University of Bath

Department of Chemical Engineering

Centrifugal Separator
Individual Unit Design

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AUTHORSHIP DECLARATION

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Executive Summary

Background

The extraction of casein from milk was first documented in the 1860's using acid precipitation. Upon analysis, the protein was identified as different to those known at the time. Whilst this would be coined 'casein', the remaining liquid after precipitation was described as 'whey', a solution containing proteins, salts, vitamins, lactose and other minerals. The first infant formula was created at this time as the health benefits of casein were slowly realised. Cow's milk-based formulas quickly gained the interest of the public in Europe. This paved the way for Eugene Sandow, who was given the title of the 'godfather of modern bodybuilding', to release one of the first protein supplements on the market. 'Sandow's Strength and Health Cocoa' contained both whey and casein but did not gain enough attention until the rise of bodybuilding culture grew in the 1980's, with large brands appearing on the market, one being Met X. This first protein supplement presented was marketed first in 1911 in London.

The fractionation process is the modern way to produce Whey and Casein powder supplements, as this process is the only one that can keep up to the growing demand in supplements and produce them at a high quality that the consumers demand. This process involves the extraction of raw milk from cows and transferring it safely to the plant without spoiling the milk. The milk is then directed to a HTST pasteuriser, where the microbials that are harmful to human health after digestion are eliminated. It is then transported to the centrifugal separator which is used to separate the fat from milk based on their molecular size and centrifugal forces. Casein micelles are then separated with a microfiltration setup which has comparatively large pores compared to the size of whey and lactose particles letting them pass through. The whey and lactose then proceed to an array of ultrafiltration membranes, where the whey is separated off to be spray dried, whilst the heavily diluted lactose is sent to wastewater treatment. The fractions in milk can also be separated through enzymatic hydrolysis, which uses enzymes to coagulate the milk and enables liquid whey to be separated from solid casein curd.

Process Overview

The main raw material of the process is unpasteurized milk, which is first pasteurized to EU standards to remove bacteria and viruses within the milk. The fat within the milk is a sellable side product within the process and would heavily foul the subsequent separation membranes due to its large molecular size. A centrifuge is utilised to separate the fat from the milk using the density difference between the fat and the rest of the milk, producing skimmed milk and a cream product. This centrifugal separation step is what this design project is focused on in the greater fractionation process to produce Whey an Casein Powder. From here the skim milk stream produced in the separator is directed to microfiltration and ultrafiltration to remove the Whey and Casein micelles from the lactose permeate, where the retentate streams are Casein micelles after microfiltration and Whey after ultrafiltration, as these molecules are too large to pass through the pore of the microfiltration and ultrafiltration steps. The Whey and Casein are then processes in an evaporator and dryer to produce the final product of Whey and Casein protein supplements.

To gain a brief understanding of how the fractionation process works, a Block Flow Diagram is produced. From here, it is easy to locate and visualise where the Tetra Pak H80 centrifugal separator lies in the milk fractionation process to produce Whey and Casein Protein supplements, which is labelled as Figure 1 below:

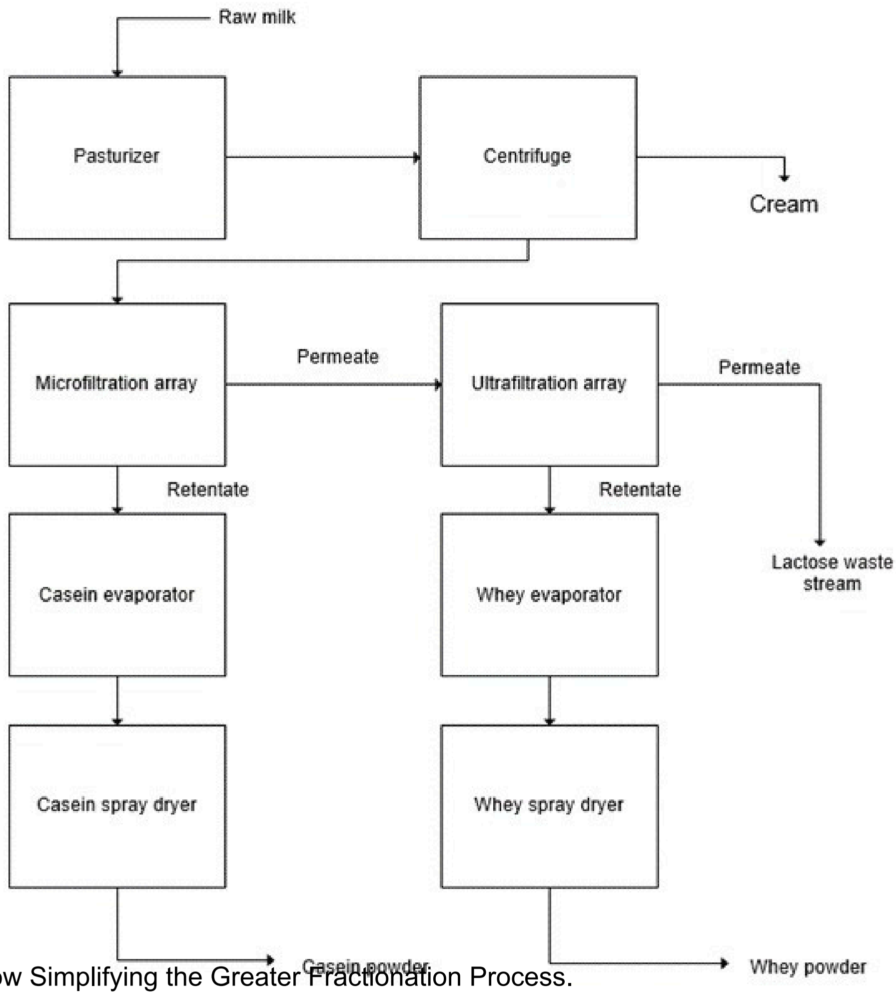


Figure 1: Flow Simplifying the Greater Fractionation Process. Block Diagram

This design project primary focuses on the Tetra Pak H80 centrifugal separator and the CIP system put in place to efficiently clean and sanitise the inside of the separator and its components. This unit uses centrifugal forces to separate particles using their respective specific gravities, to force the particles outwards from the centre of the unit. The lighter phase, cream, will settle closer to the centre and heavier phase particles, skim milk, will move outwards. The unit operates at 650 kPa and at a constant temperature of 50°C. It also requires 26.9 kW of energy to run at the given optimal temperature and pressure parameters. The centrifuge rotates at speeds between 6000 – 10000 RPMs depending on demand. The preliminary P&ID shows the general process and the respective streams, as seen in Figure 2. The P&ID essentially highlights and elaborates on the centrifuge step seen on Figure 1, to give an idea of how this process is undergone and which streams are desirable and undesirable, which are the skim milk and cream streams, respectively.

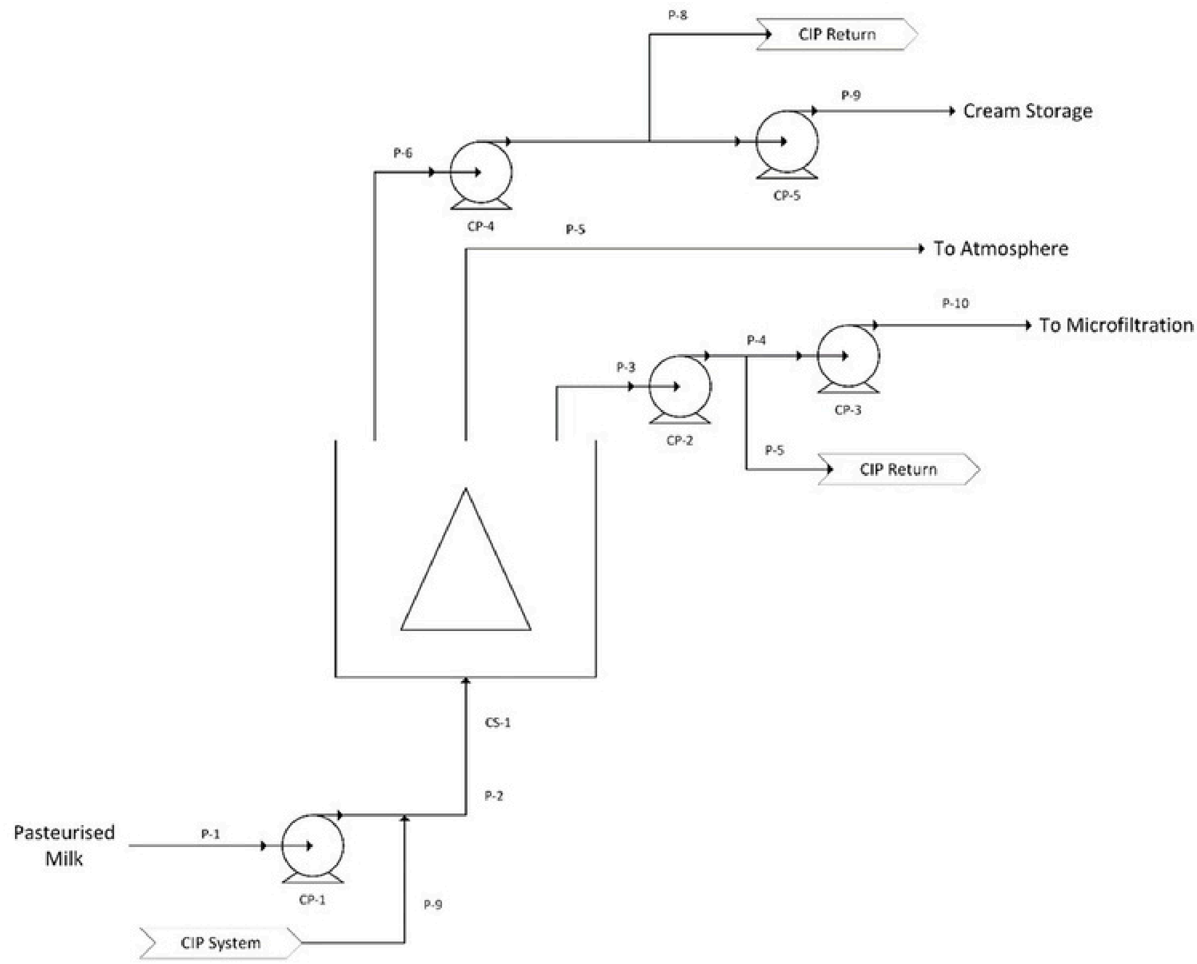


Figure 2: Preliminary P&ID for the Tetra Pak H80 separator displaying the respective streams. However,

in this design project, there was one specific part that stated to have minimal impact on the overall pressure drop, flowrate, energy and material balance, the sizing of the reactor and the OPEX (Operating Expenses). This was the discharge port on the Tetra Pak H80. The company Tetra Pak specialises in food and beverage processing, including dairy processing. In separation of milk, the separator also has a function which removes microscopic impurities which are the bacteria which may have survived the pasteurisation process or somatic cells, the discharge port essentially expels these contaminants from the milk, which are in minute amounts. Therefore, in this design, it was assumed that all of the bacteria and impurities were neutralised and killed, therefore there would be no need for a discharge port, which was another reason to overlook this extra factor, which already has negligible impact on the performance of the separator. Therefore, it is assumed that the pasteuriser neutralised 100% of these impurities, and the discharge port was excluded from the design calculations. This same approach was applied in the group project with the consent of other members, and was agreed upon as a team.

Energy Balance

It is stated in the data book for the Tetra Pak H80 that there is no heat exchanger in the separator, therefore there were no changes in temperature in the milk. It was heated to 60°C in the pasteuriser and cooled down to 50°C before entering the Tetra Pak H80 system. The basic assumptions were that it was steady-state system and neglecting any significant heat losses.

Material Balance

The material balance is performed with a pasteurised raw milk inlet rate of 61,800 kg hr-1, as this was stated by the datasheet of the Tetra Pak H80 that it was the flowrate in which the highest separation efficiency was achieved, around 95%. The outlet streams for skimmed milk, the desirable product, was

55,710 kg hr-1 and the cream stream, the undesirable yet profitable product, was 3090 kg hr-1. Key assumptions included in the material balance were steady-state operation and constant fat composition in the pasteurised milk stream

Unit Design

Tetra Pak H80 separator was chosen due to its efficiency in separation and ease of operation. It can skim milk up to rates of around 80,000 L hr-1. The design process choice abides by the guidelines set by the ASME (American Society of Mechanical Engineers) , to ensure that the unti designed can withstand the harsh conditions required for effective separation of milk and cream, while operating safely without posing a danger to the operator or personnel. The unit uses a bowl made from Super Duplex stainless steel to withstand corrosion and stress, as well as polynode discs to promote turbulence in the separator and allow for better mixing and separation. It also utilises grade 304H stainless steel, which has shown to be a promising material in many dairy processing applications. A self-cleaning CIP (Clean-In-Place) system was integrated to eliminate any sludge left in the bowl and pipes after separation. Also, Encapt technology, developed by Tetra Pak, was incorporated into the unit so that there is less friction in the separator, which then saves energy. The dimensions of this unit include an optimal liquid level of 1.129 m, height of 2.056 m, a width of 1.028 m, inlet diameter of 51 mm and outlet diameters of 12.2 mm for cream and 50.2 mm for skim milk and volume of 568.9 L.

Safety Considerations

Operator safety in the workplace is imperative for a safe process. Slips and trips are responsible for a large majority of workplace injuries, especially in dairy processes. A hazard identification system is to be implemented in the plant, supplemented by ongoing dialogue between staff regarding injury prevention. Through regular health and safety meetings, staff are to be frequently reminded of their responsibilities in maintaining a safe working environment; these responsibilities include the identification and removal of any hazards from the plant perimeters, as well as the immediate cleaning of any spillages and the use of wet floor signage to reduce risk of slips.

As a result of the harmful chemicals utilised in the cleaning of the system, it is imperative that effective leak prevention and detection is in place to minimise risk to operators. Swift detection can be achieved through the implementation of level gauges on all chemical storage tanks to detect abnormal level fluctuations.

This safety assessment of the unit was finalised with a LOPA (Layer Of Protection Analysis). This is essentially evaluation of potential hazards that could arise from numerous scenarios, identifying the probability of occurrence and summing up the multiple risk reduction factors derived from the PFD (Probability of Failure on Demand) of the IPLs (Independent Protection Layers) that were implemented to mitigate any chance of this hazardous event occurring. The company also has a risk tolerance, which the total risk reduction factor, which is calculated by summing up the inverse of the PFDs identified for the IPLs. The risk tolerance is determined by the company so that the total risk reduction factor can be compared to it. If the total risk reduction factor is within the acceptable range, then the IPLs are successful in mitigating the chances of a hazardous event from occurring. The company tolerable risk factor was lower than 106 yr-1. To this, the 3 scenarios were: seal failure, overheating of vessel and pipes and overpressure of vessel and pipes. These scenarios produced a total risk reduction factor of 21,200, 10,100 and 21000, which all lied in the companies tolerable risk, therefore, it was concluded that the countermeasures implemented into the system were successful in maintaining a safe working environment for the operators and the personnel.

The main objective of this project is to design a Tetra Pak H80 separator to be as efficient and reliable as possible when skimming milk during the whole fractionation process, and to minimise the downtime. The more specific objectives are:

- Finding the optimal design and process parameters for the Tetra Pak H80 to perform efficiently, specifically at around 95% separation efficiency.
- To assess the influence of the design of the Tetra Pak H80 on the product quality and the process efficiency.
- To make sure that the design calculations comply with the numerous codes, procedures and regulations in every step of the design of the Tetra Pak H80.

1.2. Tetra Pak H80 Separator

Centrifuges and separators play a key role in sustainable dairy processing (Huppertz, 2022). Tetra Pak Separator H80 is the chosen model of centrifugal separator for this process because of its ability for continuous operation meaning that production can remain constant and therefore a constant supply of whey and casein and consistent generation of revenue. It can process very high volumes of milk, where the maximum flowrate in the unit is 80,000 L hr-1. For this specific application, the Tetra Pak H80 utilises centrifugal forces to its advantage. The skimmed milk and cream have different densities, where the skim milk density is higher. Due to this density difference, the centrifugal forces acting on the fluids, will force the heavier fluid, the skimmed milk, outwards the outside of the bowl of the separator. On the other hand, the cream, being the lighter phase, settles nearer to the centre of the bowl radius. With this, the fat globules are separated into the skimmed milk with the help of the separation discs in the separator. The centrifugal force is generated by the motor rotating the separator at high RPMs, between 6000-10000 RPM (Tetra Pak Separator H80, 2020)

The separator will be the second stage from obtaining the raw milk in the fractionation process. The milk will arrive from the pasteuriser after the milk is treated with heat to eliminate any microbials that are harmful to the consumers. After this, the milk is directed to the inlet of the Tetra Pak H80, where the milk is skimmed using principles discussed before, where the cream is directed elsewhere for use, as the sales of cream can also contribute to the revenue made from the sales of products. The skimmed milk is then directed to the next stage after being reduced to the desired fat content of 0.01-0.05% (Chen, Lewis and Grandison, 2014). The stage that comes after the skimming is the removal of lactose via microfiltration.

The performance of the Tetra Pak H80 is vital for the efficiency of the overall fractionation process. An efficient separation process will increase the quality of the product at the end, as the cream removed will increase the concentration of Whey and Casein proteins in milk, and therefore increase the process yield of Whey and Casein powder final product. The influence of the separator will reach beyond just the skimming process, the fat content left over in the skim milk will affect the microfiltration and ultrafiltration steps as well as the spray drying, therefore and accurate and consistent separation means that there is predictability of the composition of milk in the following stages, which contributes towards optimization of the fractionation process. This will increase the profitability of the process plant as Whey and Casein can be obtained from them milk and will be at high quality if the Tetra Pak H80 is in optimal operation. This will also bring about a decrease in overall energy consumption of the fractionation process, as the separator requires high levels of energy to run uninterrupted for 8-hour shifts. Optimization of the flowrate into the separator will not only decrease the overall OPEX of the plant, but will also contribute to the environmental footprint and its sustainability.

1.3. Group Design Calculations – Review

Upon further assessment of the group project, it was found that the inlet flowrate calculations were incorrect. In the group project, the inlet of the Tetra Pak H80 was determined by the outlet flow from the HTST pasteuriser, which came out as 99,092.2 kg hr-1, which when converted to litres per hour, gives a value of 96,206.0 L hr-1. This is incorrect because the maximum flowrate allowed in the Tetra Pak H80 is 80,000 L hr-1 and does not have a capacity to handle this flowrate. In the tetra Pak H80 data sheet, it explicitly states that 80,000 L hr-1 is the maximum allowed flowrate through the separator, but also that the optimal flowrate was 60,000 L hr-1. For the objective of accurate designing of the separator, the inlet flow was changed to this, and therefore the outlet flow from the HTST pasteuriser should be adjusted to be as close to this value as possible.

The mass and energy balances were impacted due to the changes made to the group project calculations, the integration of the correct flowrate into the calculations affected other design parameters as well, mainly the separation efficiency and energy consumption. The re-evaluated calculations will provide for a more reliable and accurate design of the separator, which will improve the overall performance of the unit and the whole fractionation process. By incorporating the corrected values into the design, efficient milk fractionation is ensured and as a consequence, higher product quality will be achieved. Table 1: Comparison of the Tetra Pak H80 Parameters in the Individual and Group Projects

Parameter	Group Project	Individual Project	% Difference
Inlet Flowrate (kg hr-1)	99,092.2	61,800	46.6
Separation Efficiency (%)	95	95	0
Outlet Flowrate (kg hr-1)	Cream: 17985.2	Cream: 3090	141.4
	Skim: 81,107	Skim: 58710	32.0
Power (kW)	22	26.9	20.0
		Average	48

Several adjustments were made to the individual design of the Tetra Pak H80, these were based on the potential errors identified in the group design, the inlet flow rate for the unit was the main change made, which would be a reason for improved overall performance of the unit. This was necessary because looking at Table 1, the percentage difference between the individual design and the group design seems to be 48%, which is a significant amount that will affect the efficiency, performance and quality of product. Correcting the inlet flow was the first step in optimization, which will lead to more accurate design in sizing and determining optimal parameters for the skimming process. In conclusion, the individual project built upon the findings and errors in the group project by enhancing refining the design of the Tetra Pak H80 centrifugal separator.

