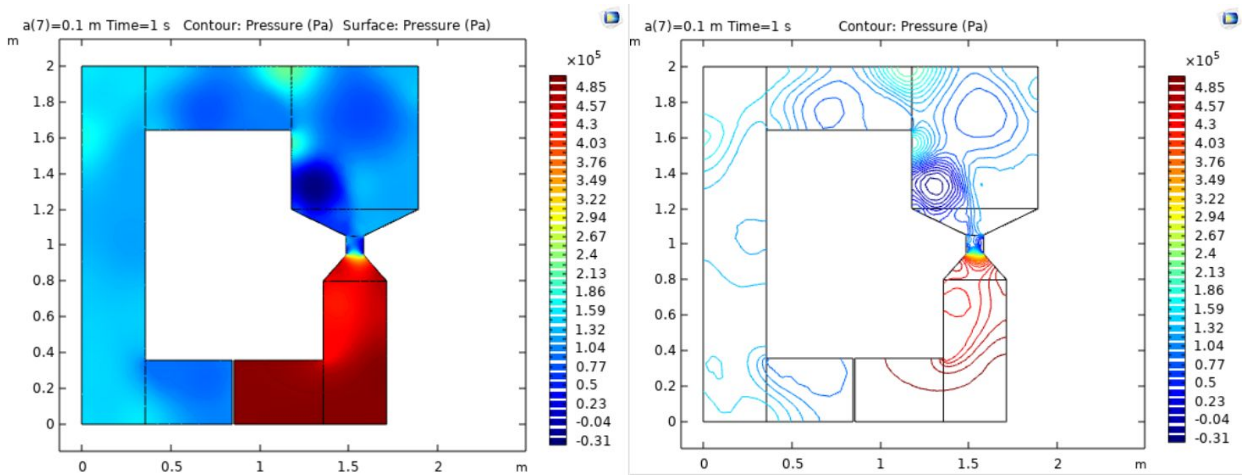


Figure 11 - Stage 4 2D simulation results showing the pressure distribution in the system

While this simulation does correctly show the movement of the fluid and how pressure is distributed in the system it cannot be used to find out how long it takes for the temperature of the fluid to reach 70°C. This is because this simulation is non-periodic (i.e. the same fluid does not recirculate). For this simulation to be able to track heat transfer over time it would have to have been periodic and time-dependent.

10.0 Simulation Results

10.1 COMSOL Calculations

Heat Transfer in fluids

The equation below was used within the COMSOL model to study the heat transfer properties of the liquid within the system. This equation takes into account the continuous addition of energy provided by the pump. In order to simplify the simulation, a perfectly insulated system was assumed, meaning that no heat was dissipated from the machine. Since heat was being supplied, but not exiting the system, the temperature would keep rising, and steady-state would never be achieved. Since one of the parameters at the time was to bring the pomace to 70 degrees celsius, only the time needed to reach this temperature was needed.

$$d_z \rho C_p \frac{\partial T}{\partial t} + d_z \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = d_z Q + q_0 + d_z Q_p + d_z Q_{vd}$$

$$\mathbf{q} = -d_z k \nabla T$$

Variable list:
Rho = Density (kg/m^3)
Mu = Dynamic viscosity (Pa*s)
K = Thermal conductivity (W/(m*K))
Cp = Heat capacity at constant pressure (J/(kg*K))
T = Temperature (K)
q = Heat Transfer (W)
Qp = Pressure work (J)
Qvd = viscous dissipation (W/m^3)

Turbulent flow

Unfortunately, limited access to COMSOL software as well as the necessary computing power made it impossible to simulate the turbulent flow which would occur within the machine. If possible, we would have used the following formulae to study the pomace flow. This would have been able to provide a visual representation of both the fluid flow around the machine as well as the exact location where cavitation would occur. The simulation also would have been able to show how cavitation was affecting the viscosity of the liquid, and would continuously change until the solution was homogeneous, simulating more precisely what this machine is designed to accomplish.