2. Unit Design:

In this section, the detailed design considerations of the centrifugal separation process are analysed, along with the material and energy balances, operation, features and performance evaluation. The centrifugal separators purpose in the process is to separate the cream from the raw cow milk, to ensure a lower fat content in the Whey and Casein proteins extracted for producing baby formula and protein supplement. It does this by exploiting the difference in densities of the fat droplets in milk and the skimmed milk, centrifugal force is exerted onto the fluids and the fluids will move towards the outwards of the bowl if they have a higher relative density that other fluids in the separator. The unit of choice, the Tetra Pak H80 centrifugal separator was chosen as the ideal separator due its high efficiency and optimisation methods that was both calculated and provided by the company.

The way that the Tetra Pak H80 Separator operates, is to receive the milk from the previous pasteurisation process, where the microbes that are harmful to bodily functions are eliminated by heating up the milk to 60°C. Once the milk is in the separator, it goes up into the unit through a rotating hollow spindle, this helps to separate the light and heavy phases by exerting centrifugal force on the fluid. Once it enters the bowl of the separator, the centrifugal separation process begins. The unskimmed milk entering the bowl is then rotated at speeds of 6,000 – 10,000 RPMs, the centrifugal force will then act on the fluids, which will make the less dense fluid, the cream, to settle near the centre of the bowl, whilst more dense fluid, the skimmed milk, will be forced outwards of the bowl. The cream and milk will separate and flow between the disc stack in the separator and the separator will direct the separated cream and milk into 2 separate outlets. With the pressure gradient in the unit, the fluids are forced upwards and the cream settling in the centre will be directed to the outlet, the light phase outlet, situated in the top centre of the unit. Underneath this outlet will be a second one, which is the outlet for the skimmed milk, the heavy phase outlet. Before the outlets, there is a components called the rotating outlet pump, this allows for the direction of the fluid to the next stage of the production, the pump ensures that the phases are efficiently and continuously pumped out of the separator.

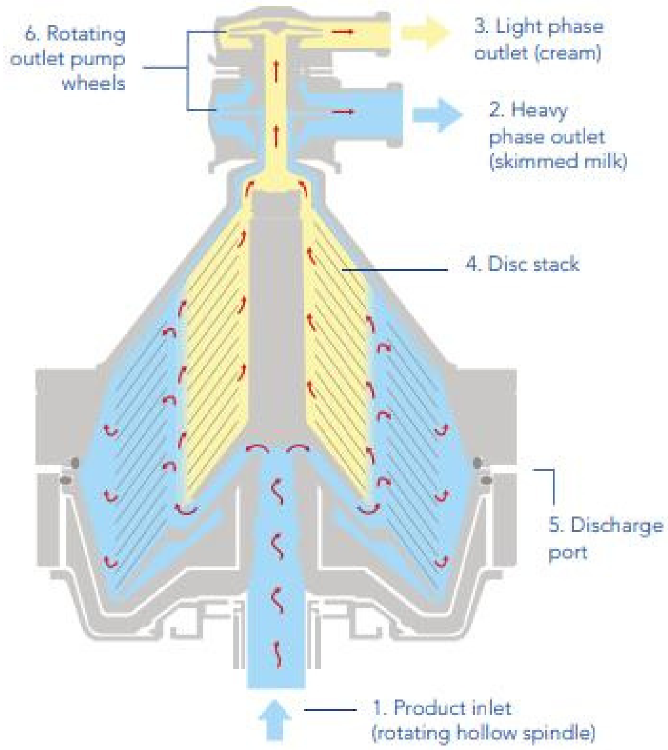


Figure 2: Diagram of a Tetra Pak H80 Separator showing direction of flow of heavy and light phase (Tetra Pak, 2020).

This specific model was chosen due to many factors that deem it superior to the alternative methods. Tetra Pak H80 separator is the latest model among centrifugal separators, which shows performance above alternative methods in milk skimming processes used by other industries. It is a hermetic, high-capacity separator that boasts significant advantages over alternative methods (Tetra Pak, 2021). However, there are also alternative separators of choice that could be considered and potentially have higher separation efficiencies, performance and costs. Some alternative methods used to skim raw, pasteurised milk are Open-type centrifugal separators, gravitational cream separation, microfiltration and flotation.

2.1. Alternative Options:

2.1.1. Open-Type Centrifugal Separators:

Open-type centrifugal separators are the same principle as Tetra Pak, where they utilise the centrifugal forces to separate fluids based on their density, however, the main difference is that they do not have closed bowls, or a chamber for a separation process. The milk will flow directly into the rotator and not directed by piping.

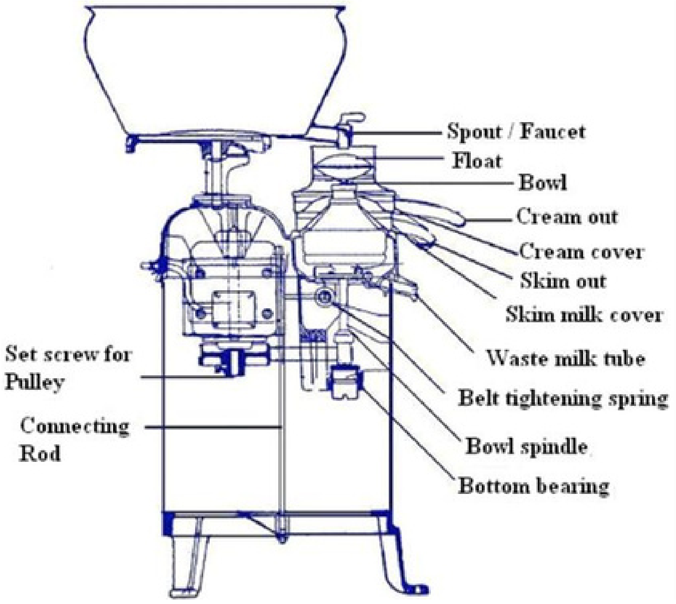


Figure 3: Diagram of Open-Type Centrifugal Separator (Dairy Engineering, 2012)

When comparing it to the Tetra Pak centrifugal separator, the first difference in components of each units is that the open-type is not hermetically sealed and these types of cream separators are fed by milk open to atmospheric pressure (Dairy Engineering, 2012). The problem with the open-type being exposed to atmospheric pressure means that there is a higher chance of contamination for the milk process, this in turn can lead to bacterial contamination, which can pose a health and safety threat to the consumer of the product. It can also reduce the quality of the product with other particulates in the air entering the system, therefore, this means that the open-type separation will require more maintenance to ensure safety and purity of the product, meaning the maintenance costs will increase with the use of this unit. Even though the upfront cost of the Tetra Pak H80 can be higher, in the long run, they offer better value due to the previous advantages already discussed. Compared to the Tetra Pak, the open-type separator's capacity is much smaller, with a capacity of 1000 L hr-1 (Dairy Engineering, 2012), whereas the Tetra Pak can handle up to 60,000 – 80,000 L hr-1 (Tetra Pak, 2021), meaning for a mass production and wholesale, the Tetra Pak separator can handle volumes that are required to meet the demand from the companies. This is because the Tetra Pak Centrifugal Separator is designed for high-capacity milk processing. It is stated Hermetic (closed) centrifugal separators offer several advantages over open-type separators, including improved efficiency and a lower risk of contamination (Tamime, 2009). The lower efficiency from the open-type, shows another disadvantage as to why it cannot be integrated into a mass production plant. Therefore, the Tetra Pak H80 separator performs better in every aspect, when comparing them in context of a Whey and Casein production plant.

2.1.1. Microfiltration:

This is an alternative separation process that is fundamentally different to the previous method, instead of utilising gravitational forces, it is defined as a membrane separation process used to remove the particles with an average molecular weight > 400kDa, using membranes with a pore size varying between the 0.05 and 10μm under an operating pressure of less than 2 bar (Ray, Singh and Polisetti, 2020). In the context of dairy processing, it is used for fractionating milk components such as proteins and fat globules, rather than separating the cream as a whole (Daufin et al., 2001). A Tetra Pak spiral wound membrane unto could be used, with the pore sixes are discussed earlier, the membrane element can be seen in a diagram, Figure 4, below:

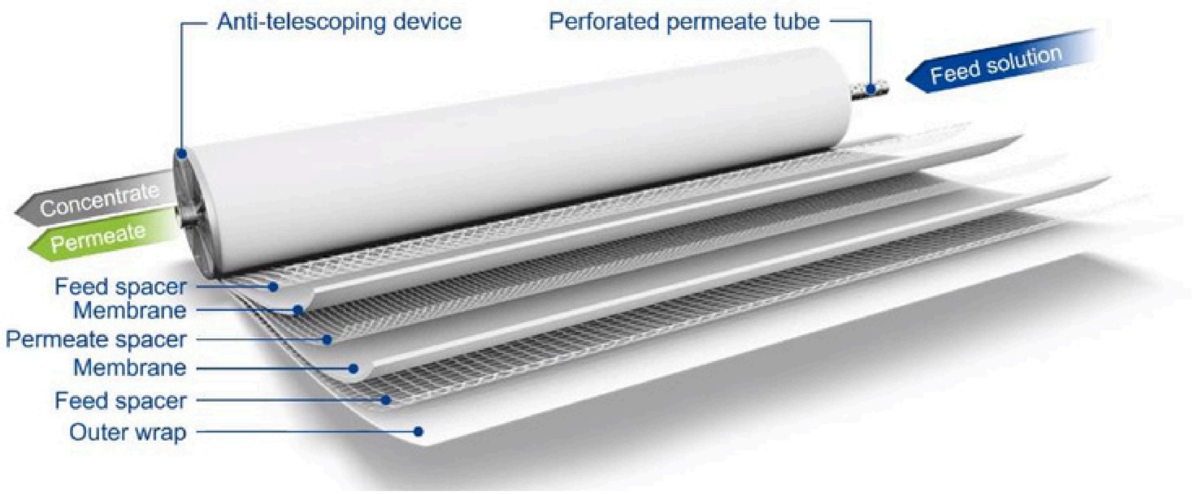


Figure 4: The construction of a Spiral wound membrane that can utilise microfiltration

In context of the milk skimming process, microfiltration operates under cross-flow conditions, where the milk will flow tangentially to the membrane surface. The transmembrane pressure (TMP) is the driving force that pushes the milk components through the membrane (Daufin et al., 2001) With this selective separation, it allows for smaller components of milk to pass through the membrane pores as permeate. These include proteins, lactose, minerals and water, while the fat globules and casein micelles will be collected as retentate once stripped from the smaller molecules. Unlike the Tetra Pak separator, it does not use the difference in densities of the molecules, but rather the size of them, to remove the cream from the milk.

The initial advantage that can seems more suitable for the skimming stage is the selectivity that the membrane brings to the process. With this selectivity, there is better control over the separation and therefore can allow for higher quality skimming of the milk. This in turn means that the final composition of the milk after skimming can be controlled and some optimisation can be undergone to increase the separation efficiency of the skimming process. Another advantage over centrifugal separation is the fact the milk components are less impacted. Microfiltration is a gentler process that preserves the native structure of proteins and fat globules (Daufin et al., 2001). Therefore, the probability of denaturation of the desired proteins are lower and maintains the quality of the product. Centrifugal separators apply centrifugal force onto the milk, this exposure to high shear forces induce high mechanical stress onto the protein, which can lead to disintegration of the protein structure. One possible explanation for this is that shear forces may cause the hydrophobic amino acid residues, which are usually buried within the protein structure, to become exposed to the aqueous environment (Morris, E., 2012). This makes the microfiltration seem more suitable for a dairy processing plant, however, there are setbacks as to why the Tetra Pak H80 centrifugal separator is better suited.

The one disadvantage that made it inferior to the centrifugal separation, is the lower separation efficiency. It can also be less time efficient, this is because it relies on the passage of milk components through a membrane (Daufin et al., 2001). The time inefficiency is not acceptable in mass production as the high volumes produced must be done in a reasonable time as to not lose trust from the customers, as well as producing it on time, it has to be at the quality ensured to the customer, therefore a lower separation efficiency is not going to benefit the process, and the quality of the product will not be high enough to be able to compete in the already competitive market. This in turn will mean less money is generated from the process. Microfiltration also has a higher investment cost. This is for the membrane systems and more frequent membrane replacements compared to centrifugal separators (Daufin et al., 2001). They have higher energy requirements to operate and maintain the TMP needed to force the milk through the membranes. For maintenance, there is a risk of fouling. Fouling is essentially an accumulation of the proteins and minerals on the membrane surface, eventually blocking the pores and reducing the separation efficiency. Eventually, fouling can lead to a decline in permeate flux, necessitating more frequent cleaning or replacement of the membranes (Gésan-Guiziou, G., et al., 1999). Membrane fouling can reduce the overall efficiency and performance of the filtration process, leading to increased processing time, reduced product quality, and increased costs associated with cleaning and replacing the fouled membranes (Gésan-Guiziou, G., et al., 1999; Marshall, A.D., 2004). Overall, microfiltration does bring a lot of useful properties, the main one being selective separation, and less mechanical stress induced onto the milk components. However, the Tetra Pak H80 does have higher performance, efficiency and lower costs, it also requires less maintenance and replacing of parts as the risk of fouling is not as high as it would be if the Microfiltration membrane was used.

2.1.2. Flotation:

This is a technique that utilises the differences in hydrophobicity of the particles suspended in a liquid medium. The idea behind the flotation method involves introducing air bubbles into the milk, causing the fat globules to attach to the air bubbles and rise to the surface where they can be separated (Morris, E., 2012). Unfortunately, this method is not common in industry and very rarely is used, however, the principle behind it makes it seem like an interesting option

The milk is pre-treated to make sure that it becomes homogenised and the large particles, which can interfere, are eliminated. From this, air bubbles are generated in the tank, where air is dissolved into the milk. With the help of pressure and diffusers, microbubbles are formed in the liquid in the tank Rubio et al., 2002). The bubble-particle interaction happens when the bubbles rising to the surface, attach to the hydrophobic surface of the fat globules, which can form clumps. The layer formed above the milk will be a cream layer, which can then be separated and extracted.

One of the advantages of this is the lower energy consumption, this is because the mechanism relies on natural forces of buoyancy of the air bubbles to separate fat globules, rather than high-speed centrifugal forces (Morris, E., 2012). However, the disadvantages outweigh the advantages once again.

One of which is the lower efficiency of the unit in terms of separation performance, as it may not be able to remove all fat globules effectively, leading to incomplete separation (Morris, E., 2012). This also means that there can be inconsistencies with the separation, as it may be hard to ensure a set range of values to give for a separation efficiency. This means that each batch produced can have more variation with purity between them, which can lead to lower quality product. This will mean that the process will fail to meet the demands to the customers at the required quality and will lead to less generated revenue for the company. Designing a flotation unit for a large-scale production is also not feasible and is not preferred in high-volume processing of milk. On the other hand, the Tetra Pak H80 is able to process the high volumes required to produce the required amounts of Whey and Casein powder that is demanded by the customers. With the flotation separation system, the process is very sensitive and the temperature, composition, pH, etc can easily affect the bubble-particle attachment and separation efficiency (Rubio, J., Souza, M.L., and Smith, R.W., 2002). The Tetra Pak separator however, has controlled conditions, with control systems to maintain the temperature, pressure and flowrate within the unit, ensuring that the separation efficiency is consistent and high and if affected by any change in the system, can counter the change and return to the required conditions for the highest quality milk possible from the unit.

2.1.3. Gravitational Cream Separation:

This is a process that also utilises gravity to achieve separation of fat globules from milk, it is a physical process much like centrifugal separation. It can occur naturally When milk is left undisturbed, the cream, which contains a higher concentration of fat globules, will rise to the surface due to buoyancy (Deeth and Lewis, 2017). This process can also be accelerated using centrifugal force, as this process would take longer if left under the influence of only gravitational force. This is because in centrifugal or cyclone separators, centrifugal forces act on a droplet at a force several times greater than gravity (Joseph, 2017). It is also stated that the process is slower, less efficient, and has a lower yield compared to the Tetra Pak H80 separator (Kessler, 2002).

One of the few advantages that makes gravitational separation appealing is its ease of operation and maintenance. The simplicity that comes with the gravitational separation is the fact that it relies purely on natural forces to achieve separation, this would be good for small-scale farmers that would want to produce and manage their own product at their own desired pace. However, in a mass production business, the demand needs to be met consistently and with a reasonable quality and time. The lower cost of the unit overall could also seem appealing to the producer, as it requires less equipment and lower energy input than centrifugal separation, making it a more cost-effective option for small-scale operations (Ghosh and Mehla, 2013).

Unfortunately, the flaws of this method are greater than the benefits that it could bring to the fractionation process of milk, the main disadvantage of this unit is the efficiency of the separation. Gravitational separation takes much longer than centrifugal separation to achieve the same quality, this is not a factor that can be overlooked as meeting the demand is key to generating revenue from the plant. The process is also a manual one, there are no control systems in place or not accurate value for the separation efficiency therefore the separation may be inconsistent. Therefore, the cream obtained through gravitational separation might be inferior to that obtained through centrifugal separation. The cream obtained through gravitational separation often has a higher fat content variation and may not be as homogenous (Deeth and Lewis, 2017). This means that the energy and time efficiency are not desirable for the process and is lesser than the Tetra Pak H80 separator. The scalability of the unit is also a major disadvantage because centrifugal separators can process large volumes of milk much more efficiently than gravitational methods, making them a better choice for large-scale dairy processing facilities (Chowdhury and Ray, 2008). In conclusion, the Tetra Pak H80 separator is better in performance, efficiency and cost effective in a longer time scale.

2.2. Material and Energy Balance

Before the design of the centrifugal separator, it is important to do the mass and energy balances to ensure that the unit is capable of handling the flow rate that is chosen. For the Tetra Pak H80 separator, the flowrates that the unit can handle are given on the technical datasheet supplied by Tetra Pak. It is also to mathematically prove that the separator is capable of achieving the separation needed to successfully produce a high quality separation, so that when the milk is transferred to the next stages of the fractionation process, the product is as pure as possible. The unit must also be producing at a rate that can meet the demand by the customers, when sold in wholesale.

2.2.1. Mass and Component Balance:

The mass balance is a way to calculatethe inlet and outlet flows in the unit, in the technical data sheet for the unit, it is stated that the separatorcan handle skimming flowrates up to 60,000 L hr-1 (Tetra Pak, 2020). If the 60,000 L hr-1 is chosen, thenthe flowrate must be converted to kg hr-1:

$$Q_{Raw\ Milk} = 60000\ L\ hr^{-1} \times \frac{1030\ kg\ m^{-3}}{1000} = 61800\ kg\ hr^{-1}$$

Before any calculations are made, the fat content of each stream must be defined: Fat content in raw milk, being between 3.35-4.2% depending on time of the year for UK cows, assumed to be 4% (Chen, Lewis and Grandison, 2014), Desired fat content in skimmed milk being 0.01-0.05%, assumed to be 0.03% (Day, 2018). For the fat content of the cream stream, this can be found using the separation efficiency, assumed 95%. From these parameters, the fat content in the cream stream can be expressed as:

$$Sepration\ Efficiency = \frac{x_{Fat-Cream} - x_{Fat-Raw\ Milk}}{x_{Fat-Cream} - x_{Fat-Skimmed\ Milk}}$$

The subject of this formula can then be changed to the fat content of the cream stream, which would end up as:

$$x_{Fat-Cream} = \frac{[(Separation\ Efficiency \times xFat-Skimmed\ Milk) - x_{Fat-Raw\ Milk}]}{(Separation\ Efficiency - 1)}$$

$$\therefore xFat-Cream = \frac{[(0.95 \times 0.003) - 0.04]}{(0.95 - 1)} = 0.743$$

This shows that the fat content of the cream stream is 74.3%. Once allofthe variables have been obtained, the mass and component balance calculations can be written andcalculated:

$$??_{RawMilk} = ??_{Skimmed\ Milk} + ??^{Cream}$$

$$??_{Raw\ Milk}\ x_{Fat-Raw\ Milk} = ??\ Skimmed\ MilkxFat-Skimmed\ Milk + ??_{Cream}\ x_{Fat-Cream}$$

Where: $??_i$ = Mass flowrate of component i in kg hr-1 and x_i = Fatcontent of componentiin %.