$$\rho\frac{\partial \mathbf{u2}}{\partial t} + \rho(\mathbf{u2}\cdot\nabla)\mathbf{u2} =$$

$$\nabla\cdot\left[-p2\mathbf{I} + (\mu+\mu_T)\left(\nabla\mathbf{u2} + (\nabla\mathbf{u2})^T\right)\right] + \mathbf{F}$$

$$\rho\nabla\cdot(\mathbf{u2}) = 0$$

$$\rho\frac{\partial k2}{\partial t} + \rho(\mathbf{u2}\cdot\nabla)k2 = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k2\right] + P_k - \rho\epsilon$$

$$\rho\frac{\partial \epsilon}{\partial t} + \rho(\mathbf{u2}\cdot\nabla)\epsilon = \nabla\cdot\left[\left(\mu + \frac{\mu_T}{\sigma_\epsilon}\right)\nabla\epsilon\right] + C_{\epsilon 1}\frac{\epsilon}{k2}P_k - C_{\epsilon 2}\rho\frac{\epsilon^2}{k2}, \quad \epsilon = \mathrm{ep2}$$

$$\mu_T = \rho C_\mu \frac{k2^2}{\epsilon}$$

$$P_k = \mu_T\left[\nabla\mathbf{u2} : \left(\nabla\mathbf{u2} + (\nabla\mathbf{u2})^T\right)\right]$$

Variable list:
u = velocity field (m/s)
Rho = density (kg/m^3)
P = pressure (kPa)
k = Turbulent kinetic energy (m^2/s^2)

mu = Dynamic viscosity (Pa*s)
F = force (N)
Ce, e, sigma = parameters

Laminar Flow

Unfortunately, since turbulent flow could not be studied at the present time, only the following laminar flow, see equation below, was used in our simulations. While it could not take into account cavitation, it was able to give a visualizational aid to better understand the flow through the system. More specifically, flow velocity was calculated throughout the machine, giving a better understanding of the positioning of the mass throughout the machine. Laminar flow also allowed us to visualize where the highest and lowest pressures would occur within the system.

$$\rho\frac{\partial \mathbf{u}}{\partial t} + \rho(\mathbf{u}\cdot\nabla)\mathbf{u} =$$
$$\nabla\cdot\left[-p\mathbf{I} + \mu\left(\nabla\mathbf{u} + (\nabla\mathbf{u})^T\right)\right] + \mathbf{F}$$
$$\rho\nabla\cdot(\mathbf{u}) = 0$$

Variable list:
Rho = density (kg/m^3)
Mu = dynamic viscosity (Pa*S)
u = velocity field (m/s)
F = force (N)
l = length (m)

10.2 Obtained results

Fluid Temperature

One of the objectives of our simulation was to figure out how long it would take our pomace to reach an average temperature of 70°C since energy was being continuously added by the pressure of the pump, and we were assuming that our machine was perfectly insulated (so no heat was lost). In Stage 3, we were able to observe the temperature change in the fluid over time. By analyzing the extracted data, we found that it would take 760 seconds or 12.67 minutes for the average temperature of the fluid to reach 70°C (see APPENDIX 6 for time versus temperature data). This was much faster than we had anticipated. However, since the simulation was not fully functional, there are multiple explanations for why the fluid heated up so quickly.

It is possible that the simulation correctly delivered the amount of heat a pump would release while pumping pomace at the specified rate and pressure. If this is the case, then the originally assumed cycle time would have to be lowered from one hour to around or below 12 minutes. However, since Stage 3 was unable to simulate the movement of the fluid, it is also possible that the energy that the fan was supposed to be utilizing to move the fluid was just being released as heat into the fluid instead. In this case, in reality, the fluid would increase in temperature much faster as most of the pump's energy would be going towards moving the fluid.

Pressure at and after Cavitation Orifice

Using the simulation from Stage 4, we performed a parametric sweep of the diameter of the cavitation orifice in order to see how the pressure at and after the cavitation orifice. In theory, the most effective cavitation of the pomace would occur when the pressure difference between the cavitation orifice and after the cavitation orifice is the largest since cavitation is caused by an abrupt change from high pressure to low pressure.

The parametric sweep was performed on diameters from 4 cm to 10 cm with a step of 1 cm. This range was chosen because we thought that anything larger than 10 cm would not create a drastic enough change in diameter when compared to the piping before and after, and anything smaller than 4 cm would be too small to allow food chunks to pass through early on in the cycling process (especially if the machine is being used for carrot stems) and would increase the risk of clogs. Unsurprisingly, the smallest diameter of 4 cm caused the largest pressure at the cavitation orifice at 423637 Pa, with the pressure dropping as the diameter increased (see Figure 12, first graph). The smallest pressure after the cavitation orifice was obtained at 8 cm with the two extremes, 4 cm and 10 cm, having the largest pressures after the diameter with pressures of 86725 Pa and 85151 Pa respectively (see Figure 12, second graph). However, the largest difference between the pressure at the orifice and after was achieved with a diameter of 4 cm with a pressure difference of 336912 Pa (see Figure 13).

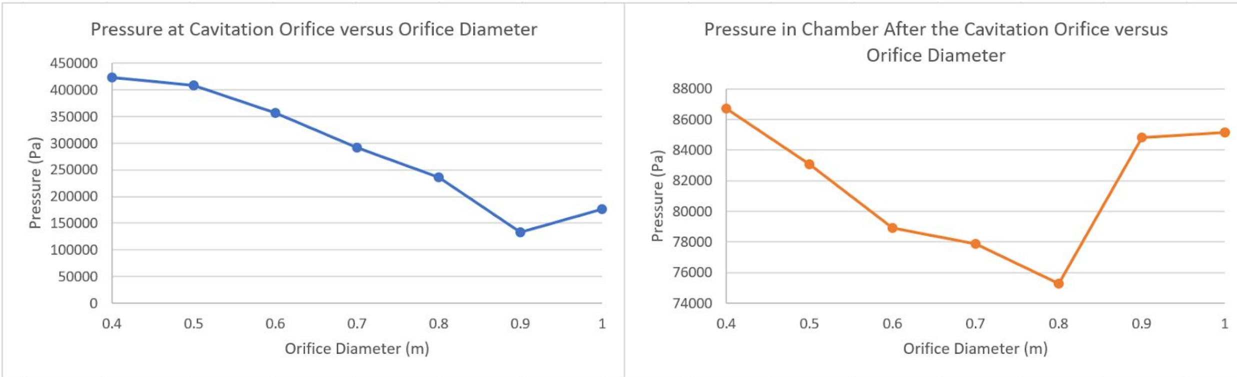


Figure 12 - Comparison of pressures for different orifice diameters at the cavitation orifice (first graph) and in the large chamber following (second graph) (see APPENDIX 7 for exact values)