Once the variables have been substituted into the equations,itisessentially solvingsimultaneous equations and the outlet flowrates can be calculated, which is donevia MATLAB as seenin Appendix:

$$??_{Skimmed\ Milk} = 58710\ kg\ hr^{-1}$$

$$??Cream = 3090\ kg\ hr^{-1}$$

2.2.1. Energy Balance:

Energy balance assesses the effect of thermal energy on the process fluids, being raw and skimmed milk and cream. In the greater fractionation process, the raw milk will be coming in at 4°C after being cooled down at the end of the pasteurisation process. The milk is then heated to a 50°C, this is because the milk needs to be heated to around this temperature to achieve efficient separation (Tetra Pak, 2021). Therefore these calculations are done to account for the heat transfer between the inlet and outlet streams, excluding the cream.

If we assume that the temperature of the raw milk at the inlet is after its preheated temperature, being 50°C. For the energy balance across the whole unit, there is no heat addition to minimize the temperature increase in the system. If the basic assumptions are included, being a steady-state system, whilst neglecting any significant heat losses, this equation will be used to calculate the outlet temperature for the milk stream. An assumption is that Q = 0, this is because there will be no heat added or removed from the separator system. Therefore the energy balance equation is presented as:

$$??_{Raw\ Milk}\ C_{P-Raw\ Milk} T_{Raw-Milk}$$
$$= ??\ Skimmed-Milk\ CP-Skimmed-Milk\ (TSkimmed-MIlk - T_{Raw-Milk})$$
$$+ ??\ CreamCP-Cream(TPreheated\ MIlk - TRaw-Milk)$$

Where: C_{P-i} = Specific Heat Capacity of Component i and T_i = Temperatureof Component i.

$$??Raw\ MilkCP-Raw\ MilkTRaw-Milk = 0$$

As there is no extra energy flow to the process fluid in the separator.The remaining equation is:

$$\therefore 0 = ??_{Skimmed-Milk} C_{P-Skimmed-Milk}\ (T_{Skimmed-MIlk} - T_{Raw-Milk}) + ??_{Cream}\ C_{P-Cream}\ (T_{Cream} - T_{Raw-Milk})$$

If we assume that there is no significant temperature change in the cream stream, then the equation can be expressed as:

$$TCream = T^{Raw-Milk}$$

$$0 = ??\ Skimmed-Milk\ CP-Skimmed-Milk\ (TSkimmed-MIlk - T_{Raw-Milk})$$

$$\therefore TSkimmed-MIlk = TRaw-Milk = 50°C$$

The Tetra Pak H80 separator does not have a heat exchanger component, therefore, there must be a lack of the heat addition to the system, which in turn meant that the temperature of the inlet and outlet streams should not change in temperature during the process.

2.2.2. Assumptions

For both these balances,themostimportantassumptionisthesteady-statesystemfortheseparator. This means that thereareconstantflowratesfortheinletandboththeoutlets.Italsomeansthatthere is no accumulation intheseparatorandtherateofchangeinmassandenergywithinthesystembeing negligible, thereforethecalculationswillonlyhavetoconsidertheinletandoutletconditions. It essentially means thatthefluctuatingbehaviourofthesystemdoesnothavetobeconsideredduring the mass and energybalances.

Another assumptionwastheneglectingofanyphasechangesintheseparator,suchascondensation or evaporation. Thiscouldhaveaddedvariationtotheseparationefficiencyvalue,affectingthe assumption mentionednext,whichmadetheequationssimplerandstraightforward. Constant separationefficiencyfortheseparatormeantthatthevalueforthefatcontentinthecream phase could be calculatedwithoutanyvariationswhichcouldaddcomplexitytotheequationstofind the fat content. Thisalsomeantthatthecalculatedfatcontentoftheother2streamswereconstant, which contributestothesimplicityofthecalculations.Thisiselaboratedinthenextpoint.

Homogenousmilkcompositionwasalsoanimportantone,astheassumptionmeansthattherawmilk that flows intotheseparatorisuniformlymixed.Usingthismadecalculationseasierbecausethevalues that were foundthroughresearchforthefatcontentsandspecificheatcapacitiescouldbeaverage values and thismadethemeasiertofind.

The fact that therewasnosignificanttemperaturechangeinthesystemmeantthatthespecificheat capacities, viscosityanddensityofthefluidscouldbeassumedconstant.Thiseliminatedanyfurther complexity in the calculationsforthebalances,oranydesignequationsthataretobeundergone. Adiabatic operating conditionsindicatethatnoheatisexchangedbetweenthesystemandthe surroundings. To show this mathematically:

$$QSystem=WS=0$$

Which displays that the change in the energy in the systemisequaltotheworkdoneonorbythe system, which is negligible.

2.3. Unit Component Design

Although the Tetra Pak H80 centrifugal separator may seem like the perfect unit for the skimming process of raw milk, there are still variations in the design of the components of the unit, some of which can increase the performance of the separator and even increase the separation efficiency. The components which have variation in structure could be the design of the bowl of the separator, disk stack, self-cleaning systems, inlet and outlet ports, motor system and safety features. These options will be explored to choose and integrate the best components possible that will make the Tetra Pak separator as efficient as it possibly can, with both time and energy consumption.

2.3.1. Inlet and Outlet Pipes:

Knowing our inlet mass flowrate is 61800 kg hr^{-1}, the volumetric flowrate can be calculated via:

$$\frac{61800\ kg\ hr^{-1}}{1035\ kg\ m^{-3}} = 59.7\ m3hr^{\ -1}$$

To convert to m3 s-1:

$$F_{inlet} = \frac{59.7}{3600} = 0.0166\ ms^{3\ -1}$$

It is stated by Tetra Pak, that for milk processing and centrifugal separation, the recommended fluid velocity range should not exceed 3 m s-1. Therefore, if we choose a value of 2 m s-1 :

$$A_{inlet} = \frac{Finlet}{u} = \frac{0.0166}{2} = 0.0083\ m2$$

$$\therefore rinlet = \sqrt{\frac{Ainlet}{\pi}} = \sqrt{\frac{0.0083}{\pi}}$$

$$\therefore rinlet = 0.051\ m = 51\ mm$$

This concludes that the nominal pipe size will be 51 mm radiusor102 mm in diameter, for the outlet piping, the same calculation can be applied, for both the separatedcomponents outlet port, using cream density of 915 kg m-3 (H. Douglas Goff, Hill and Mary Ann Ferrer,2023) and skim milk density of 1028 kg m-3 the calculations can be found in the appendix:

$$r_{cream\ ,outlet} = 0.0122\ m = 12.2mm$$

$$r_{skim\ milk,outlet} = 0.0502\ m = 50.2\ mm$$

Some assumptions that help simplify these calculationsare:Steady-stateflow,meaningthatthe parameters such as flowrate, temperature, pressure, etc.remainconstantthroughouttheprocessand means fluctuating conditions are neglected. Incompressiblefluids,ifassumeincompressible,the density will remain constant, meaning that the calculationforvolumetricflowrateismuchsimpler. Constant viscosity, this again will make the calculations forthedimensionslesscomplex,asviscosity can change with conditions. Gravity effects are negligible,therotationalspeedscausingforcentrifugal force acting on the fluid are not considered. Head loss duetofrictioncanalsobeneglected,asthisis the basic design phase, the head losses due to pipe frictionarenotconsideredinthecalculations.

To further confirm the suitability of these calculated pipingsizes,thepressuredropacrosstheTetraPak H80 separator could be taken into account. Using specificequations,torelatepipediameterandlength to the pressure drop, a graph could be plotted to analysewherethesecalculatedvalueslie,andiftheir corresponding pressure drops are within acceptable ranges.Themaxpressurethatissafetooperate the unit in the inlet and outlet is 700 kPa (Tetra Pak, 2021),therefore,thepressuredropacrosstheunit must be lower that this pressure range to confirm a safe andefficientseparationprocessintheunit.A pressure of 650 kPa would be a good choice to operate theunit. The equation that relates pipe diameter,

length and pressuredropistheDarcy-Weisbachequation,as seen below (Dejan Brkić, 2011):

$$\Delta P = f()(\frac{l}{d}\ \frac{\rho u2}{2})$$

Where: ΔP = Pressure Drop across separator (Pa), l = Length of pipe (m), d = Diameter of Pipe (m), ρ = Raw Milk Density (kg m-3), u = Velocity of Fluid flow (m s-1) and f = Darcy Friction Factor.

To calculate the Darcy friction factor, the Reynolds Number and relative roughness of the pipe must be calculated first to then refer to the Moody diagram to find the friction factor, which lies in the interception point of these 2 variables. Reynolds Number:

$$Re = \frac{\rho ud}{\mu}$$

Where μ = Dynamic Viscosity of Milk = 2 x 10-3 Pa s (Walstra, P., et al., 2006).

$$Re = \frac{1035 \times 2 \times 0.102}{2 \times 10-3} = 105570 \therefore Turbulent\ Flow$$

The log of this value is calculated to identify the value easier on the x-axis ofaMoody diagram

$$\log_{10} 105570 = 5.02 \approx 5$$

Stainless steel is our choice for the pipe material, especially grade 304. Grade 304 is the choice as it is the preferred material for both the pasteuriser and the centrifuge, as these 2 units will be connected, it is the most suitable material, as stated by the International Stainless Steel Forum (Sustainable Stainless, 2010). It can also be the material of choice as it is stated to be durable and is corrosion and oxidation resistant, meaning it can endure average exposures. Its melting point ranges from 2,550° F to 2,650° F, allowing it to withstand very high temperatures (Nicole, 2021).

From here the relative roughness is calculated via the equation below, with the roughness of stainless tell being 0.0015 (TiSoft, 2023):

$$Relative\ Pipe\ Roughness = \frac{\varepsilon}{d} = \frac{0.0015}{0.102} = 0.0147 \approx 0.015$$

Looking at this value, it can be seen that the relative roughness of 0.015 iscorresponds to a Darcy friction factor of 0.045 on the Moody diagram, as can be seen in the AppendixasFigure 11. With the physical properties of raw and skim milk being similar, the difference betweentheviscosity and density are deemed negligible, therefore the calculate pipe length for the inlet raw andoutlet skim streams are estimated to be similar. From here, the Darcy-Weisbach equation can be manipulated to make the pipe length the subject of the formula, giving:

$$l_{Inlet\ Pipe} \approx l_{Outlet\ Pipe-Skim\ Milk} = \frac{2\Delta P d}{\rho u 2 f} = \frac{(2 \times 650000 \times 0.102)}{(0.045 \times 1035 \times 22)}$$

$$l_{Inlet\ Pipe} \approx l_{Outlet\ Pipe-Skim\ Milk} = 9.73\ m$$

This means that the calculated lengths for the inlet raw milk and outletskim milk pipe lengths are around 9.73 m. The calculation for the cream can be found in the Appendix, using the properties of cream being ϱ915kgm-3$Cream$= (H. Douglas Goff, Hill and Mary Ann Ferrer, 2023)and and $\mu Cream$ = 15 x 10-3 Pa s (Fox et al., 2015). The length is calculated to be:

$$lOutlet\ Pipe-Cream = 10.73\ m$$

2.3.1. Bowl design:

Shape and size of a bowl of a centrifugal separator can have a significant impact on the separation capacity, efficiency, and flow patterns within the separator (Eckert, M., et al., 2001). Larger bowls mean larger capacity of the separator and greater throughput, the greater throughput is the more important factor in large-scale processing of milk.

The shape of a bowl can influence flow patterns in the separator, as it can affect the distribution of the unskimmed milk and the velocity of the milk flowing. A bowl with a conical shape would be preferred over a cylindrical because it promotes radial flow pattern. In a centrifuge separation this is desired as it can increase the centrifugal force acting on the particles, increasing separation efficiency (Walstra, P., et al., 2006).

With an inlet flow of 61800 kg hr-1, to acquire the volume, the terminal settling velocity is calculated first, using Stokes' Law:

$$u_{terminal} = \frac{d2(\rho_{fluid} - \rho_{particle})g}{18\mu}$$

Where: $\varrho_{particle}$ = Milk Fat Globule Density = 915 kg m-3 (H. Douglas Goff, Hill and Mary Ann Ferrer, 2023), ϱ_{fluid} = Fluid Density (1028 kg m-3), d = Fat Globule Diameter (Average) = 1 x 10-5 m (Trujillo et al., 2016), μ = Dynamic Viscosity of Milk = 2 x 10-3 Pa s and g = gravitational acceleration = 9.81 m s-2, therefore:

$$u_{terminal} = \frac{(1 \times 10{-}5)2(1028 - 915) \times 9.81}{(18 \times 2 \times 10{-}3)} = 3.08 \times 10^{-6}\ m\ s^{-1}$$

From here, the required settling area can be calculated from the equation:

$$A_{required\ settling} = \frac{Finlet \times Separation\ Efficiency}{uterminal}$$

$$A_{required\ settling} = \frac{0.0166\ m3s{-}1 \times 0.95}{3.08 \times 10{-}6\ m\ s{-}1} = 5120.1\ m2$$

From here, the next stage is to divide this by the separator capacity factor, which is stated to be 10000 m2 m-3 (Bothamley, 2013) for industrial scale dairy processing, therefore:

$$V_{Liquid\ In\ bowl} = \frac{5120.1\ m^2}{10000\ m^2 m^{-3}} = 0.512\ m3 = 512\ L$$

For the optimum liquid level in the bowl, a headspace needs to be determined for the Tetra Pak H80 Centrifugal separator. If it is assumed that there is a 10% headspace in the bowl of the separator, then the total volume of the separator would be:

$$V_{bowl} = \frac{512\ L}{(1-0.1)} = 568.9\ L$$

From here, it is already known that the Tetra Pak H80 has a conicalshape.To calculate the dimensions, itcan be assumed that the shape is a cone, as one can see fromFigure1. With this, a 2:1 height to diameter ratio is chosen to be suitable, therefore:

$$V_{bowl} = \frac{1}{3}\pi r_{bowl}^2\ hbowl = \frac{4}{3}\pi r^3 bowl = 0.5689 m^3$$

$$\therefore dbowl = 2r_{bowl} = 2 \times \sqrt[3]{\frac{3V_{bowl}}{4\pi}} = 1.028\ m$$

$$\therefore h_{bowl} = 4rbowl = 2.056\ m$$

Therefore our base diameter is 1.028 m and the height of ourseparator is 2.056 m, this is a very simplified calculation, as the shape is conical, however, it is not acone shape. This does not represent the dimensions of the separator as accurately as possible. Forhere, the optimal liquid level in the separator can be found from the liquid volume in the bowl:

First to find the ratio of the radii for similar triangles:

$$r_{liquid\ level} = r_{bowl} \times \left(\frac{h_{bowl}}{h_{liquid}}\right)$$

Then, insert into the volume of cone equation to solve for height ofliquid (h_{liquid}):

$$V_{liquid\ in\ bowl} = \frac{1}{3}\pi\left(r_{bowl} \times \left(\frac{h_{liquid}}{h_{bowl}}\right)\right)^2 h_{liquid}$$

$$h^3_{liquid} = \frac{3V_{bowl}\ h^2_{bowl}}{\pi r^2_{bowl}}$$

$$\therefore hliquid = 1.129\ m$$

Therefore, the liquid level in the separator should always remain at this level for optimal separation efficiency.

2.3.2. Motor Design:

When looking for a specific motor type for this process, the one that showed the most beneficial specifications was a three phase induction motor. An induction motor is an electric motor which uses alternating currents, the electric current in the rotor needed to produce torque is obtained via electromagnetic induction from the rotating magnetic field inside the component. This type of motor was chosen, due to it possessing simple and rough construction, affordable and low maintenance, high reliability and highly proficient, no requirement of additional starting motor and necessity not be synchronized (Princy, 2020).

Induction motors are widely used in centrifugal separators and other high-torque applications in the dairy industry (Dairy Processing Handbook, Tetra Pak, 2013). Although permanent magnet synchronous motors offer higher efficiency, they come with a higher initial cost and may require more advanced control systems (Boldea, I., & Tutelea, L.N., 2019).

When looking at the manual available for the Tetra Pak H80 Centrifugal Separator, it is stated that the power consumption during operation is 22kW, if a 10% safety margin in the motor is assumed, which could account for the energy losses, the required motor power can be calculated as seen below:

$$P = P_{Centrifugal\ Separator} \times \frac{(1+Safety\ Margin)}{Efficieny\ of\ Motor}$$

Where: P is the required power by the motor to run the centrifugal separatorat desired separation and PCentrifugal Separator is the power consumption of the Tetra Pak H80 during operation.

If we assume a 90% efficiency of the motor, the power required from the motor to run the centrifugal separator can be calculated:

$$P = 22\ kW \times \frac{(1 + 0.1)}{0.9} = 26.9\ kW$$

This concludes thatapowerof26.9kWisrequiredtooperatethecentrifugalseparatortoachievethe desired separationfortherawmilk.

For this, theSiemens1LA5motorwaschosenasitiscapableofgeneratingbetween11-45kWof power, whichissuitableasthepowerrequirementoftheTetraPakH80lieswithinthisrange.Thisisan AC inductionmotorisamotorthatutilisesalternatingcurrentandelectromagnetismtogenerate rotationalmotion.IntheInternationalElectrotechnicalCommission(IEC)standards,therearedifferent classesofefficiencyformotors,whichareIE1,IE2IE3andIE4,withIE1beingthestandardefficiency and IE4beingthehighestefficiency(MenzelMotors,2018).Thismodelisaninductionmotor,where for mostinductionmotorsratedfrom0.75to357kW,isIE3(Collins,2020).IE3isstatedtobepremium efficiency(MenzelMotors,2018),therefore,itcanbeclassedashighenoughefficiencytobe implementedintothesystemandthesemotorshaveanefficiencyofaround90-95%,asshowninFigure DDDintheAppendix,isagraphpublishedbySiemenswhichshowstheefficiencyandpowerdiagram withtherelationshipbetweentheparametersforIE3efficiency(Siemens,2015).

Thenextstepforamotordesignisthedrivesystemselection,thisisthekeypartofthemotorasthe purposeofadrivesystemistocontrolandregulatethespeedofthemotor,andthereforecontrolthe RPMsinthecentrifugalseparator.Itusesisacombinationofelectricalandmechanicalcomponentsto controlandregulatethemotor'sspeed,torque,anddirection(Bose,2002).Thedrivesystemalso improvesthemotorreliability,performance,andefficiency.Thechosentypeofdrivewasthevariable frequencydrive,thisisbecauseitcancontrolthespeedatwiderrangesandmoreaccurately,whilst possessingtheabilitytomakethemotorenergyefficient(Mohan,UndelandandRobbins,2007).Itis stated byTetraPakthatVariableFrequencyDrives(VFDs)arecommonlyusedindairyprocessing applicationsforcentrifugalseparatorsandothervariablespeedequipment(DairyProcessing Handbook,TetraPak,2015).Withtheconfirmationofoneofthelargestdairycompanies,itcanbe safely assumedthatthistypeofmotordriveitthemostsuitableforourprocess.

2.3.3. **Disc stack design:**

The bowl of a Tetra Pak H80 separatorhousestheinternalcomponentsandisthepartoftheunitwhere the raw milk undergoes separation. Thedesigncanbeoptimizeddependingontheprocessandmore importantly, the desired separation efficiencytoproducetherequiredqualityofproduct.Formilk skimming, the most common design is thediskstackseparator,whichisspecificallydesignedtohandle liquid-liquid and liquid-solid separations withhighefficiency(Walstra,P.,etal.,2006).Thediscstack separator isessentiallyastackofdiscsthatarecloselypacked,whichprovidealargesurface area for settling of thecream,thiswillleadtoamoreefficientseparationprocessofcreamfrommilk. The configuration of the discs are key to optimizing the separation in the bowl of a separator.

One ofthedesignfactorsofdiscsisthespacingbetweendiscs,thiscanaffecttheseparationefficiency, as wellasthecapacityoftheunit.Thisisbecausethedistancebetweenthediscsdetermines the settlingdistanceandflowpatternswithintheseparator,impactingtheoverallperformanceofthe system (Anema,S.G.,andKlostermeyer,H.,1997).Ifthesettlingdistanceforparticlesordropletsare shorter, then finerseparationcanbeachieved.However,withthis,therateoffoulingwillincreasebecause the spaceinwhichparticlessettlewillbesmallerandconstricting,therefore,moreaccumulationoccurs for solids.Inastudy,itwasseenthatdiscstackcentrifugeswereideallysuitedforseparatingparticles 3–30µm(TarletonandWakeman,2007).Thisshowsthatadiscstackseparatorissuitableforour process astheparticlesizeoflipidglobulesrangefromdiameters0.2tomorethan15µm(Michalski., et al, 2002).Thismeansthatmostoftherangeofdropletdiameterscanbeseparatedasitliesinthe range ofparticlesizesthatthediscstackcentrifugecanseparate.Itisalsoimportanttoachievethe correct flowregimeintheseparator.Theidealflowregimewouldbetheonethatpromotestheformation of thin film of fluid along the surface of the discs, as this maximises the settling area.

Toestimatethenumberofdiscsrequired,somevaluesareneeded,suchastheinletflowand target separationefficiency.Thetargetseparationefficiencycouldbesetataround95%fortheproduct to be abletocompeteasanewproductinacompetitivemarket.Thisequationbasedontheunderstanding thatthecentrifugalseparator'sperformanceisrelatedtothetotalsedimentationareaprovided by the discs,whichisamultiplicationofthenumberofdiscsandtheirsurfacearea.Thissimplifiedequation is meanttoprovideanapproximatevaluefor thenumberof discs.

For manydairyseparators,thesigmavalueisgiventobe10000m2 m-3 (TarletonandWakeman, 2007), with a discareaof0.2m2.

$$N = \frac{F_{inlet} \times Separation\ Efficiency}{\Sigma \times A_{Disc}}$$

$$\therefore N = \frac{60000\ L\ hr^{-1} \times 0.95}{10000\ m^2 m^{-3} \times 0.2} = 28.5 \approx 29\ Discs$$

The results of the calculations show that to achieve the desired separationefficiency, an estimated 29 discs are required in the bowl of the separator.

The angle of the discs can also affect the efficiency of separation, as it can affect the flow patterns in the bowl. Different angles can be optimized based on the specific application and the desired separation performance (Anema, S.G., and Klostermeyer, H., 1997). The disc angle affects the overall flow regime in the centrifuge by balancing the radial and axial flow patterns because it directly affects the fluid dynamics inside the separator. Larger disc angles will promote axial flow patterns, whereas the smaller angles will promote radial flow pattern (Cui, Z., and Chang, S., 2003). A recent study had found the optimal angle to be 40°, as this showed the highest levels of separation in a centrifuge during the experiment (Lalita Kanwar Shekhawat et al., 2017). A material that seems to be suitable for the ideal separation has already been released by Tetra Pak, with their encapt polynode disc technology. Each disc contains a series of nodes or raised points, which create a series of mini chambers. These nodes are arranged in a specific pattern to create turbulence and promote the different components to mix effectively, with the denser phase forced towards the outside of the disc (Tetra Pak, 2018).

The polynode technology means that the nodes are smaller than usual, so more individual discs can be inserted into the separator and increases the separation surface (Tetra Pak, 2021). These nodes can be installed in the Tetra Pak Separator H80, instead to the traditional welded discs. The capacity of a separator equipped with polynode discs is 9% higher compared to the previously largest hot-milk separator, therefore, the design of polynode discs enables significantly lower energy and water consumption per 1,000 litres of processed product, both saving money and resources (Tetra Pak, 2021).

2.3.4. Self-Cleaning systems:

The cleanliness of a centrifugal separator is imperative as it can preserve the product quality and prevent contamination of the milk. If contamination is prevented, then the probability of microbial growth is significantly decreased and the product will not become sour or lose its taste and texture. It will also prevent any consumption of potentially harmful microbials by the customer, meaning the product can be classified as safe to consume. Regular maintenance is also important because if a faulty or a setback is detected earlier in its process, the equipment can be replaced or cleaned and the magnitude of damage to repair will be smaller. This means the downtime for the process will be minimised and the unit will operate efficiently.

A Clean-In-Place (CIP) system could be introduced to the unit, these are automated systems used to clean the interior surfaces of food and beverage process pipes, processing vessels, tanks, spiral freezers, mixers, blenders, homogenizers, roasters and associated fittings, without disassembling the process (Sani-Matic, 2023). It is also stated by Chris Purvis, the sales engineer article that such automated cleaning and sanitation will increase the safety of the employees and quotes that “Minimizing operators’ exposure to caustic chemicals and hot temperatures is something companies consistently work toward. Incorporating automated cleaning and sanitation equipment into their sanitation program helps achieve that goal.” (Purvis, 2020). These are also widely used in the dairy industry, due to reducing the downtime, which happens to be equally as important as maintaining the health and safety of customers and employees.

The chemicals used for cleaning the unit in the CIP process are:

- Acid Cleaning Agents: Acids solutions are particularly good at removing mineral deposits, being the calcium and magnesium salts. Mineral deposits can cause for scale formation on the inner surface of the equipment, which can affect the efficiency of the separation process. The two most common types of acid detergents used are:- Nitric acid and Phosphoric Acid. Nitric acid is used to remove milk-stone and other inorganic deposits, it also has biocidal properties when used either as a pure acid or in more stable, less hazardous mixtures with phosphoric acid (Kumar Bharti, 2019).
- Alkaline Cleaning Agents: These solutions are used to clean any remaining protein, fat or carbohydrate sediments. They can also remove the fats and combining with the resulting fat particles to form soap in a process called saponification. The alkaline solutions of choice are potassium hydroxide or as sodium hydroxide (LKL Services to Agriculture, 2018).
- Sanitising Agents: These solutions are required to eliminate any remaining microbials from the surface of the unit. Sodium hypochlorite is the most common sanitiser used as they have a low cost, however, they cannot kill bacterial spores even though they can halt to bacterial growth. On the other hand, peroxyacetic acid sanitizers are very effective sanitizers against a wide range of bacteria and bacterial spores. They work well in cold conditions. Because they break down into vinegar, water, and oxygen they are considered environmentally friendly. One disadvantage is that they are expensive to use (Sanitary Design Industries, 2013).

It is stated by Federal Manufacturing, that a flow rate of between 5 and 10 feet per second (1.5 to 3.0 meters per second) should generate a Reynolds number greater than 4,000 in a straight length of stainless steel sanitary tubing. When flows are measured within the 5 and 10 feet per second range, the flow is generally considered turbulent and thus provides good cleaning (Collins, 2014). For this, if we assume a flow velocity of 1.5 meters per second, then we can calculate the required flowrate for the CIP system:

$$F_{CIP} = A_{pipe,inlet} \times u_{CIP} = 0.0083\ m2 \times 1.5\ m\ s^{-1}$$

$$\therefore F_{CIP} = 0.01245\ m3s{-}1 = 12.45\ L\ s{-}1$$

This is the required flowrate for the cleaning system to effectively eliminate the deposits and microbials that may settle in the pipes of the unit. A higher flowrate could increase the cleaning efficiency, however, this will then come with extra mechanical stress on the surface of the piping and will need more energy to maintain, increasing the operating costs of the unit. A lower flowrate will simply not be sufficient as the process will take longer to remove the same amount of residue in the piping.

2.3.5. Heat Exchanger:

Unlike other sections of the milk fractionation process, the milk is not directly heated to a temperature, but the CIP water is heated so that it can effectively wash away the chemicals between cleaning agent flushing. A heat exchanger will have to increase the temperature of the cleaning water from its storage temperature to its inlet temperature of the process. The data book for the Schneider Electric states that the storage temperature of fresh water in a CIP system is 10 – 15°C (Jude and Lemaire, 2019), from this we can conclude that the storage temperature should be 15°C. This is because the temperature difference between its storage and operation temperatures will be lower and less energy will be consumed heating the water up. The system temperature is 50°C, therefore this will be the temperature the cleaning water will be heated to. The temperature of the steam will be 100°C in both its inlet and outlets

It is deducted that plate-and-frame heat exchangers are the most suitableforthis system, as it is already said to be a common choice for CIP systems. This is because witharelatively low steam pressure requirement of around 50 psi, plate and frame heat exchangers arecommon in CIP systems. High efficiency and modest pricing make them the first choice for manyCIPdesigns (Central States Industrial, 2020). The individual plates on the heat exchanger can alsoberemoved and attached easily, meaning that cleaning the heat exchanger will also be a simpler process.

When designing the plate-and-frame heat exchanger, the very first stepistocalculate how much heat energy is required to achieve this temperature raise of 35°C. For this, theequation below is used:

$$Q = ??Cp(TCIP\ out - T_{CIPin}) = 12.45 \times 4180 \times 35$$

$$Q = 1{,}821{,}435\ J\ s^{-1} = 1.821\ MJ\ s{-1}$$

Where: C_p= Specific Heat Capacity (J kg-1 °C-1), TCIP in = CIP StorageTemperature (°C), TCIP out = CIP Temperature at process inlet (°C).

The overall heat transfer coefficient (U) must be calculated in order to obtain the sizing for the heat exchanger. The next step is calculating the heat transfer coefficients for the steam at 100°C and water at 50°C and for this, the concept of electrical resistance can be applied to material and fluid resistance to transport heat. The equation will also have the fouling factors for the steam and water, which were determined to be 0.00018 and 0.00009 m2 K W-1, respectively. With this, the convective heat transfer coefficients for steam and water were found to be 11630 and 4000 W m-2 K-1. The overall heat transfer coefficient equation is then ready to apply:

$$\frac{1}{U} = \frac{1}{h_{steam}} + \frac{1}{hCIP\ Water} + R_{f,Steam} + R_{f,CIP\ Water}$$

$$\frac{1}{U} = \frac{1}{4000} + \frac{1}{11630} + 0.00018 + 0.00009$$

$$\therefore U = 1650.21\ W\ m\ K^{2}\ ^{-1}$$

The overall heat transfer coefficientisessentiallythetotalheattransferinaheat exchanger by taking into account fouling factors. Thenextstepistocalculatethelogmeantemperature difference (LMTD), this the logarithmic value for thetemperaturedifferencesinthehotandcoldfluids flowing at different directions. This also bring aboutanotherdiscussionofacounter-currentheatexchange system, which is because counter-current flowhasahighertransferofheatfromonefluidto another. It is stated by many heat exchanger manufacturersthatcounterflowissignificantlymoreefficient and, depending on the flow rate and temperature, theheattransferperformancecouldbeupto15% more efficient, possibly enabling a smaller heat exchangertobeused,savingspaceandmoney(EJBowman, 2021). The outlet temperature of the steam in theheatexchangerisassumedtobe96°C,thisis accounting for the heat transfer efficiency, where someoftheheatwillnotbetransferredandconverted into wasted energy, hence it is partially condenseddueto thepressuredropaffectingtheperformance of the heat exchanger. From here, the steammassflowrateisachievedbyusingtheequation below:

$$??_{Steam}\ C_{P\ Steam}\ (T_{Steam\ In} - T_{Steam\ Out}) = ??_{CIP}\ C_{P\ CIP}\ (T_{CIP\ In} - T_{CIP\ Out})$$

Where:

$$??_{Steam} = \frac{??_{CIP}\, C_{CIP}\, (T_{CIP\ In} - T_{CIP\ Out})}{C_{PSteam}\, (T_{Steam\ In} - T_{Steam\ Out})}$$

$$\therefore ??_{Steam} = 0.136\ kg\ s^{-1}$$

The equation for the co-current and counter current flow are different due to the temperature gradients being different, the equation for the latter option is:

$$\Delta T_{lm} = \frac{(T_{Steam\ In} - T_{CIP\ Out}) - (T_{Steam\ Out} - T_{CIP\ In})}{\ln\left[\frac{(T_{Steam\ In} - T_{CIPOut})}{(T_{Steam\ Out} - T_{CIP\ In})}\right]}$$

$$\Delta T_{lm} = 65.96°C$$

From here, the area of heat transfer can be calculated, which will help us with the sizing of the plate-and-frame heat exchanger. The equation for the heat transfer area can finally be utilised to start the sizing:

$$Q = UA\Delta T_{lm}$$

$$\therefore A = \frac{Q}{U\Delta T_{lm}} = 17.18\ m^2$$

This is the total area that is required for the temperatureoftheCIP water to raise from 15 to 50°C. The type of plates that will be used is a Hisaka Plate and Heatexchangers, specifically the RX-30 model. The reason this model was chosen was because of thecorrugated patterns on the plates, Alfa Laval had made a statement that the corrugated plates createturbulence in the fluids as they flow through the unit. This turbulence gives an effective heat transfercoefficient (Alfa Laval, 2021). Turbulent flow is preferred in heat exchangers and the swirling and unpredictable particle flow can enhance the heat transfer in the component. The dimensions of the platesinthis heat exchanger are: 1850 mm height and 650 mm width, with this, the number of plates requiredfor the system can be calculated:

$$N_{Plates} = \frac{A_{Plate}}{A}$$

$$\therefore N_{Plates} = \frac{(1.85 \times 0.65)}{17.18} = 14.3 \approx 15\ Plates$$

With this, the conclusion is that 15 Hisaka RX-30 model plates are needed to effectively achieve this heat transfer and raise the temperature of the CIP water. The water used for the system would ideally be soft water, this is because the mineral concentration in hard water can lead to fouling by leaving deposits of Calcium and Magnesium. This choice can lead to the decrease in the OPEX as the lower levels of fouling will mean less frequent maintenances and decrease the downtime of the cleaning system.

The heat exchanger is required to achieve the temperature raise in the CIP as smoothly as possible during every start-up and shut-down procedures. With a total area of transfer of 17.18 m2 and 15 Hisaka RX-30 plates, this heat transfer can be achieved through every run of the CIP system

2.3.6. Safety Features:

With every unit, there is always a risk that the operating conditions fluctuate due to some kind of failure in the system. This can come in mechanical, pressure and temperature hazards. If there is a scenario where the pressure can exceed the operating limits of the separator, the operator and anyone in close proximity to the unit will be in serious danger. These sudden pressure increases could arise from a few different factors, one being the blockage in the inlet or outlet pipes. This can be caused because of fouling in the pipes due to the CIP system being unable to clean the pipes, therefore the flow is constricted due to the cross-sectional area decreasing. Overloading the unit can also be one of the causes of such malfunctions.

The answer to this is to incorporate a pressure control valve (PCV) to protect the unit from situations of overpressure scenarios. Using the data for the Tetra Pak H80 Centrifugal Separator, a sizing of the pressure relief valve is undergone, to identify which manufacturer has the most suitable PCV. The value of interest is the valve flow coefficient, which is the flow capability of a control valve at fully open conditions relative to the pressure drop across the valve. The definition used in engineering is the volume of water (GPM in the US) at 60°F that will flow through a fully open valve with a pressure differential of 1 psi across the valve (Nobel, 2021).

Assumptions include: the set pressure for the relief valve being 110% of the maximum allowable working pressure of the separator (American Petroleum Institute, 2006, p.39), with the chosen operating pressure for a Tetra Pak H80 separator being 650 kPa or 6.5 bar. The maximum process fluid rate is 60,000 L hr-1 and the process fluid is milk, with a specific gravity range of 1.029 to 1.032 kg m-3. The average value is taken at 1.031 kg m-3.

$$Set\ Pressure = 1.1 \times MAWP = 1.1 \times 6.5\ bar$$

$$Set\ Pressure = 7.15\ bar$$

For the pressure difference, it is known that atmospheric pressure is 1.0135 bar, which is 0 psi. If the set pressure is converted to psi:

$$7.15\ bar = 103.7\ psi$$

Assuming a flowrate on 60000 L hr process fluid through theseparator, this should be converted to gallons per minute, as this is what the equation requires for thevalveflow coefficient:

$$\frac{60000\ L\ hr{-1}}{(3.785\ L\ gal{-1} \times 60\ min)} = 262.2\ GPM$$

With all the variables acquired, the valve flow coefficient can be calculated via the equation below (Nobel, 2021):

$$C_v = \frac{Q_{Process\ Fluid}}{\sqrt{\Delta P \times SG}} = \frac{262.2}{\sqrt{103.7 \times 1.031}}$$

$$\therefore C_v = 24.62$$

Once theparametersarecalculated,asuitablepressurereliefvalveisidentifiedwhichhasavalveflow coefficienthigherorequalto24.62,canhandleasetpressureof7.7barandiscompatiblewiththe processfluid,beingmilk.ThemostsuitablecontrolvalvechosenwasaSamsonType3241Globe Valve,whichhastemperatureandpressurerangesthatarecompatiblewiththeoptimalconditions neededfortheTetraPakH80.Thisglobevalveisknowntoprovideaccurateflowcontroltothesystem and hasthemodelwiththecorrectdiametersneeded,aroundDN100andDN20whichbothhaveaCV above 24.62, therefore can handle the pressure difference across the unit (Samson Group, 2023).

Anotherwaytopreventpressurebuild-upinthebowloftheseparatororthepipingwouldbeto incorporateaPromag53electromagneticflowmeasuringsystem.Thisflowmeasuringsystemwillallow for accuratedetectionofflowratesupto60000Lhr-1 (Endress+Hauser,2009).Withaflowcontrol,the probabilityofoverflowingorundershootingoftheseparatorbowldecreases,meaninganysignificant pressure changes in the system can be mitigated as quickly as possible. For a

highaccuracypressuredetection,aHoneywellPX3seriesheavydutypiezoresistivepressure transducer,whichisasilicon-basedmeasuringelementandextendsminimallyunderpressure, changingtheelectricalresistanceinthisway(Kistler,2023).Itwouldbethemostsuitableforthismilk skimmingprocess.ThisisbecauseinthedatasheetprovidedbyHoneywell,itstatesthattheerrorband for this pressuretransduceris±1.0%,whilebeingdurable,intheoperatingtemperatureandpressure ranges of-20°Cto85°Cand15psito700psi,respectively(HoneywellInternationalInc.,2022).Italso states thatoneofthepotentialapplicationsisindustrial,specificallyprocesscontrolsandautomation, which furthersolidifiesthechoiceofmodelforpressuredetection.

Temperature exceeding the operating limits of the unit is also dangerous to everyone in close proximity to the unit, as well as the operator. The temperature could go to high enough temperatures to cause burning or even worse, could start a fire. The reasons for this to occur could be the overheating of the motor, this would happen from the motor malfunctioning and applying max power onto the centrifuge system, causing it to rotate at the max speed of 10000 RPM, which could cause for friction between the moving parts. This mechanical energy can turn into thermal energy, which would increase the likelihood of dangerous accident. The temperature sensor may also fail, where the input for the sensor is error values and not reflective of the system, meaning that it will not be able to detect the temperature exceeding the safe limit. Another reason could be the heat transfer from the process fluid, the milk coming from the pasteuriser could potentially not be cooled down to 50°C, meaning that the milk will be at 60°C after pasteurisation and if not cooled down, will be above the operating temperature of the separator.

A temperature control valve can also be a suitable addition to the unit, this will be used to maintain the temperature of the process fluid, the milk, within the necessary range during the separation process. After pasteurisation, the milk is rapidly cooled to 4°C. The temperature in the separator should be 50°C, therefore before the inlet the temperature of the milk will be heated up to 50°C. Our chosen flowrate through the separator was also at 60,000 L hr-1. With the specific heat capacity of raw milk being 3.918 kJ kg-1 K-1 (Mladen Josijevic, Šušteršič and Dusan Gordic, 2020):

To calculate the heat load:

$$Q_{Heat\ Load} = m \times Cp \times \Delta T$$

Where:

$$Q_{Heat\ Load} = 61800\ kg\ hr{-}1 \times 3.918\ kJ\ kg^{-1}\ K^{-1} \times (50-4)$$

$$QHeat\ Load = 16{,}544{,}930.4\ kJ\ hr^{1}$$

For the cooling water, a calculation is not needed because the temperature that the milk is raised to (50°C) is the temperature that the milk needs to be for the next stage in the greater fractionation process.

Another addition could be a thermal safety switch, this is a switch that shuts down the separator, if the temperature limit chosen for the unit is exceeded. For this unit, a maximum temperature of 60°C is chosen, meaning that a activation temperature must be determined. This is the temperature that the switch starts shutdown for the unit. A safety margin of 10 – 50 % can be chosen in process design (Peters and Timmerhaus, 1968):

$$T_{Activation} = Maximum\ Operating\ Temp. \times (1 - Safety\ Margin)$$

With a chosen safety margin of 10%:

$$T_{Activation} = 60℃ \times (1-0.1) = 54℃$$

Therefore, the thermal safety switch will shut down the separator, ifthe temperature exceeds 54°C in the process fluid.