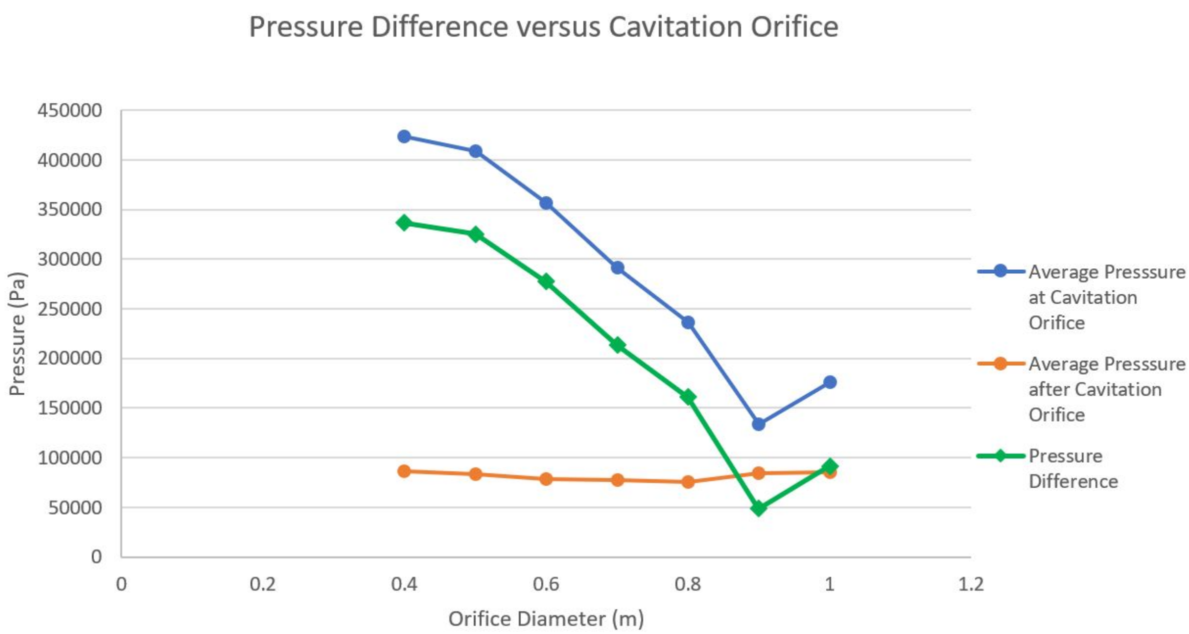


Figure 13 - Comparison of pressure differences between the cavitation orifice and the large chamber following for different orifice diameters (see APPENDIX 7 for exact values)

10.3 Limitations

In section 9.4 (Stage 3), we were unable to use turbulent flow. To briefly summarize the difference in both flows, laminar flow is characterized by having negligible mixing of fluids, therefore the fluid is smooth and noiseless, whereas turbulent flow is characterized by the mixing of fluid particles, resulting in the motion of a given particle being random and irregular (Potter & Wiggert, 2007). Cavitation can only occur in turbulent flow (Moholkar & Pandit, 1997), and due to insufficient computing power, we could not implement this factor into our simulation. Without turbulent flow, the pomace is not broken down, so the viscosity of the fluid in the simulation never changes and we essentially just have a system with the same fluid running through it over and over again without a change in viscosity. Furthermore, the lack of turbulent flow might also have been the reason that maximum pressure was never at the cavitation orifice in our simulations.

Furthermore, when we installed a pump in Stage 3, the fluid seemed to have become stagnant (no sign of fluid flow). Since the flow was not moving, it calls into question the accuracy of our temperature over time results. It is also possible that the energy that the fan was supposed to be utilized to move the fluid was just being released as heat into the fluid instead. In this case, the fluid would increase in temperature much faster as most of the pump's energy would be going towards moving the fluid. If this is the case, our results for how long it would take to the fluid to increase in temperature would all be flawed.

Lastly, during the Stage 4 simulation trials, the pressure simulation was steady-state. In order to create a time-dependent simulation where the pomace would recirculate through the system repeatedly, we needed to make the system periodic. COMSOL did not allow a periodic simulation to have a continuous influx of heat, as is the case for the high shear pump. As the cycle repeats itself multiple times, in theory, the mixture should heat up from both the energy of the pump and at the point of cavitation. It was necessary to calculate the heat flux in order to find the amount of time it takes to reach temperatures of pasteurization (discussed in section 2.0 of this report).

10.4 Final Recommendations

As was already stated above, the models that were developed were flawed in many ways. However, we can still offer design suggestions with the obtained results.

We suggest that the cavitation orifice have a diameter of 4 cm because it creates the largest difference in pressure between the cavitation unit and the large chamber following it. Since we were unable to test how the viscosity of the fluid changes along the course of the cycles, we can not know if a diameter of 4 cm will create adequate pressure for the pomace to be turned into a fine powder. If it is the case that a diameter of 4 cm cannot turn pomace into a powder, we suggested using a cavitation unit with a smaller diameter because, based on our data (see Figure 13), it seems like the smaller the diameter, the larger the pressure difference. However, it should be kept in mind that the diameter chosen should allow the largest chunks of pomace to pass through.

We had originally assumed that a full run time of the machine would be around an hour. However, based on the results obtained in Stage 3, this run time might need to be changed. Even though it is very likely that the Stage 3 results are flawed, we still suggest that the run time of the machine be reduced to 12 minutes in order to be completely sure the temperature of the pomace stays below 70°C, thus ensuring the phytochemicals are not destroyed. Since the run time, and thus the number of cavitation cycles has been drastically reduced, the pulverization happening during each cycle should be maximized for there to be adequate results. Since this means that cavitation needs to be increased, this further backs up the above recommendation about using the diameter that causes the largest pressure difference.

The testing that was conducted here was subject to time constraints and software and material limitations. In order to more accurately determine the parameters for ideal results, we recommend that more testing is needed. This product has the potential to drastically reduce the amount of food waste created by the juice industry if the necessary time and resources are put into making it a reality.

APPENDIX 1 - Design Parameters

Parameters of our Design		
Machine		**Source**
Operating Temperature °C	80	Our decision
Pump Outlet pressure (kPa)	500	(Osipenko et al., 2009)
Processing Time (s)	3600	(TEKMASH, 2019)
Cycles per hour	300	(Osipenko et al., 2009)
Mass flow rate (kg/s)	8.333333333	Calucated
Volume flow rate (m3/s)	0.008333333333	Calucated
Total pipe distance (m)	4	Our decision
Velocity of pomace (m/s)	0.3333333333	Calculated
Area_cs of pipes (m^2)	0.025	Calculated
Diameter of pipes (m)	0.178412487	Calculated
Pomace		
Absolute Viscolsity (cP)	1000	(Saravacos, 1970)
Mass per cycle (kg)	100	Our decision
Density (kg/m3)	1000	(Bifani et al., 1994)
Thermal Conductivity (J/kg.K)	600 at 20°C	Estimated from water
Heat Capacity (mW/m.K)	4179.6	Estimated from water
Ratio of Specific Heat (i.e. cp/cv)	1	Estimated from water

APPENDIX 2 - STUDENT FOUND PUMP DATA

(M. Fortin, personal communication, March 28th, 2019)

Pump Data Sheet - Fristam Pumps USA

Company:
Name:
Date: 03/28/2019

Fristam PUMPS®
Engineered For Lasting Performance™

Pump:

Size:	FSI 3542	Dimensions: Suction:	3 in
Type:	FSI	Discharge:	2.5 in
Synch Speed:	3600 rpm		
Dia:	159 mm		
Curve:	---		

Fluid:

Name:	Water		
SG:	1	Vapor Pressure:	0.256 psi a
Density:	62.4 lb/ft³	Atm Pressure:	14.7 psi a
Viscosity:	1.1 cP		
Temperature:	60 °F		

Pump Limits:

Temperature:	400 °F	Sphere Size:	---
Wkg Pressure:	---	Power:	50 hp

Search Criteria:

Flow:	132 US gpm	Near Miss:	---
Head:	73 psi	Static Head:	0 psi

Motor:

Standard:	NEMA	Size:	60 hp
Enclosure:	TEFC	Speed:	3600 rpm
Frame:	364TS		
Sizing Criteria:	Max Power on Design Curve		

Pump Selection Warnings:

Design curve maximum power exceeds limit for the pump.