To enhance the overall temperature control system, sensors are a good addition to further counter the potential hazards that can arise from sudden temperature increases. There are 3 types of temperature sensors that are suitable candidate for the unit, these are RTDs, thermocouples, or infrared thermometers (Omega, 2022). RTD is a resistance temperature detector, they measure the temperature of materials that have a predictable change in resistance as the temperature of the material changes (IQS, 2023). Thermocouples are comprised of two dissimilar metallic wires joined together to form a junction. When the junction is heated or cooled, a small voltage is generated in the electrical circuit of the thermocouple which can be measured, and this corresponds to temperature (Process Parameters, 2023). Our final option, the infrared thermometers, this is a sensor that consists of a lens to focus the infrared (IR) energy on to a detector, which converts the energy to an electrical signal that can be displayed in units of temperature after being compensated for ambient temperature variation (Omega, 2023).

It is stated that the RTDs are particularly suited for dairy processing, where precise temperature control is crucial for product quality and safety (Tamime, A. Y., 2009). Therefore, a the model of RTD that is chosen for this particular system is the PT100. This is because it can operate from a temperature range of -182.96°C to 630.74°C and is made of platinum. Platinum is especially suited to this purpose, as it can withstand high temperatures while maintaining excellent stability. As a noble metal, it shows limited susceptibility to contamination (Omega, 2023).

There may also be a case of mechanical failure, meaning that the rotating parts in a centrifuge can also be thrown around in any random direction and again, putting operators in danger. The cause of this could be the fatigue caused by high centrifugal forces, or corrosion of the material. The corrosion can cause for the integrity of the structure to fail over time, eventually malfunctioning and breaking. Jamming of the units could also be a factor that contributes to mechanical failure. Another factor could be blockages, the prevention of proper flow in the inlet or outlet of the unit can cause the fluid could lead to sudden pressure increase, which will mean the mechanical hazard probability will increase. To

counter this hazard, guarding and enclosures will have to be designed to prevent any contact with rotating components in the unit, which could be the spinning of the separator bowl. A simpler way would be to consider using interlocks to ensure that the equipment cannot be operated when the guards are removed (HSE, 2021).

3.Optimization and Performance Evaluation

3.1. Operation Design Limits

The Tetra Pak H80 is optimised so that it may perform at high levels and produce high quality products safely and consistently. Optimisation of this unit lie in finding the maximum and minimum allowable flowrates and solid content of the milk to provide maximum yield with minimal fouling of the system by clogging via solid settling. This section aims to determine the operational and composition limits of the unit and upgrade options to mitigate any issue that may negatively affect the performance of the unit, mainly fouling and corrosion. Optimisation will also ultimately reduce the OPEX of the unit, due to the lower energy consumption at optimal performance.

3.1.1. Flowrates - Maximum and Minimum Limits

The Tetra Pak H80 separator is designed for optimal production, however, these optimal conditions are achieved in a specific range of flowrates. Looking at the Tetra Pak separator range, the maximum and minimum flowrates are stated for the H80 model, and on the website displaying maximum and minimum operation parameters (Tetra Pak, 2021):

$$F_{Minimum} = 7000\ L\ hr^{-1}$$

$$F_{Maximum} = 80000\ L\ hr^{-1}$$

$$F_{Skimming} = 60000\ L\ hr^{-1}$$

The FSkimming value is the skimming flowrate. This value was thechosen operation flowrate because it was stated by the manufacturer data book that the skimming flowrate for each model is the optimal flowrate to achieve the highest separation efficiency of the process. The flowrate limits determined by Tetra Pak are acquired based on the capacity of the pumps used, hydraulic factors in the system and residence time. The values here are all process parameters for hot milk separation, which is what the fractionation process needs to ensure a smooth overall production of Whey and Casein powder.

It is important to operate within this boundary for the Tetra Pak H80 to operate smoothly, ensure minimal damage from friction and wear and tear and increase product yield and quality. Exceeding a flowrate of 80,000 L hr-1 will lead to problems with the separation efficiency due to an increase of mechanical stress being applied to the system or lead to inadequate mixing. It will also increase the OPEX of the unit as it will have higher energy requirements to run the separator at such high flowrates and RPM. On the contrary, being below the minimum flowrate can lead to problems such as damage to components due to an excessive residence time and insufficient processing as to not achieving the necessary pressure drop in the unit to achieve optimal performance. Excessive residence time can lead to an increase in fouling due the organic and inorganic matter in the milk having more time to settle in the piping or the separator bowl. The proteins can also become denatured due to the shear stress applied, protein molecules typically unfold (denature) when subjected to extremes of heat, cold, pH, solvent composition, or mechanical stress (Jaspe and Hagen, 2006).

3.1.2. Milk Composition - Maximum and Minimum Limits

The Tetra Pak H80 separator must be handle a wide range of milk compositions, as this will vary depending on the cows and the milk batches that arrive at the fractionation plant. It is stated by the Journal of Dairy Processing that a combination of factors including breed differences, lactation stage, climate, and feeding practices cause for this to happen (Lauren, 1963). Especially with cows that produce high fat milk, it can be difficult to separate the fat to an acceptable level for the Tetra Pak H80 to separate to the percentage required. There are limits to the percentage of fat allowed in the skim milk stream as if it is left too high, it can cause for difficulties in the next stage, microfiltration. This can cause for excessive fouling in the membranes and lead to more maintenance runs, increasing the downtime of the entire fractionation process. The ideal fat content in the skimmed milk is stated previously, where the suitable fat content for the next stage is (Chen, Lewis and Grandison, 2014). Also, the maximum value for milk composition is a legal requirement is the milk is to be classed as skimmed, it is stated that "skimmed milk" means milk the fat content of which has been brought to not more than 0.30 percent (UK Legislation, 2023):

$$x_{Maximum\ Fat} = 0.3\%$$

$$x_{Minimum\ Fat} = 0.01\%$$

If the fat percentages fall below the minimum, problems canstill arise. One being the flavour of the Whey and Casein at the end, which may cause customer dissatisfaction and could affect the consumers view towards the powder and lead to decrease in revenue andtherefore decreasing the profitability of the plant.

3.1.3. Upgrade Options

These options suggested will increase the adaptability of the Tetra Pak H80 to anomalous flowrates and compositions, as these can occur at any time during production, it is essential to mitigate such problems to reduce the operation downtime as much as possible.

CIP System:

In the context of mitigating fouling and corrosion, a CIP system is crucial, as it cleans the interior of the system, without having to disassemble the unit. It uses alkali, acid and water in intervals to clean the system in different ways. The Nitric Acid in the CIP system will specifically target the fouling by removing the residues from the milk that have accumulated on the inner surface of the piping and bowl, while the Sodium Hydroxide is used to will eliminate organic and fatty contamination, gels and emulsions (Spectrum Chemical, 2020). This cleaning procedure every start-up and shut-down will remove the organic residues after an 8-hour shift of processing, to ensure that there is no milk or cream accumulated in the unit, which leads to fouling. Unfortunately, the use of industrial grade acid and alkali solutions can cause for corrosion to the components of the unit. The corrosion factor that the use of these chemicals bring is mitigated with a simple CIP water cycle between the intervals of flushing the system with CIP acid and alkali. This is done after each chemical is pumped through the system, to ensure that there is no corrosive liquid left in the system and is all washed away with CIP water.

Piping and Bowl Material:

There are such materials that reduce the wear and tear and fouling effects on the efficiency of the process. This will ultimately lead to reduced maintenances and reduced downtime, which is why for both of these key components, stainless steel was the material of choice. Grade 304 stainless steel is known for its high thermal and corrosive resistance, in which both properties can prevent the increase in the rate of fouling and wear and tear of the material. Specifically, the grade 304H is the type of material chosen as it is a high carbon form with a carbon content between 0.04 and 0.1%. 304H stainless steel is often used in the food industry for a number of applications. These include cooking pots, cutlery, kitchen appliances and sinks because of its resistance to corrosion and high tolerance for extreme temperatures (Masteel, 2022). For the bowl of the separator, the SuperDuplex stainless steel. This material is also praised for its high thermal resistance and high corrosion resistance, making it ideal for dairy processing, where fouling can occur at high rates and is stated to be used in vessels and piping, which then led to the choice of this type of stainless steel for the bowl (Corrotherm International, 2019). It is important for the vessels and piping to be corrosion resistant, as there will be acid, water and alkali flowing through the system in intervals every start-up and shut-down.

Parameter Control Systems:

Control loops are added to the system to ensure that there is an accurate response to any fluctuations in the system and was designed with safety margins for pressure and temperature, where there would be a alarm going off if the safety margin is exceeded. A flowrate control loop was added to all of the inlets and outlets, this is because the flowrates can determine the temperature and pressure in the separator, therefore, the change in the process conditions are detected by transmitters, in which then it is electrically connected to the pressure indicator and controller, which detects the signals from the transmitter to process the information. This is then connected electrically to the control valve, which can open and close to counter the change in conditions in the separator. Accurate temperature sensors such as resistance temperature detectors talked about in the unit design and pressure gauges to detect the changes in the condition by both the control system and the personnel or operators. There are also temperature, pressure and level control loops, as all of these factors can affect the performance of the separator. With all of these control loops working together with accurate detectors, the probability of the system parameters falling out of the given ranges drops drastically. This will be discussed in further detail in the control and safety section.

3.2. Performance Evaluation

The Tetra Pak H80 centrifugal separator is one of the most important units in the whole fractionation process of milk. Achieving and maintaining the highest possible separation efficiency is the main goal with a performance evaluation, finding the factors that affect the performance that lie beyond just the process parameters and conditions. To further develop the design of the unit, the fundamentals of engineering need to be put into consideration, which may include pressure drop calculations across the separator, fouling rate within the unit and some non-Newtonian effects of our process fluids raw milk, skimmed milk and cream.

This is done to obtain a deeper understanding of the performance of the unit with the current parameters calculated and how these can be manipulated to design a more efficient centrifugal separator, whilst maintaining the product quality and minimising the energy consumption. By undergoing an optimisation process, as well as minimising the energy consumption, the potential damage to the unit is evaded and the product quality is maintained to a high standard, as promised to the customers that buy the Whey and Casein powder.

3.2.1. Pressure Drop

The pressure drop is an important parameter to consider in a centrifugal separator because it directly correlates with separation efficiency and energy consumption, which would be ideal to optimise, so that the OPEX is minimised and the separation efficiency is as stable as possible, at around 95%. As discussed before, the Darcy-Weisbach equation is inserted into MATLAB coding, to produce a 3D plot that shows the relationship between the 3 important parameters that was assessed in the design of the unit. These are the pressure drop across the unit, the pipe length and diameter.

Using these constants and equations, the MATLAB code is developed displayed the different pipe lengths and pressure drop that it generates in the unit, choosing the dimensions that would be deemed safe to operate, this code can be found in the Appendix, which led to the creation of the plot in Figure 5:

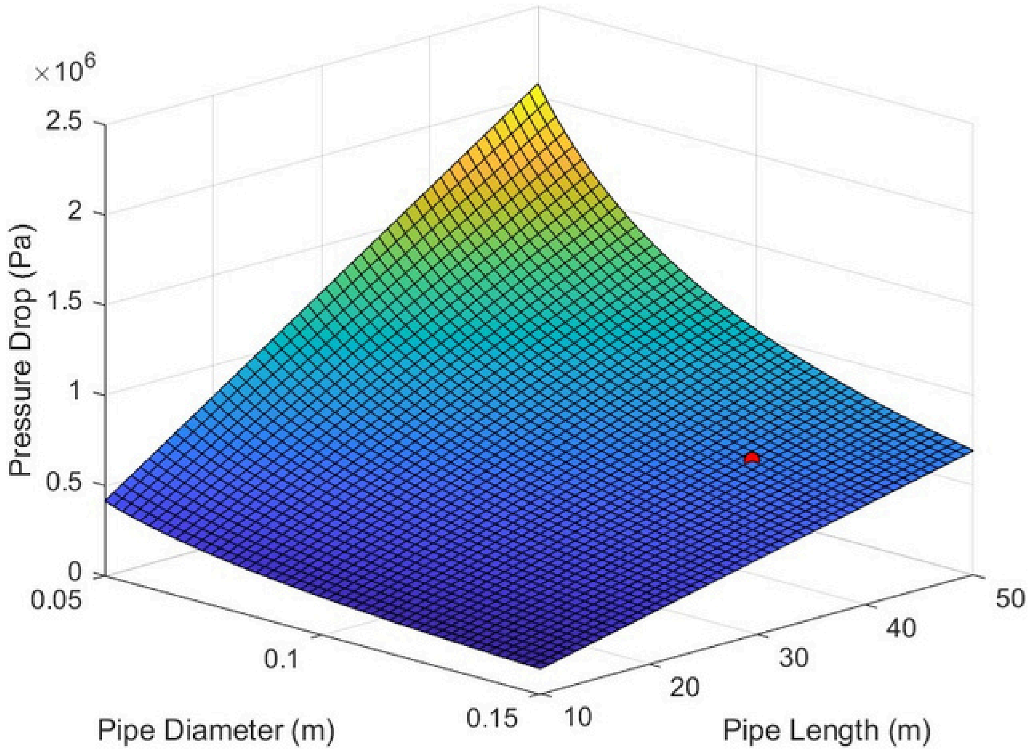


Figure 5: Graphical Relationship between Pressure Drop, Length and Diameter in a pipe

Analysing Figure 5, the general pattern is proof that the graph is consistent with the Darcy-Weisbach equation, where there is a directly proportional relationship between pressure drop and pipe length and an indirectly proportional relationship with pipe diameter. From this, the pipe diameter and length has to be identified which correlates with 0.65 x 10-6 Pa, which is the 650 kPa operating pressure in the unit. This is done to ensure that the pressure in the unit does not exceed this pressure and cause and damage to the operators, the unit or the components.

The pipe diameters for the raw and skim milk streams are roughly 0.1 m long in the calculations in the unit design, however, a script is added to find the optimal spot where the length and diameter intercept at a pressure of 650 kPa. For the cream outlet, this graph would not be used, as the diameter fall short of the range of values for the pipe diameter axis. Knowing that the separator operating pressure will be 650 kPa, a point on the 3D plot must be found that lies on the line for the diameter and at 0.65 x 106 Pa to find the correct pipe dimensions for this unit outlet and inlet. A marker was set at the pressure of 650 kPa, which corresponds to:

$$l_{Inlet\ Pipe} = l_{Outlet\ Pipe,Skim\ Milk} = 39.39\ m$$

$$d_{Inlet\ Pipe} = d_{Outlet\ Pipe,Skim\ Milk} = 0.1255\ m$$

Even though it could decrease the accuracy, the graph could be extrapolated to shorter diameters for the cream stream, which lowered the degree of accuracy. Therefore, the corresponding pipe length is:

$$lOutlet\ Pipe,Cream = 5m$$

The diameter of the outlet The analysis and optimisation of theTetra Pak H80 centrifugal separator is important for the design of the unit, was done by the observedrelationship between the variables in the Darcy-Weisbach equation. Not only does the optimisation reduce energy consumption and maintain efficiency in the fractionation process, it also prevents or decreases the rate of fouling significantly. It can also give an insight when choosing a pump that could give the process fluid the velocity and give the unit the separation performance required.

Although the graph seems to increase the precision of the design calculations, by displaying a visual relationship, it does also have its limitations. The graph was extrapolated to find the required length for the cream outlet pipe, this already gave the results a lower degree of accuracy. Another problem is that it does not take into account the fouling effects and the non-Newtonian properties of the milk in the separator, this will be discussed in the next section. Therefore, if these 2 factors are incorporated into the calculations, then the optimisation process will be enhanced and generate much more accurate data.

3.2.1. Non-Newtonian Effects

Milk can behaveasanon-Newtonianliquidasitsviscosityisaffectedbytemperature,fatcontent, protein content.Inskimmilk,caseinmicellesarethemaincontributorstotheviscosityofmilkanyfactors that alter the aggregationstateofcaseinmicelle,suchaspH,saltbalanceandheattreatment,affect the viscosity ofskimmilk(Bienvenue,Jiménez-FloresandSingh,2003).However,therearesome studies to showthatitcouldbetreatedasaNewtonianfluid,whichwillbeexploredinthissection.

This will happenparticularlywhenthefatandproteincontentofthemilkarehigh(Walstraetal.,2006). Non-Newtonianfluidshavedifferentvelocityprofilescomparedtothe Newtonianfluids,thiswillinturn decrease the measurementaccuracyofflowmetersthatrelyonexpectedflowvelocityprofiles(Alicat Scientific, 2021).Thisisbecausetheyhaveadifferentrelationshipbetweenshearstressandshearrate and the variablethatrelatesthese2factorsisthefluidviscosity.Withthis,itisapparentthattheviscosity of the fluidsarenotconstantandisdependentontheshearrate.ThisaffectstheReynoldsnumber,as the viscosityvalueisnotconstant,thenneitheristheReynoldsnumber,astheyareindirectly proportional,asseenintheequation,therefore,apparentviscositywillbeused.Thisisbasicallythe viscosityunderspecificconditionsandisdefinedastheratiobetweenshearstressandshearrateover a narrowrange(RosatoandRosato,2003).IfitaffectstheReynoldsnumber,thenitwillaffecttheDarcy frictionfactor.ThisisbecausethevariationintheReynoldsnumberwillmakeitmuchmorecomplexto findthefrictionfactorastheMoodydiagramcannolongerbeusedtocalculatethefrictionfactorand otherequationsneedtobeconsidered.Thiswillfinallyaffectthepressuredropcalculationsforthe centrifugalseparator,meaningthatitwilladdadegreeofuncertaintytothepressuredropcalculations andthereforeleadtoinaccuraciesinthedesigncalculationsandleadtoinefficientseparationinthe unit.

Topreventthis,thepowerlawmodelcanbeusedtoobtaintheapparentviscositydiscussed.Thepower lawischosenasitcanofferanewapproachtoanalysingthebehaviourofnon-Newtonianfluidsina muchsimplerwayanddoessowithagooddegreeofaccuracy (Barnes,HuttonandWalters,2023).In industrialapplications,havinganin-depthunderstandingofthisbehaviourcanhelpdesigntheseparator toahigherlevelofefficiencyandsaferoperationwhichcomeswithabettercontrolofhandlingthe milk'sunpredictablebehaviourwhenflowing.Thepowerlawmodeltocalculatetheapparentviscosity for the milk is expressed as the following equation:

$$\mu app = k??^{n-1} = k\left(\frac{du}{dy}\right)^{n-1}$$

Where: μ_{app} = Apparent Viscosity (Pa s), k = consistencyindex, $\left(\frac{du}{dy}\right)$ =shearrate(s-1)andn=flow behaviour index.

The consistency index is essentially a constant to expressthefluidsresistancetodeformation, whilst the flow behaviour index shows the rate of shear thinningofthickeningbythefluid.To calculate the shear rate, an equation is used that utilises the flowrate andtheradiusofpipescalculated previously:

$$\left(\frac{du}{dy}\right) = \frac{4F_{inlet}}{\pi r_{inlet}^3}$$

To find the consistency index of raw milk, the study donebyHernandezetal.(2013),showed that the consistency index of milk at 20 - 40°C had a range of0.03–0.06Pasn.Knowingthat the viscosity decreases with increasing temperature, a linear extrapolationcouldbeundergone,ifitis assumed that every 10°C increase in temperature leads to a 0.0015Pasn decrease,thentheconsistency index at 50°C could be 0.0285 Pa sn. The flow behaviour indexissaidtoremaincloseto1at the operating temperatures, meaning that after all, the milk can be treatedasafluidwithnearNewtonian behaviour.