--- Duty Point ---

Flow:	149 US gpm
Head:	92.8 psi
Eff:	24.9%
Power:	32.1 hp
NPSHr:	---
Speed:	3500 rpm

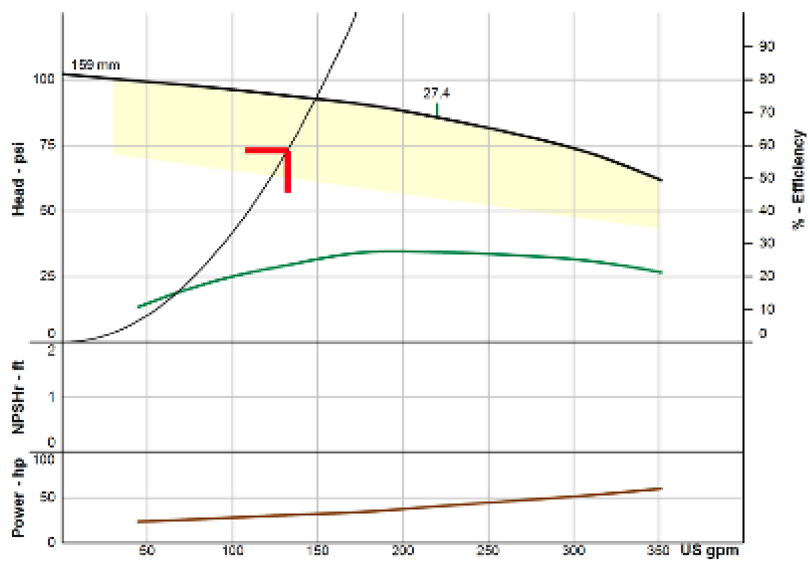
--- Design Curve ---

Shutoff Head:	102 psi
Shutoff dP:	102 psi
Min Flow:	22 US gpm

BEP: 27.4% @ 220 US gpm
NOL Power:
59.7 hp @ 352 US gpm

--- Max Curve ---

Max Power:
59.7 hp @ 352 US gpm



Maximum Inlet Pressure is 150 psi.

Performance Evaluation:

Flow	Speed	Head	Efficiency	Power	NPSHr
US gpm	rpm	psi	%	hp	
158	3500	92.1	25.7	32.8	---
132	3500	94	23.5	30.8	---
106	3500	95.8	20.5	28.6	---
79.2	3500	97.5	16.8	26.4	---
52.8	3500	99.1	12.3	24.4	---

Selected from catalog: Fristam Pumps.60, Vers 7.3.2

APPENDIX 3 - ASME Standards for Grade 304 Stainless Steel

(ASME B31.3 Process Piping Guide)

Piping Specification 202 Date: March 16, 2009 Revision: 0 Page 1 of 2

Design Parameters

P-Spec	PS-202(A, B, C, D)						
Design Pressure (psig)	600	505	455	415	380	360	350
Design Temperature (°F)	100	200	300	400	500	600	650
Minimum Temperature (°F)	-425	-425	-425	-425	-425	-425	-425
Minimum Test Pressure (psig)	900	760	680	660	645	645	640
Maximum Test Pressure (psig)	935						

Calculation Reference:	00-00-CALC-M-0004-R0
Code of Reference:	B31.3 - 2002
Fluid Service:	Normal
Material:	Stainless Steel (304L)
Pressure Rating:	Class 300
External Pressure Rating:	15 psi

General Notes

Refer to General Notes 1-12, 16.

Allowable Pipe Materials

Component	Size	Rating	Standard	Material	Material Grade	Additional Requirements
Piping	¼ - 12	Schedule Tables	ASME B36.19	ASTM A312	TP 304L	Welded
Piping	¼ - 12	Schedule Tables	ASME B36.19	ASTM A312	TP 304L	Seamless

Required Schedules for Non-Threaded Pipe

P-Spec	Corrosion Allowance	Pipe Size	¼	½.	¾	1	1 ½	2	2 ½	3	4	6	8	10	12
A	0.00	Schedule	10S	10S	10S	10S	10S	10S	10S	10S	40S	40S	40S	40S	40S
B	0.03	Schedule	10S	10S	10S	10S	10S	40S	40S	40S	40S	40S	40S	40S	40S
C	0.05	Schedule	80S	40S	40S	40S	40S	40S	40S	40S	40S	80S	40S	40S	80S
D	0.08	Schedule	-	80S	80S	80S	80S	80S	80S	80S	80S	80S	40S	40S	80S