Once the apparent viscosity equation is acquired, it can be incorporated into the Hagen-Poiseuille equation to give a modified form of this equation to plot the pressure drop with relation to the pipe length and diameter:

$$\Delta P = \frac{8\mu_{app}\, l_{Inlet\ Pipe}\ F_{inlet}}{\pi r_{inlet}^4}$$

A3D graph is drawn as a visual representation of how these parameters relate to one another with the inclusion of non-Newtonian properties, which can be seen in Figure 6 below:

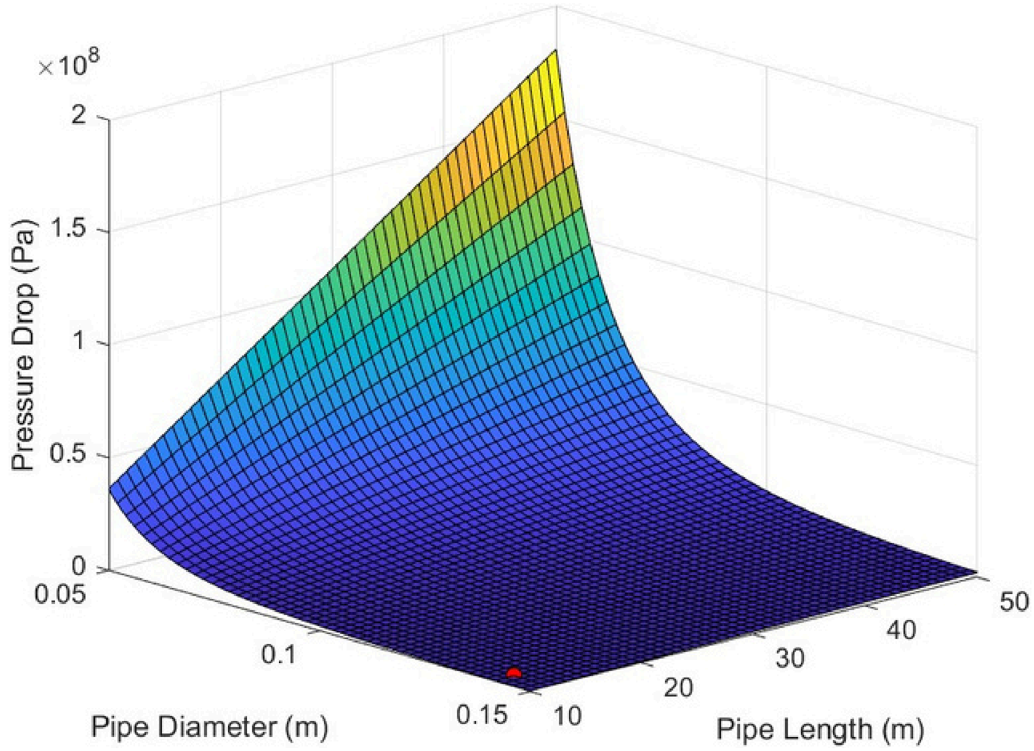


Figure 6: Relationship between Pressure Drop, Length and Diameter in a pipe including Non-Newtonian Properties

The objective of producing this graph was to understand the properties of the milk in the Tetra Pak H80 centrifugal separator, and how manipulating the dimensions of the piping can affect the overall efficiency of the system. The main goal in this optimisation process is to keep the pressure difference within the unit at 650 kPa. The code displays the pressure drop for a range of different pipe lengths and diameters, whilst marking the optimal point on the 3D plot, which shows the necessary dimensions required to operate the unit at 650 kPa.

The code written is essentially a calculation for the pressure drop, and how it changes with piping diameter and length. The relationship between pressure difference and pipe diameter and length can be seen in this graph, again, where the pressure drop and the diameter of pipes are indirectly proportional, whilst the pressure drop and pipe length are directly proportional. Again, a marker was added at the 650 kPa pressure and 0.1 m diameter. This time, however, the corresponding pipe diameter and length were generated in the script, which came out as:

$$l_{Inlet\ Pipe} = l_{Outlet\ Pipe,Skim\ Milk} = 11.63\ m$$

$$d_{Inlet\ Pipe} = d_{Outlet\ Pipe,Skim\ Milk} = 0.1418\ m$$

However, for the dimensions of the cream outlet, an extrapolation had to be done again, as the dimensions of the pipe diameter of 0.0122 m are outside the range that the graph was plotted. This point couldn't not be plotted into the graph, as the length required is also out of the range of the pipe lengths. Therefore, using the previous method considering non-Newtonian effects, the pipe length estimated was:

$$l_{Outlet\ Pipe,Cream} \approx 5\,m$$

When looking at the new results, after including the non-Newtonian properties of milk, the apparent difference can be seen from the original pressure drop calculations. When assessing the different pipe diameters and lengths from these 2 models, it can be seen that the difference between inlet and skim outlet on the original plot, 39.39 m, and the non-Newtonian plot, 11.63 m is a significant one. The difference between the pipe lengths after considering non-Newtonian properties, have decreased by 27.76 m, which shows that the inclusion of non-Newtonian properties can indeed affect the performance of the unit. The situation for the pipe diameters are similar, they have undergone change with the original calculations for the unit design showing a 0.102 m diameter, whilst the original plot and the non- Newtonian plot show 0.1225 and 0.1418 m, respectively.

For the outlier, the cream outlet for the unit was assumed to have the optimal diameter as one of the dimensions were required in order to extrapolate the length, which was done for the graphs. In the original unit design, the length was calculated using the Darcy-Weisbach equation, which gave a pipe length of 10.73 m. For the other 2 generated answers using MATLAB, the extrapolations gave the same values of around 5 m length, which shows a difference of 5.73 m between the calculations and the optimisations. This was expected as the relationship between the pressure drop and the non-Newtonian graph is visibly similar with the 3D plots having similar structures, in the identical range of values for the x, y and z axis'.

One of the most important factors is put into consideration next, which is an inevitability in any food processing plant, including the fractionation of milk. Fouling is one of the main problems in such industries and the fouling rates have to be considered in calculations of optimisation, this topic will be explored in the next part.

3.3.3. Fouling:

Fouling is the gradual formation of undesired deposits on the surfaces of equipment. In the context of dairy processing, these can be organic and inorganic material such as sugars, fats, minerals and proteins, it can also be particulate matter (Guerrero-Navarro et al., 2020). These can affect the overall performance and efficiency of the separator, it can affect the efficiency by forming an accumulation of particles on the surface of piping, walls of the bowl and the discs in the separator, increasing the surface roughness of the pipe.

Using a mathematical perspective, if the settling area for the light phase, the cream, consists of the sum of all the areas of the discs, the fouling will cover the surface area of the discs, decreasing the settling area and therefore the efficiency in separation in the unit. Another scenario could be that there is fouling on the walls of the pipes, which could lead to the constriction of the cross-sectional area of the pipe, which would cause for fluctuation of the flowrate into and therefore out of the system, causing for an unpredictable process. It may also cause for cross-contamination within the product, decreasing the quality and consistency of the skimmed milk, this one is the main problem that fouling brings as in the food and beverages industry, product quality and safety are taken seriously and customers and regulations have strict requirements. Another reason why fouling can be a problem in food processing, is the increased consumption of energy, this is because one the separation efficiency is lowered, the separator will have to work harder in order to achieve the separation that is expected from the unit. This can come with consequences such as the increase in the OPEX to keep the unit consistently running for 8 hour shift days. It can also lead to greater emissions of greenhouse gases, which would negatively affect and cause environmental problems. The fouling can also lead to wear and tear, meaning that it can reduce the lifespan of any component, and increase the probability of major damage to the components. The fouling cannot always be removed, there are some situations where a whole component of the separator need to be changed. This means that the frequency of maintenance will have to be higher to ensure that there is no significant damage to the system, which means that the whole system will have to be shutdown. This leads to increased downtime, and will lead to a decrease in yield from the process, as production is halted, it may mean that it can prevent the company from reachingitsrequiredannualproductionrate.Themaintenancealsocostsmoney,toreplaceorrepair any partsandthisontopofthesystemshuttingdowncanleadtoexcessivecostsfortheoperationof the unit.

Therefore,themainwaysthatfoulingcandecreasetheseparatorsperformance,isthatitcanreduce the efficiency,itcanaffecttheflowratecausingfluctuations,whichinturnwillaffectthepressuredrop, making itsbehaviourunpredictableandcanbedangerous,itcanincreasetherequirementsof maintainingandreplacingthecomponentsthatitdamages,whichinturndecreasesthelifespanofthe equipme nt.

There aremultiplewaystoreducefoulinginthesystemandminimiseit.Oneofwhichistheselection of appropriatematerials,whichiswhystainlesssteelischosenandiswidelypreferredinmany branchesoffoodandbeverageprocessing.Stainlesssteelhowever,waschosentominimisetheimpact of foulinganddoesnotdirectlydecreasethefouling.Asalreadystatedpreviously,stainlesssteelhas goodcorrosionresistanceandalreadybeingasmoothmaterial,thefoulingifminimised,willcause smalldifferencestothesurfaceroughnessofthepiping.Cleaningprotocolsthatwereimplemented earlierarealsogoodatthepreventionoffouling,theCIPsystemdesignedearlierwasoneofthe methods,thecirculationofthealkali,acidandsanitisingsolutionwilleliminatetheaccumulationof organicdepositsmeaningthatlessfoulingwilloccur.Specificcleaningagentsandoptimalcleaning processconditionscouldalsocontribute.Antifoulingcoatingcouldalsobeimplementedintotheinner surfaceofthepipesandbowloftheseparator,astudyundergonehasshownthesuccessofusing amphiphilicsiliconecoatingsfordairyfoulingmitigationonstainlesssteel.Itwasstatedthatthesilicone coatingappliedtopre-treatedstainlesssteelwasexceptionallyresistanttofouling.Afterfivecyclesof pasteurization,thesecoatedsubstrataweresubjectedtoastandardclean-in-placeprocessand exhibitedaminorreductioninfoulingresistanceinsubsequenttests.However,thelackoffoulingprior to cleaningindicatesthatharshcleaningisnotnecessary (Zouaghietal.,2018).Thefinalandmost importantwaytomitigatefoulingisthefrequentmonitoringandcontrolofthesystem,themainaimof this constantmonitoringistopreventtheneedtomaintenanceandreplacingofpartssothatthe downtimeisalsominimisedandtheprocessisnothalted.Controllingtheconditionsoftheprocesswill mean controllingthetemperatureat50°Candnotexceedingitsothattheproteinswillnotunfoldand denature,whichcanincreasethefouling.Additionally,thefluidvelocityshouldalsobecontrolledtoa reasonablevalue,astheincreaseinfluidvelocitywillincreasetheshearstressapplied,meaningthat again the3Dproteinstructureiscompromisedandtheproteinisdenatured.Thedenaturationof proteins istheorganicmatterthatusuallyaccumulatesandformsthefouling,therefore,aswellas maintaining the process parameters, the protein structure integrity should also be maintained. The

mathematicalanalysisofthisisdoneby,again,incorporatingtheDarcy-Weisbachequation.Except this time, insteadofthedarcyfrictionfactorfromtheMoodydiagram,itwillbecalculatedviaiterative methods. Thisisbecause,asalreadystated,thefoulingcancausealayerofaccumulatedmaterial, which will affecttheroughnessoftheinnersurfaceoftheunitanditscomponents,increasingit.The relative pipe roughnesscalculatedwillsimplybetoohighandoutsidetherangeofvaluesoftheMoody diagram, therefore,theColebrook-Whiteequationisintroduced,whichusesiterativemethodstofind the friction factor (ĆojbašićandBrkić,2013):

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{2.51}{Re\sqrt{f}} + \frac{\varepsilon}{3.71 d Inlet\ Pipe}\right)$$

The calculations were done on MATLAB via iteration, and concludedthatwiththegivenparameters, the friction factor for the normal pipe was, 0.0015. For the fouling, a newroughnessshouldbeidentified. The lack of literature specific to fouling in the pipes in the dairy processingindustryhasledtotheuse of a study done on fouling in heat exchangers in dairy processing, whichstatesthatitcouldbeina range of 0.05 and 0.1 mm (Datta, 2008). The absence of a heat exchangerhasledtotheassumption that the lowest value would be used due to a lack of a heat source willmaketherateoffouling significantly slower, meaning there will be the least amount of fouling in apipe,whencomparedtoa heat exchanger. Therefore the assumed value for the pipe roughness in thissystemwillbe0.05mm. With this, all of the variables required for the iteration are obtained, These calculationsareincorporated into the MATLAB code to generate an accurate graph. The equations are displayedbelow:

$$\frac{1}{\sqrt{f_{Normal\ Pipe}}} = -2\log\left(\frac{2.51}{Re\sqrt{f_{Normal\ Pipe}}} + \frac{\varepsilon_{Normal\ Pipe}}{3.71 d_{Inlet\ Pipe}}\right) \therefore f_{\ Normal\ Pipe} = 0.0113$$

$$\frac{1}{\sqrt{f_{Fouled\ Pipe}}} = -2\log\left(\frac{2.51}{Re\sqrt{f_{Fouled\ Pipe}}} + \frac{\varepsilon_{Fouled\ Pipe}}{3.71 d_{Inlet\ Pipe}}\right) \therefore f_{\ Fouled\ Pipe} = 0.0164$$

With this, the pressure drop can be calculated, including the fouling, non-Newtonian effects and the pressure drop, which will then be plotted on a 3D coordinate to find the optimal parameters for the piping. This graph can be seen in Figure 7 displayed below:

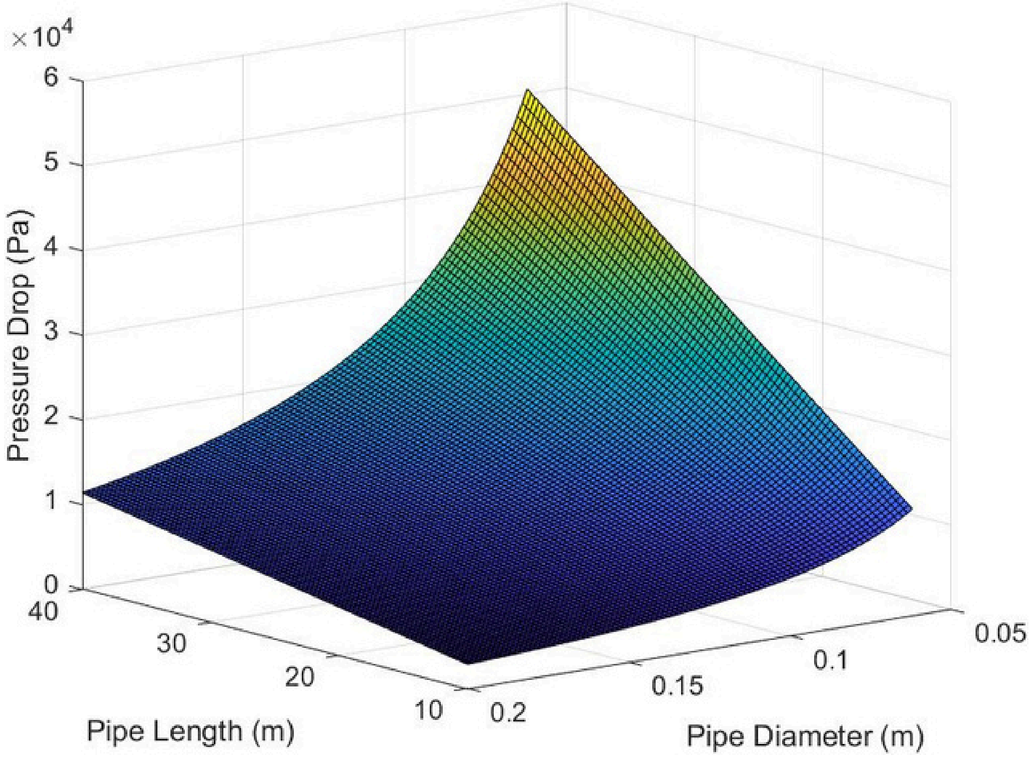


Figure 7: Relationship between Pressure Drop and Pipe Dimensions including fouling and non-Newtonian properties

As one can see from the graph, with fouling present, the pressure drop of 650 kPa cannot be achieved with the maximum pipe length and diameter, it is calculated that pipe lengths of up to 500 m are required to achieve a 650 kPa pressure drop. These are not realistic dimensions that can be present in any food processing plant, therefore another graph should be plotted. This graph will assume that the optimal conditions for the pipe dimensions are an average taken between the Pressure drop, the non-Newtonian graph and the original design calculations. The calculations can be found in the Appendix, where the calculated dimensions are:

$$l_{Inlet\ Pipe} \approx l_{Outlet\ Pipe,SkimMilk} = 20.25\ m$$

$$d_{Inlet\ Pipe} \approx d_{Outlet\ Pipe,SkimMilk} = 0.1224\ m$$

$$l_{Outlet\ Pipe,Cream} = 6.91\ m$$

$$d_{Outlet\ Pipe,Cream} = 0.0122\ m$$

With these dimensions, the relationship between fluid velocity andpressure drop is expressed but with the presence of fouling. If the dimensions are not realistic to achievesuch pressure drops, then the fluid velocity can be manipulated to achieve such pressure drops withthese dimensions, once again, the Darcy-Weisbach equation is utilised, where the fluid velocity againstpressure drop will be plotted, on a 2D graphs this time, which can be found in the Appendix.

With this, it can be seen that it would be impossible to achieve a pressure drop of 650 kPa within a range of 0.5 to 5 m s-1. The general pattern of the graph is that the pressure drop exponentially increases with increasing fluid velocity, the problem arises when it is realised that to achieve the desired pressure drop, an extrapolation is required to estimate the fluid velocity at 650 kPa. The fluid velocity will need to be above at least 5 m s-1, which means that the velocity will have to be above the safe range of values with centrifugal separators, being between 1.5 and 2.5 m s-1. This seems to be higher than the usually encountered velocities.

High fluid velocity means that a greater shear stress will be applied to the walls of the pipe, which will lead to further wear and tear. This in turn means that more maintenance runs will have to be done to prevent the damage to the equipment and the downtime of the process will increase and lower the overall yield of the process. The increase in shear stress will also cause for lower quality product being produced, because the shear forces will promote structural modifications of the milk proteins leading to unfolding via denaturation and subsequent interactions (Gedara, Thejangani and Mediwaththe, 2017). This brings the problem of trade off in achieving the desired pressure drop and the velocity being within acceptable ranges.

These problems may have risen from the assumptions and design parameters made for the graphs and calculations. They may have not been the suitable dimensions or assumptions for this specific unit or process and applying such concepts could lack specificity to the actual process of fractionation of milk to produce Whey and Casein powder. In an actual application, the design of this unit would require the compromise in one of the 2, velocity of pressure drop, it is assumed that the ideal pressure dop would be 650 kPa, however, the unit can actually run efficiently between pressures of 600 – 700 kPa, therefore the leeway that this provides may not even cause for such a significant compromise in a real application. This leeway could mean that in application, the fluid velocity may lie in the acceptable limits of fluid velocity in a milk processing scenario, as well as generate a pressure drop between the safe parameters as given in the Tetra Pak H80 separator manual.

Overall, the aim of such optimizations are to achieve an equal trade-off between the design of parameters of the unit and a desirable pressure drop in the separator to achieve the required separation efficiency and produce high quality products. This optimization process has shown how imperative it is to consider the non-Newtonian and fouling properties of the fluid and system, respectively. Even though the optimization yielded high values of pipe dimensions and fluid velocity, a more suitable result should be achieved when considering the system parameters of the specific fractionation process, which will end up with acceptable values for the design of the centrifugal separator. By also implementing mitigation strategies, the rate of fouling can be maintained, the effects of fouling on the system can be minimised and the efficiency of the unit can be maintained, all whilst increasing the life span of the unit and its components.

4. Mechanical Design

4.1. Material Selection

As discussed previously, the material chosen for the piping and the bowl of the separator must be thermal and corrosion resistant. It must also be able to withstand the process conditions with no issue or damage to the piping and bowl.

Piping:

Stainless steel is our choice for the pipe material, especially grade 304. Grade 304 is the choice as it is the preferred material for both the pasteuriser and the centrifuge, as these 2 units will be connected, it is the most suitable material, as stated by the International Stainless Steel Forum (Sustainable Stainless, 2010). It can also be the material of choice as it is stated to be durable and is corrosion and oxidation resistant, meaning it can endure average exposures. Its melting point ranges from 2,550° F to 2,650° F, allowing it to withstand very high temperatures (Nicole, 2021).

It has already been stated that Grade 304H will be chosen specifically. This is because it is the preferred material for food and beverage processing and is commonly used in many process vessels and piping. It also has higher carbon content, which gives the material greater heat resistant qualities and higher tensile yield strength, which makes the unit sturdy (Aalco, 2013).

Bowl:

The bowl of the separator is stated to be a certain grade of super duplex stainless steel. Super duplex is a shorthand term for a family of high-performance stainless steels designed with around 25% chromium content in the alloy's makeup. This family of alloys have a microstructure made up of both austenitic, containing austenite, and ferritic, containing iron, grains of steel (Langley Alloys, 2022). The material chosen, UNS32750 Super Duplex Steel, was selected due to the following benefits (Masteel, 2017): Improved corrosion resistance in comparison to Duplex, Greater tensile and yield strength, Good ductility and toughness, Good stress corrosion cracking resistance (SSC) and Opportunity for purchases to reduce their material costs without compromising on quality. Super duplex steel can operate in conditions of up 150°C (TWI, 2023) to 200 MPa (Special Piping Materials, 2015). UNS32507 is the most common Super Duplex alloy which contains 24% chromium and a minimum of 3% molybdenum (AZoM, 2009). The molybdenum increases strength, hardness, hardenability, and toughness, as well as creep resistance and strength at elevated temperatures. It improves machinability and resistance to corrosion and it intensifies the effects of other alloying elements (Diehl Tool Steel, Inc, 2020).