Required Schedules for Threaded Pipe

P-Spec	Corrosion Allowance	Pipe Size	¼	½	¾	1	1 ½	2	2 ½	3	4	6
A	0.00	Schedule	40S	40S	40S	40S	40S	40S	40S	40S	40S	80S
B	0.03	Schedule	80S	80S	80S	80S	80S	80S	80S	80S	80S	80S
C	0.05	Schedule	-	80S	80S	80S	80S	80S	80S	80S	80S	80S
D	0.08	Schedule	-	-	-	-	-	-	-	80S	80S	80S

Fittings

Component	Size	Rating	Standard	Material	Material Grade	Additional Requirements
Socket-Weld Fittings	¼ - 2	3000#	ASME B16.11	ASTM A182	F304L	
Threaded Fittings	¼ - 4	2000#	ASME B16.11	ASTM A132	F304L	
Buttweld Fittings	½ - 12	Schedule Tables	ASME B16.9	ASTM A403	WP304L	
Buttweld Fittings	½ - 12	Schedule Tables	ASME B16.28	ASTM A403	WP304L	

Flanges

Component	Size	Rating	Standard	Material	Material Grade	Additional Requirements
Socket-Weld Flange	½ - 2	Class 300	ASME B16.5	ASTM A182	F304L	
Weldneck Flange	½ - 12	Class 300	ASME B16.5	ASTM A182	F304L	
Slip-on Flange	½ - 12	Class 300	ASME B16.5	ASTM A182	F304L	
Blind Flange	½ - 12	Class 300	ASME B16.5	ASTM A182	F304L	
Threaded Flange	½ - 6	Class 300	ASME B16.5	ASTM A182	F304L	
Backup Flange	½ - 12	Class 300	ASME B16.5	ASTM A105	N/A	Min Temperature - 20°F, See note 8
Backup Flange	½ - 12	Class 300	ASME B16.42	ASTM A395	N/A	Min Temp. - 20°F, Max. Temp. 650°F, See note 8

Mechanical Fasteners

Component	Size	Standard	Material	Material Grade	Additional Requirements
Fasteners	½ - 1 ⅛	ASME B18.2.1	ASTM A193	B8 Cl. 2-HH	Min Temperature - 325°F, See Note 10
Nuts	½ - 1 ⅛	ASME B18.2.2	ASTM A194	8F-HH	

APPENDIX 4 - Risk Matrix

Possible Risk	Level of risk L=Low M=Medium H=High	Cause	Risk Mitigation/Control
Microbial Contamination	M	- Supply-Chain (i.e. pesticide residue, moulds/fungi) - Improper cleaning (i.e. Accumulation of food in system)	- Supply-Chain controls - Follow proper codes and standards for cleanliness as shown in section 8.0 - Carry out cleaning procedure, similar to the example shown in section 8.1
Pressure build up (burst pipes)	H	- Excessive pressure in the cavitation unit - Obstructed pipe	- Pressure relief valve - Pressure gauges - Making sure the pipes are clear of any obstruction by cleaning them on a regular basis
High shear pump	M	- Malfunction (mechanical and/or electrical) - Entanglement	- Easily accessible for maintenance - Control box - Safety kill switch in case of emergency.