Anti-Fouling and Anti-Corrosion Treatments:

Anti-fouling and anti-corrosion treatments can be applied to the materials. These are treatments done to the material to reduce the negative effects of fouling and corrosion to improve the equipment lifespan and ensure optimal performance. These can come in the form of coating, epoxy coatings have been widely used for corrosion resistance. The epoxy/graphene possesses highly hydrophobic surfaces, water contact angle, and moisture resistance properties. Epoxy polymer has better heat stability, toughness, adhesiveness, and chemical resistivity (He et al., 2021). For the anti-fouling treatment, amphiphilic silicone coatings are used. in a study on fouling mitigation from amphiphilic silicone coatings, it was found that silicone coating applied to pre-treated stainless steel was exceptionally resistant to fouling (Zouaghi et al., 2018). These coatings could be applied to the inner surface of the piping and the bowl to ensure that the negative effects of fouling and corrosion are minimized.

4.2. Thickness and Weight of Unit

For the calculations, only the thickness of the bowl, discs and piping and weight of most components, including motor and frame/base to keep in into position. The first step for this section will be to calculate the thickness of the separator walls. It is important to do such calculations as the weight of the separator will then lead to deciding the transport of the unit, assembling, securing to ground, etc. The thickness can tell about the actual sizing of the pipes, as the thickness will now be added to your diameter of pipes and give its real dimensions, which can be important for the calculations of layout of the plant and to see if it looks like a feasible value and that there are no errors.

4.2.1. Thickness of Piping and Vessel

Bowl: When ensuring the safe deign of bowl and piping of the Tetra Pak H80 centrifugal separator, it is

required
to adhere to the ASME Boiler and Pressure Vessel Code (BPVC). The ASME BPVC is the standard for the safe design, manufacture and maintenance of boiler and pressure vessels, power-producing machines and nuclear power plant components. Today, more than ever, ASME BPVC users around the world – boiler and pressure vessel manufacturers, operators, stamp holders and inspectors – rely on updated information in the latest version of the ASME Boiler and Pressure Vessel Code to ensure safety and compliance (S&P Global, 2023). Division 1 is chosen for the bowl ASME BPVC Section VIII because it seems to have a wider acceptance is industry, adhering to these regulations and rules will insure that the design can be easily accepted by any clients interested.

For the bowl of the separator, some assumptions are going to be made, the shape of the Tetra Pak H80 is conical and the frustrum of the cone will be the same diameter as the inlet pipe diameter. This assumption is based off the geometrical similarity of these 2 parts of the component, as the exiting cream and skim milk through the frustrum and the inlet seem to have similar dimensions. The semi apex angle (α) is the easier variable to calculate and is necessary for the next steps. α can be calculated by basic trigonometry:

$$\alpha = Arctan(\frac{R}{H}) = Arctan(\frac{0.514}{2.056})$$

$$\therefore \alpha = 0.4636\ Radians$$

Once this angle is calculated, the thickness of the Tetra Pak H80 bowl walls can be determined according to the ASME BPVC regulations. The joint efficiency is essentially the reliability of the joints, and these welded joint are checked with radiography to ensure it is fully welded and no exposure to atmosphere (ESAB University, 2020). It can be seem in the Joint Efficiency and Code Reference in ASME Section VIII, Div.1 that out efficiency for a single welded and fully radiographed joint is 80% (Inspection LLC, 2013). The corrosion allowance for super duplex stainless steel is stated to be 0.008 m (Wermac, 2023). The maximum allowable tensile stress on super duplex steel is stated to be 206 MPa and the manufacture tolerance is 12.5% with these properties, the equation for the thickness of the vessel is displayed below:

$$t_{Vessel} = \frac{P \times dbowl}{(2Cos(\alpha) \times S \times E) + (0.4P)} + C$$

Where: P = Internal Pressure of Vessel (Pa), rbowl = radius of the bowl(m), S = Maximum allowable stress on material (Pa), E = Joint efficiency (%), C = Corrosion Allowance (m), M = Manufacture tolerance (m) and α = semi-apex angle for the conical reactor (Radians).It can therefore be concluded that the thickness of the bowl of the separator walls are:

$$t_{Vessel} = \frac{650000 \times 1.028}{(2Cos(0.4636) \times 206000000 \times 0.8) + (0.4 \times 650000)} + 0.008$$

$$\boldsymbol{tVessel} = 0.01026\ m = 10.26\ mm$$

Multiply this by the manufacture tolerance to obtain the total thickness of the wall of the separator:

$$t_{Bowl} = t\boldsymbol{Vessel} \times 1.125$$

$$\therefore t_{Bowl} = 0.01154\ m = 11.54\ mm$$

Therefore the thickness of the wall of the separator must be 10.26mm to be able to safely withstand the pressure in the system, being 650 kPa, which also takes intoaccount the corrosion damage so extra allowance thickness is added for super duplex.

Piping:

The equation needed for the thickness of the piping, is Barlow's formula, which is as displayed below. The Formula relates the internal pressure that a pipe can withstand to its dimensions and the strength of its materials (American Piping Products, 2021):

$$t_{Pipe\ Inlet} = [\frac{dInlet \times P}{2SE} + C]M$$

Where: $dInlet$ = Inlet Diameter (m), and the other variables in theequation are identical to the previous. Although all 3 inlets and outlets have to withstand the process pressure, they have different diameters, as concluded in the mass balance, the thicknesses of the respectivepipes are:

$$tPipe\ Inlet = 0.00226\ m = 2.26\ mm$$

$$tPipe\text{–}Skim\ Outlet = 0.00223\ m = 2.23\ mm$$

$$t_{Pipe-Cream\ Outlet} = 0.000541\ m = 0.541 mm$$

Assumptions: In this section, the pipe and vessel thicknesses havebeencalculated with respect and adherence to the ASME B31.3 standards. The equations used tocalculatethethickness values use assumptions to simplify such relationships that are affected by numerousvariables.These can include perfectly welded joints, where there are no inconsistencies detectedwithradiography, steady-state conditions, temperature and pressure uniformity in the vesselsandpipes,thickness calculated is identical at all points in the vessel, the shape is assumed conicalandnotaveryaccurate depiction of the Tetra Pak H80. Another assumption would also be homogenousandisotropic material of the piping, where the physical properties are identical in every point in thematerial,whereas, isotropic materials mean that the physical properties are identical in all directionsanddimensions (Thomas, 2023). One can also assume that the materials, stainless and super duplexsteelfollowHooke's law, in which:

$$Stress \propto Strain$$

Within the elastic limits, it can be assumed that deformationsarereversible and therefore negligible and the material can return to its correct form once thestressinremoved.

4.2.1. Weight of the Unit

This section will show calculations to ensure that the values calculated for the weight of the unit are backed by mathematical equations and is accurate. If the weight of the unit is given, then the structural support can be designed to hold the unit steadily in place and can support the weight throughout the process and any process errors that may occur. It also provides information for transport, as the weight and size can determine what kind of transport method should be used to support it and these 2 factors can also determine the pricing of the unit, as most materials are sold per kg, and this total weight can ensure that all the material can be bought in wholesale with extra to account for any error that may occur in production.

The individual calculations can be found in Appendix 2, the weight of individual components and their respective manufacturers can be seen in Table 2 below:

Table 2: Weights of each component of the Tetra Pak H80 Separator and respective manufacturers.

Component	Weight (kg)	Manufacturer
Bowl	64.13	Tetra Pak
Piping	253.37	Thyssenkrupp
Valves	426	Samson
Pumps	350	Alfa Laval
Motor	78	Siemens
C.I.P. Total (Approx.)		
Total		

Temperature, Pressure and Expansion Effects

Separation in the Tetra Pak H80 centrifugal separator occurs in specific conditions of 50°C temperature and 650 kPa of pressure. These conditions are vital to achieve maximum separation efficiency and produce a high volume of Whey and Casein powder that is both high quality and safe from contamination. However, there are cases where the materials of the unit are subjected to these harsh conditions for excessive amounts of time, which contribute to wear and tear, thermal shock, mechanical stress, etc. To maintain the performance of this separator, the effect that these conditions have on the material is important, to ensure separator reliability.

4.2.2. Effects on Mechanical Properties

The material of choice was Grade 304H stainless steel and UNS32750 Super Duplex Steel for piping and bowl, respectively. Stainless steel is stated to be an ideal choice for materials for components in dairy processing. Throughout this process, the stainless steel will maintain good tensile strength, exceptional corrosion and thermal resistance, these 2 properties ensure suitability to the high temperature and pressure environment as well as resisting the high and low pH of the CIP solutions during cleaning.

Temperature:

Temperature fluctuations can affect the properties of the stainless steel types chosen for both the piping and the bowl, This can lead to thermal fatigue, and the sudden expansion or contraction of the material. Thermal shock on the materials is discussed in the Cleaning and Maintenance sections. If thermal expansion or contraction happen suddenly, this can lead to cracks and irreversible damage to the components. The volume of any material, especially steel, will change with temperature, which will lead to changes in the geometric dimensions of the material, resulting in deviations in width and thickness. Therefore, the thermal effect (ie, thermal expansion) of the volume of steel materials will directly affect the accuracy, product qualification rate and yield of hot-rolled products, and accurate measurement of the thermal expansion coefficient of the strip material is the premise to correct the dimensional errors caused by thermal effects (HSCO, 2023).

Pressure:

There may be cases where the pressure fluctuations inside the system are significant, this is where the yield and tensile strength are affected. Yield strength is the point of irreversible deformation of the material, in the case of dairy processing, the material chosen has a yield strength greater than the operation pressure, meaning that a risk if deformation from pressure is low in the pipes and bowl. Tensile strength can also affect the properties as this is how much a material can be stretched without breaking. If the components were not designed to withstand such pressures and forces, it could lead to a rupture in the system, exposing the system and damage to personnel and equipment. Fatigue can also affect the material, this is a common occurrence due to the cyclical nature of pressure and stress on parts and components (Fushun Special Steel Co., Ltd, 2022). Constantly being under high temperature and pressure could eventually lead to fatigue in the material, leading to small cracks, which can lead to decrease in yield and eventually failure of the process.

4.3. Design Procedures and Codes

Design procedures and codes are put in place to ensure a safe design of pressurised vessels and pipes. The design must adhere to these codes to ensure that it complies with the industry standards in efficiency and safety. . The American Society of Mechanical Engineers (ASME) develops standards for compressors, flow measurement, environmental control, piping, pressure vessels, pumps, storage tanks, turbines and much more. The most referenced code is the ASME Boiler and Pressure Vessel Code (learn more) which is widely used worldwide by manufacturers, technicians and inspectors (Accuris, 2021).

4.3.1. ASME B31.3

The procedures and codes that are included in the ASME B31.3 are set to ensure that the design of the pipes concur with the guidelines when choosing the materials, designing the pipes and testing. ASME B31.3 contains requirements for piping typically found in petroleum refineries; chemical, pharmaceutical, textile, paper, semiconductor, and cryogenic plants; and related processing plants and terminals. It covers materials and components, design, fabrication, assembly, erection, examination, inspection, and testing of piping (ASME, 2022). Compliance with this code is usually a legal requirement, because there may be national or international regulations that make this a mandatory procedure for any design process including piping design, however, this is not the case because standards become mandatory when they have been incorporated into a business contract or incorporated into regulations (ASME, 2023). Also, if it is a nationally or internationally recognised and mandatory code, it will ensure easier communication of design methods for engineers of different backgrounds of educations, which makes communication between design teams efficient. It is stated by ASME that careful application of these B31 codes will help users to comply with applicable regulations within their jurisdictions, while achieving the operational, cost and safety benefits to be gained from the many industry best-practices (ASME, 2022).

4.3.1. ASME BPVC Section VIII – Division 1

The BPVC in the name of this procedure and code stands for Boiler and Pressure Vessel Code, section VIII division 1 is the guideline for the design of pressurised vessels, which is exactly what the Tetra Pak H80 separator is and therefore is applicable for this context. These guidelines must be followed to design the Tetra Pak H80 so that the separator can withstand the optimal conditions for the process to have as high efficiency as possible during the skimming process. It is important to comply with these codes and procedures as it enables a safe design that can contain the harsh conditions needed for the skimming process and prevents any ruptures or explosions that may occur if designed inefficiently. This can cause excessive damage to the equipment and be potentially fatal for the operator but also increase the OPEX because if the vessel is barely withstanding the pressure, then the separator will need components being replaced and need more Much like the ASME B31.3, these codes, there may be cases where it may be mandatory to ensure that every designed pressurised vessel is efficient, safe and has maximum production. This is confirmed as the 2021 Edition of Section VIII, Division 1 of the ASME Boiler & Pressure Vessel Code has added Mandatory Appendix 47, "Requirements for Pressure Vessel Designers". This mandatory appendix specifies the qualification requirements of those individuals involved in the design of pressure vessels (Hedderman, 2021).

4.3.2. 3-A Sanitary Standards and Practices

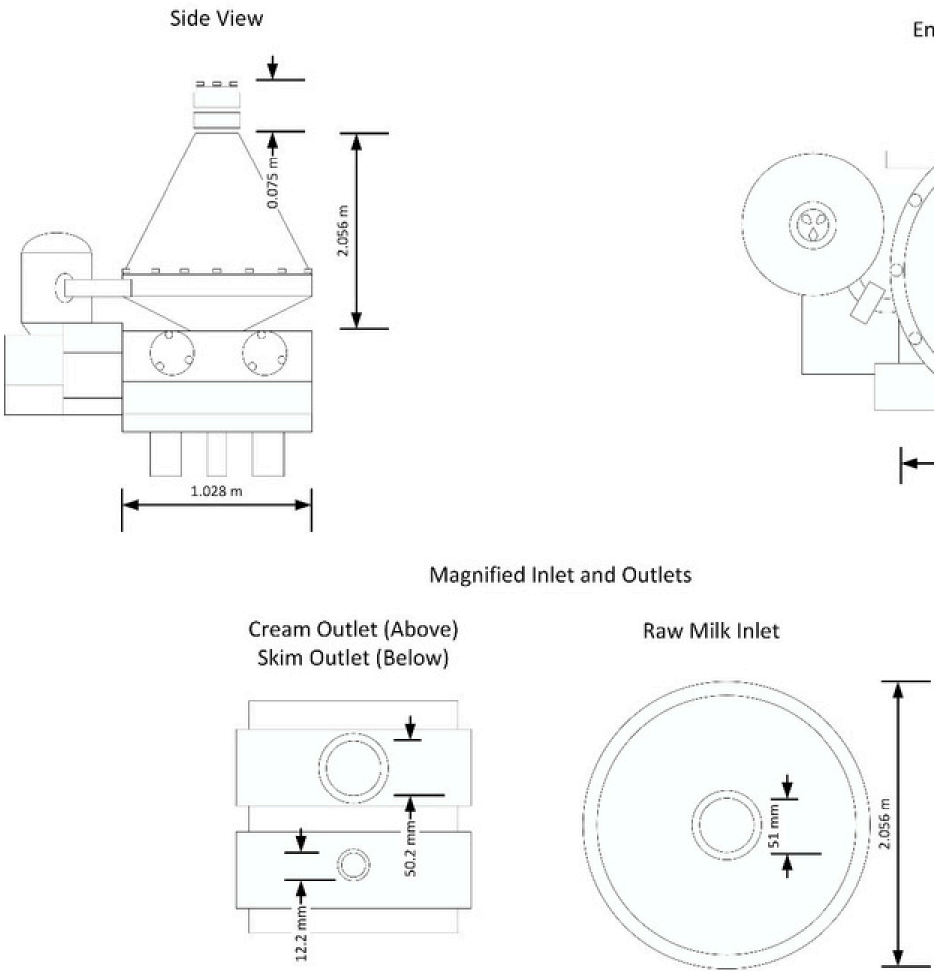
Food and beverage production are very strict when the hygiene of the food is considered, as the consumption of any unhygienic or contaminated product can pose a health hazard for the consumer. For this not to happen, there are a set of standards set that ensure that these problems are prevented. 3A standard has been formed by the US food and dairy industry, 3A Sanitary Standards Inc. It defines specifications and best practices for the project, manufacture, fitting, and use of hygienic equipment. It is globally established and intended to protect consumers from potential risks of food contamination (M Barnwell Services, 2022). As it is globally established, it means that it is a mandatory practice and the process design must comply with the standards set. There are benefits to complying with these practices, the main one being obtaining the 3-A symbol, which shows the customers that the food produced is safe and has little risk of contamination, this means that the company will gain the customer's trust, as well as preventing any contamination of the food. As well as this, it may look good to businesses as they will have access to such information. 3-A standards are designed to be clean and sanitized in a simpler way, reducing the OPEX and other maintenance costs. With the customer trust, it can also bring marketability, as there may be some customers buying the Whey and Casein powder which require the 3-A symbol and proof of compliance to the sanitary standards.

4.3.3. Validity of Practices

These design cods and procedures are proven to be valid due to the number of times it is referenced in vessel and piping design literature. In the unit designs undergone online, they state that the methods described in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code (BPVC) should be used to analyse the structural soundness of the units (Narug, Passarelli and Parise, 2022). The 3A sanitary standards have been applied to many cases of dairy processing design, where the objective is to establish that the material is capable of resisting the frequent cycles of cleaning and sterilising (M Barnwell Services, 2022). The process of selecting appropriate design codes and practices was undergone by considering the process background and purpose, whilst also considering the design limitations. These codes and procedures ensure that the design complies with internationally accepted methods and regulations, which will lead to a safe, reliable and efficient centrifugal separator.

4.4. Mechanical Drawings

Figure 8: Side, End and Magnified views of Tetra Pak H80 and its inlet and outlet streams.



5.P&ID, Control Systems and Unit Safety

5.1. Piping and Instrumentation Diagram

A P&ID is a piping and instrumentation diagram which shows the whole process of the unit, showing upstream and downstream flow, with all the components and the control systems included. It displays how all of these components interact with each other to achieve optimal and safe operation.

In this design, a Tetra Pak H80 Centrifugal Separator is analysed, which is an essential unit for any dairy processing which requires the reduction of fat in raw milk, after pasteurisation. In this context, it is a part of a greater process which is the fractionation of raw milk, to produce Whey and Casein powder to be sold in bulk to the larger companies that sell supplements. The P&ID for this unit should include information that shows: the location of the inlet and 2 outlets for cream and skim milk, valves, pumps, pressure and temperature sensors, flow transmitters and other control measurements to ensure the separation efficiency of the unit is as close to 95% as possible.

Having a detailed P&ID is imperative as it allows for easier communication of information between individuals in an engineering team, with this the team can also suggest any improvements and modify the system if required. A P&ID also ensures a safe and efficient operation as the Tetra Pak H80 is designed to. With this, a P&ID is designed to be clear and easy to understand, it should also align with the industry standards and be understood and correctly interpreted by an engineer that analyses the diagram.

Notes for the P&ID:

- The TE in the Resistance Temperature Detector (RTD) stands for 'Temperature Element' which detects temperature of the fluid flowing through the piping.
- Blacked out valves are fittings that would be closed during normal operation and opened when the control systems are under maintenance.
- The indicators which are linked via piping connections to the separator are capable of controlling their status, meaning they can detect high and low boundaries of the parameters of the system and on and off meaning no manual intervention is required.

To ensure that the P&ID is easy to read, colour coding is added to the different nodes, with the separation of the P&ID into these nodes, the system can be analysed with minimal confusion and again makes the diagram easy to interpret for other engineers to analyse. These nodes are the raw milk inlet, cream outlet, skim milk outlet, the pressure safety system and the Tetra Pak H80 Separator itself. The whole of the CIP is a separate node which will be analysed later. With this, the analysis of the P&ID control loop for the main unit can begin.

5.2. Control Strategy

In the chosen Tetra Pak H80 centrifugal separator, the control system has been designed for optimal and safe operation, the control loops ensure that the unit operates in the desired parameters for flowrate, pressure and temperature. The control strategy also utilises advanced control techniques, such as PID (Proportional-Integral-Derivative) control.