APPENDIX 5 - CLIENT FOUND PUMP DATA

Page 1 of 3

QUADRO *Leading Process Equipment Innovation*

QUADRO YTRON HV SERIES QUOTATION

QUOTE ID:	**QL190534**
DATE:	**5/27/2019**
EXPIRY:	**7/11/2019**

Quadro Engineering Corp. ("Quadro") proposes to sell to University of Guelph ("Purchaser") the following equipment at the price and on the terms and conditions set forth in this Quote. The equipment quoted is based on the requirements Purchaser specified to Quadro and is generally in accordance with the accompanying Sketch Number : QD-HV1-00-02000

Base Model	Description	Quantity
Size	HV1 Wet Mill & Emulsifier	1
Mechanical Seal	Double mechanical seal – (SiC/C with FDA Viton elastomers). Requires 1-2 L/min of cooling fluid (end user to supply), includes interlocked flow switch connected to the VFD to ensure protection of the seal.	
Construction		
Elastomers	FDA Viton	
Contact Parts	316 SS	
Non-Contact Parts	304 SS	
Surface Finish		
Contact Parts	150 grit (42 Ra) contact surface finish with welds ground flush and polished	
Non-Contact Parts	Non-contact surfaces welds as laid and bead blast finish	
Housing	Housing assembled with quick connect clamps	
Connections		
Liquid Inlet	Two, 1.5" (38 mm) TC	
Outlet	1.5" (38 mm) TC	
Drive	High Speed poly-chain synchronous belt	
Rotor Speed	Variable Tip Speed up to 70 m/s, 9000 RPM	
Motor	25HP, TEFC MOTOR, c/w white epoxy coating (3600RPM for 60Hz, 3000RPM for 50Hz)	
Voltage Source	480 V, 3 Phase, 60 Hz	
Drip Cap for Motor	Drip Cap Included	
VFD	VFD ABS Plastic - 25HP , NEMA 4X mounted on a push bar (Bead Blast)	
Base	304 SS base (Bead Blast finish), with two (2) 4" Swivel/Brake Casters, two (2) 4" Rigid Casters	
Tooling		
Progressive (3.0/0.5)	Rotor - 316 SS, 150 G	
Progressive (3.0/1.5/0.5)	Stator - 316 SS, 150 G	
Documentation	One English Owner's Manual (USB)	
Packaging	Wrapped in plastic for added protection, crated in sea-worthy crate.	

NET PRICE	***Free Carrier(FCA) Waterloo, Ontario, Canada***	**CDN $ 65,660.00**
Estimated Lead Time	*After Receipt of Approval*	**10 Weeks**

613 Colby Drive, Waterloo, Ontario, Canada N2V 1A1 T(519)884-9660 F(519)884-0253
90 Glacier Dr., Suite 1000, Westwood, MA 02090 T(519)884-9660 F(519)884-0253

APPENDIX 6 - TEMPERATURE INCREASE OVER TIME DATA

(full Excel spreadsheet available upon request)

% Time (s)	Temperature (degC)		% Time (s)	Temperature (degC)
0	20.00047344		753	69.51444221
1	20.06622904		754	69.58019781
2	20.13198465		755	69.64595341
3	20.19774025		756	69.71170901
4	20.26349585		757	69.77746462
5	20.32925145		758	69.84322022
6	20.39500706		759	69.90897582
7	20.46076266		760	69.97473142
8	20.52651826		761	70.04048703
9	20.59227386		762	70.10624263
10	20.65802947		763	70.17199823
11	20.72378507		764	70.23775383
12	20.78954067		765	70.30350944
13	20.85529627		766	70.36926504
14	20.92105188		767	70.43502064
15	20.98680748		768	70.50077624
16	21.05256308		769	70.56653185
17	21.11831868		770	70.63228745
	...		771	70.69804305

APPENDIX 7 - PRESSURE VS. ORIFICE DIAMETER DATA

(full Excel spreadsheet of time-dependent data available upon request)

	Average Pressure after Steady State			
Diameters (m)	At Orifice	After Orifice	Difference (Pa)	Largest Difference (Pa)
0.4	423637.47	86725.33081	336912.1424	336912.1424
0.5	408472.47	83047.25078	325425.2193	
0.6	356258.46	78922.23176	277336.2239	
0.7	291201.69	77874.15665	213327.5348	
0.8	236167.04	75258.71372	160908.3224	
0.9	133681.18	84827.8537	48853.32813	
1	176578	85151.42386	91426.57262	

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