5.2.1. Temperature Control Loop

Temperature control is essential for the unit to operate at the desired efficiency. However, the temperature does not only affect the separation efficiency of the unit. A significant fluctuation of temperature in the system will affect fluid properties such as viscosity, density and specific heat capacity, it may also cause for acceleration in the rate of fouling in the piping and the separator bowl. Temperature increases may cause for the viscosity of the fluids to decrease which may increase the separation efficiency as the centrifugal force acts higher forces on the fluid particles in the centrifuge. On the other hand, high temperatures cause for increase in hazards and unpredictability in the system, meaning that the operator of the unit will be in danger and the separation efficiency and pressure of the system will fluctuate. The reason why a lack of temperature control would be bad is because it causes performance and safety problems with the unit, deviating the separator from optimal operation.

Temperature transmitters (TT) are used in this system to measure the temperature of the fluids in the separator, however, they are labelled as Temperature Element (TE) which is the resistance temperature detector, this component sends signals via electrical connections to the temperature indicator and controller (TIC). In the 1st and 3rd node, it can be seen that there is a resistance temperature detector present, which is connected to a thermal safety switch (TSS). The resistance temperature detector is directly connected to the TSS via electrical connection, which provides for a precise temperature control of the fluid. The RTD is then directly connected to the piping which detects the temperature change, as already stated, , they measure the temperature of materials that have a predictable change in resistance as the temperature of the material changes. The TSS is connected directly to the separator, which is also connected to a thermal safety switch and a temperature alarm. These will detect any significant changes in the temperature, where the alarm will go off when the temperature exceeds around 54°C, the alarm will set off to warn any operators or personnel in close proximity, the thermal safety switch will then shut down the separator before the system continues to increase in temperature and increase the probability of a dangerous hazard occurring. In the 4th node, it is apparent that there is a lack of a temperature control loop, this is because of a few factors. The main one is the cost considerations that come with adding as many control loops as possible and deciding whether it may be a necessity to add them to the undesired product stream, even though, the cream may generate income. Adding an extra control loop means an increase in total price of components used in the unit design, as the main product is the Whey and Casein, the majority of the efforts should be placed into keeping them as high quality as possible as these products are the priority of the whole fractionation process of milk. Also, the quality of the cream will have no impact on the quality of the Whey and Casein powder produced at the end of the fractionation process. An example may be that the final use of the cream product could be at higher temperatures in another section of the fractionation process therefore the temperature control at around 50°C may not be important in its processing. This could then mean that manual operator inspection may be enough, this node of the process may not be highly automated and just monitored by personnel to make sure that there is no dangerous temperature rise in the cream temperature. For this reason, only a temperature transmitter is installed in the 4th node.

The temperature indicator and controller are then connected to a control valve which adjusts the flow of fluid through the pipe depending on the signal that is transmitted and ensures that the temperature is as close to the setpoint of 50°C that the system was designed to operate at. A PID control loop is integrated into the control systems, which ensure a precise temperature control and to minimize deviation from the setpoint temperature of the system, which will increase the efficiency of the process. The way a PID control loop operates is that it will regulate the heat transfer flow via the control valve (CV) depending on the error between the measured temperature in the pipe and the designed temperature setpoint of the system. The proportional component will adjust the control valve so that it is in proportion to the error, the integral component will accumulate the error over time, which will get rid of any steady-state offset, finally, the derivative component will predict any future changes that could occur and will make the fluctuations from the setpoint much smaller, which will increase the stability of the system. This type of control loops will ensure that the fouling is minimal inside the components and the separator, as well as maintaining the optimal separation efficiency in the unit.

5.2.1. Pressure Control Loop

As well as temperature control, a pressure control is also needed as these 2 parameters are related to each other proportionally, therefore if a system has a temperature control, it must also have a pressure control. The aim of a pressure control is to maintain the unit pressure at around 650 kPa as this is the optimal pressure that the Tetra Pak operates at, which is stated in the Tetra Pak H80 Separator manual. Temperature control is crucial as any fluctuations in pressure in the system will affect the separation efficiency and also pose a danger to anyone in close proximity to the system. Another disadvantage that it may bring is that it will increase the energy consumption of the separator, as higher pressures mean higher energy consumption to operate, this brings problems such as higher OPEX for the unit and also could have environmental impacts.

In the 1st node, it can be seen that there are only pressure gauges that are there for inspection by personnel so that it can bring about easy troubleshooting with issues related to pressure. It also should be considered that there is already a temperature control loop for this node, meaning that the temperature is already controlled. This is enough because as already stated, pressure and temperature are directly proportional and an adequate control of one of the parameters is usually enough for both. There are however, exception such as the 3rd node. The 4th node has a pressure control loop where the pressure transmitter (PT) is connected to the separator, which detects the pressure behaviour in the separator. This pressure transmitter is connected to the separator via piping, and also connected to a pressure indicator and controller (PIC) in the 4th node via electrical connections. The PIC is then connected to a control valve which adjusts the control valve to counter the changes detected by the PT at the separator. As previously mentioned, there are some scenarios where only one of the 2 parameters need to be controlled as controlling one of these means controlling both of them, being temperature and pressure. However, in the 3rd node, it can be seen that there is both a temperature and pressure control loop, with the pressure control loop being identical in both 3rd and 4th nodes. This is because the 3rd node is the skim milk outlet, which is the desired product, the whey and casein protein structures must be maintained in all stages of the process and the quality of the product also depends on preventing denaturing of the proteins as much as possible. This can occur because the increase in pressure can cause for greater shear stress to act on the milk and therefore the proteins in milk, it is stated that hydrodynamic shear forces may cause damage to the large molecular weight proteins, resulting in denaturation and inactivation of the protein. This is a major concern as it affects the overall efficiency of protein recovery and final yield of the product (Elias and Joshi, 2023). This will ultimately decrease the quality of our product as the quality lies in the purity and the concentration of Whey and Casein proteins. Another reason to add a pressure control loop to the skim outlet as well as temperature control, is to prevent foaming in the milk. In an article written by CRU, a coffee production company, it is stated that foaming will cause the proteins in the milk will expand and 'surround' the air bubbles created by the steam wand. Combined with the sweetness from the melted lactose and thickness from the fats, you are left with the sweet, dense micro-foam (McCarthy, 2021). This is bad because it can affect the consistency, taste and decrease the concentration of the proteins found in milk, as they can denature and create spheres around the air causing bubble and foaming. Therefore, an additional pressure control loop can prevent this in the desired product and maintain the product quality, it can also prevent economic loss of product. As the separator processes large volumes of milk, the pressure control loop will prevent any foaming in these volumes and less milk is lost due to foaming, which will increase the profitability of the process and the separation efficiency in the separator. Regardless of a presence of a pressure control loop, the inlet and the outlets all have a pressure gauge for an extra step of safety. This is done so that the personnel and operator can inspect the local pressure in the nodes and identify any significant changes before there is any danger occurring to anyone in close proximity, it can also prevent any waste of product from any of the reasons already stated in the discussion for the importance of pressure control loops.

Much like the temperature control loop, a PID control loop is integrated into the pressure control loop to maintain the pressure of the system at around the setpoint pressure of 650 kPa, and does so by applying the same principles as the temperature PID system. Essentially, the proportional component will measure the difference between the error pressure and the setpoint pressure, which the control valve will be adjusted in proportion the pressure difference detected. With the integral component, any steady-state deviations are eliminated by accumulating the error over time. Finally, the derivative component will predict the future fluctuations based on rate of change, which will reduce the deviations from the setpoint pressure, which increases the stability in pressure control. This is all done by changing the control valve position according to the detected change in the system parameters.

5.2.2. Level Control Loop

To control the liquid levels in the separator, a level control loop is introduced to the system, this is introduced to maintain the level of liquid in the separator, so that it does not overflow and disrupt the process. This could also bring the operator and other personnel in danger as the hot liquid can overflow and with the support of centrifugal forces can reach far and harm anyone, even the personnel who may not be in close proximity to the separator. The level control is also crucial to achieve the desired separation efficiency and damage to the equipment as well as the personnel. In regards to the product quality, the overflowing can cause for inefficient separation of cream from milk, meaning that the purity of the product will be inconsistent and unpredictable, meaning that the quality expected from the customers of the Whey and Casein powders will not be achieved. Additionally, underfilling the bowl of the separator will cause for damage to the equipment, which will lead to increased frequency of maintenance, which increase the downtime of the process, giving lower yields of product that expected.

A level transmitter (LT) is connected to the separator, which detects the liquid level in the separator and send the information signals to the level indicator and controller (LIC). The level indicator and controller will then adjust the control valves found in the outlet streams in the 3rd and 4th nodes, which adjusts the control valve with proportion to the change detected in the fluid levels. As already discussed, this level control loop ensures that there is no underfilling or overflow, it also prevent damage to the equipment, which impacts the separation efficiency negatively. Underfilling the separator means that the weight of the separator decreases significantly, with this decrease in weight, the centrifugal forces will cause for the separator to vibrate too much, this vibration will cause damage to the equipment inside, such as the discs, where they could go into disarray, decreasing the separation area, and therefore the efficiency. The vibrations could also pose a danger to the operator, as they will be the closest to the separator, if the separator is not fastened to the ground securely. These vibrations could also cause a lot of noise pollution in the site and cause hearing damage to operator and other personnel in close proximity. If there is overflow however, there are other negative impacts on the system, as already talked about, if the level of liquid is not maintained at optimal, then the separation efficiency decreases. There are also other problems that could arise, these being contamination and reduce lifespan of components. If the milk and cream mixture in the separator spills, it could potentially spill over other parts of the process, which can lead to contamination of the system, reducing the quality of the product, and making the final product purity unpredictable. It could also lead to health risks as there could be harmful microorganisms entering the system and with the conditions in the system could grow and spoil the milk in the system. It is stated by the department of health in the government of western Australia, that food poisoning bacteria grow best at temperatures between 5°C and 60°C which is called the Temperature Danger Zone. Knowing that our process operates within this range of temperatures, it would be in the best interest to ensure that there is no contamination and that the products are safe to consume. It is in the UK and EU regulation law that passed in 1993, Regulation 315/93 states that ''Contaminant' means any substance not intentionally added to food which is present in such food as a result of the production (including operations carried out in crop husbandry, animal husbandry and veterinary medicine), manufacture, processing' (Dukes, 2023). Another problem mentioned was the reduction of lifespan of equipment, caused by underfilling or overflow of the separator bowl. This can be caused by the increase in wear and tear in the system, where the excess liquid in the bowl may cause corrosion or erosion, damaging the components and decreasing their lifespan.

Just like all the other control loops, a PID control loop is integrated into the level control loop to maintain the liquid level in the bowl of the separator at the level where optimal separation efficiency is achieved, being 1.129 m, and does so by applying the same principles as all the other PID system. The proportional component will measure the difference between the overshoot or undershoot from the setpoint liquid level, which the control valves will be adjusted in proportion to counter the error detected. With the integral component, any steady-state deviations are eliminated by accumulating the error over time. Finally, the derivative component will predict the future fluctuations based on rate of change, which will reduce the deviations from the setpoint liquid level, which increases the stability in the system. This is all done by changing the control valve position according to the detected change in the system parameters.

5.2.3. Flow Control Loop

To maintain the desired flowrates in the process, flow control loops are incorporated. This is to maintain a constant rate of production and to ensure a steady-state in the system. It is also crucial to include one in a process because it prevents problems such as overpressure of the system, lower separation efficiency, safety hazards and also increased frequency of maintenance. It may also affect the product quality which may arise due to the inconsistency of the process due to it causing unpredictability of the composition of the product, which may cause a lower than promised product purity and quality, causing for dissatisfaction of the product by the customers. To prevent such problems, it is important to include a flow control loop in the system.

A flow control loop is found on every outlet and in every node with the exception of the pressure safety valve, as this does not require a flow control. This is because the inclusion of flow control on a pressure safety valve would not contribute to the function of this component, which is to prevent overpressure in the centrifugal separator. The way a flow control loop operates is that a level transmitter (LT) is connected to the piping where the flowrate control is maintained, this is usually placed before the control valve. The flow transmitter then sends any signal it detects and sends the information to the level indicator and controller (LIC), which will adjust the control valve to counter the change in the flowrates to maintain it at the desired value. These are: 61800 kg hr-1 for the raw milk inlet (1st node), 58710 kg hr-1 for the skim milk outlet (3rd node) and 3090 kg hr-1 for the cream outlet (4th node). Compared to other types of parameter control loops, it is the simplest form of control found in this system, it does not require information transmitted from the bowl of the separator, but rather from the pipe and is a easy control to incorporate into the system. Regardless of its simplicity, it is still absolutely crucial for the system to possess this type of control, this is because it will prevent any problems that may occur, which was already discussed. Preventing overpressure is one of the dangerous problems it may bring, the behaviour of the pressure of the system fluctuating could put the operator and other personnel in close proximity in danger as the overpressure may cause for the build-up of pressure that the Tetra Pak cannot handle and may cause for bursting of pipes and other components, which can cause for the spilling of hot fluid onto personnel. Another problem that is further caused by this is contamination of the product, this will lead to problems as already discussed, causing for lower product quality, or even worse, cause for harmful microbials to enter the system and make to product unsafe to consume, which will violate many regulations based on maintaining safety of consumer products. It could also lead to the system to deviate from the optimal separation efficiency, meaning that the product quality will be much lower and will have consequences such as distrust from customers for the product and a lower quality product being produced from the promised to the customers, which will not be accepted by any marketing regulation. In the UK, the Advertising Standards Authority (ASA) is the organisation responsible for preventing such offences. It is stated on the ASA website that they take the Consumer Protection from Unfair Trading Regulations 2008 into account when it rules on complaints about marketing communications that are alleged to be misleading, one of which are 'Marketing communications must not materially mislead or be likely to do so' (Advertising Standards Authority | Committee of Advertising Practice, 2020). In the EU, there are also strict laws when it comes to the same offence, where the European Advertising Standards Authority will state guidelines that companies around Europe have to obey to prevent misleading marketing. In the Consumer Protection Act 2007 and the updated Consumer Rights Act 2022 it is stated that 'It is an offence for a business to make false claims about products, services or prices. Enforcement bodies can take action against a business that does not comply with the rules' (Citizens Information, 2022). Not obeying these laws will lead to fines and the reputation of the company producing Whey and Casein powders will be tarnished, leading to a rapid decrease in customers, which in turn will lead to a decrease in generated profit, or worse, not generate profit at all. Therefore, although it may be a simple control loop, it is absolutely necessary to include a level control in the system.

A PID control loop is integrated into the flow control of the system to maintain the flowrates in the piping that will allow the process to obtain the yield that it requires to generate revenue and is done by applying the same principles as the previously incorporated PID control loops. The proportional component will measure the difference between the overshoot or undershoot from the setpoint flowrates, which the control valves will be adjusted in proportion to counter the error detected. With the integral component, any steady-state deviations are eliminated by accumulating the error over time. The derivative component will predict the future fluctuations based on rate of change, which will reduce the deviations from the setpoint flowrates, which will increase the stability in the system. This is, again, all done by changing the control valve position according to the detected change in the system parameters.

5.3. Proportional-Integral-Derivative Control

The Proportional-Integral-Derivative (PID) control is a feedback control algorithm, this algorithm will measure the error between the detected value and the setpoint value that is chosen, this setpoint value will be the optimal parameter for the process which is calculated in the unit design stage of the Tetra Pak H80 centrifugal separator. As already mentioned, the proportional, integral and derivative term will work collaboratively to mitigate the error that has been detected and bring the process as close to the optimal conditions as possible, whilst minimising deviation from these parameters. For different parameters of the system, different PID values are required for effective tuning.

The collaboration of the Proportional-Integral-Derivative controls have already been discussed multiple times, however, the PID tuning utilises and equation, which ensures that the calculated counter measure to the change is as accurate as possible, this equation is stated as the standard method (ISA) in engineering in a separate unit design for another Tetra Pak design published by Lund University (Carlsson and Nytzen, 2006):

$$u(t)_{ISA} = Kc\left(e + \frac{1}{\tau_I}\int e(t)\,dt + \tau_D \frac{de}{dt}\right)$$

Where: u(t) is the control output and the ISA represents the standard control method in the engineering community, e is the error, the difference between the ideal value and the transmitted process variable KC is the proportional gain, τI is the integral time and τD is the derivative time.

It is important to correctly tune the PID control, as this will increase the degree of accuracy and bring about a greater stability in controlling the parameters that were just discussed, being temperature, pressure, level and flowrate. To have an enhanced efficiency of separation, it would be ideal to add any kind of PID control possible. If implemented successfully, the Tetra Pak H80 will operate and maintain the optimum conditions for the best quality product possible.

The first step to ensuring an accurate PID control loop, is to pick the best sensors possible for the Tetra Pak H80 to detect changes in temperature, pressure, level and flowrate changes in the system. This is to ensure that the measurement errors is kept at a minimal. As discussed in the unit design section, it was determined that a RTD would be chosen for the temperature detection, due to the high thermal stability and limited susceptibility to contamination, the product of choice was an Omega PT100 which is a Platinum based resistance temperature detector. For a high accuracy pressure detection, a Honeywell PX3 series heavy duty piezoresistive pressure transducer was chosen as the most suitable for this milk skimming process. For level control, a Liquidcap M FTI51 model was chosen, which is a probe level detector, due to its resistance to harsh conditions of high temperature and pressure in the separator (Endress+Hauser, 2013). Finally, for flow control, the Endress Proline Promag 53 electromagnetic flow measuring system was chosen, as it can operate in a wide temperature and pressure range, which includes the Tetra Pak H80 optimum parameters. All of these transmission components are connected to a control valve in all the nodes, therefore, the most crucial choice would be the model of the control valve. The most suitable control valve chosen was a Samson Type 3241 Globe Valve, which again has temperature and pressure ranges that are compatible with the optimal conditions needed for the Tetra Pak H80. This is imperative as every one of the control loops discussed up until this point will depend on the performance of the control valve chosen, as the ability of flow control ultimately determines the effectiveness of the whole control loop.

The next step would be the tuning method for the PID controllers, there are 2 main methods for this, which is the Cohen-Coon and Ziegler-Nichols method. Both of these tuning methods have their advantages and their disadvantages, which will be assessed in context of dairy processing to decide which one of the 2 methods are suitable for this application. It is important to consider the importance of smooth and precise control of the process parameters, these are the main features that are desired in the chosen tuning method. Another factor to consider is whether the control will be an open or closed control loop, assessing the tuning methods an open loop would be simper to adapt to the system, however, research shows a closed control loop is preferred. A study done by the University of Lancaster stated that in engineering, closed-loop control systems are generally preferred to those based on open-loop control because they respond and move the loads they are controlling quicker and with greater accuracy (Hopkins, B., 2019). A comparison of the open loop Cohen-Coon and closed loop Ziegler-Nichols must be done to assess which one is more suitable for dairy processing in a Tetra Pak H80.

5.3.1. Cohen-Coon Method

This tuningmethodfunctionsbyadjustingthesettingsofthecontrolsystemimplemented into the P&ID basedofspecificchangesorinformationabouttheskimmingprocess.Thiswillbeanopen loop control system,meaningthattheoutputofthecontrolwillhavenoeffectonthecontrolactionof the input signal (Storr,2013).Theinformationdetectedcouldbethetimetakentostabilisetheoscillations and how fast the controlloopreactstothatchange.Itessentiallydoesnotneedtheinputoftheideal settings, but ratherwilluseformulastocalculatetheidealsettingsforthecontrolloop.Thiswilleventually lead to less aggressiveoscillationsandprovidestabilitytothesystem.Theformulasthatthe Cohen-Coon methodusesrequireinputinformationaboutthesystem,theseare:ProcessGain(KP), which is the magnitudeofresponsetothedeviationfromtheidealconditions,TimeConstant(τ),which is time taken to bringthechangebacktotheidealvaluesohowlongittakestorespondtothechange and Dead Time (θ),whichishowlongittakestostartimplementingthecontroltothesystem. Using these numbers,thereareequationsthatcalculatetheProportionalGain(KC),IntegralTime(τI) and Derivative Time (τD)forPIDtuning,whicharedisplayedbelow(AkhileshKumarMishraandNarain, 2013):

$$K_C = \frac{\tau}{K_p\theta}\left(\frac{4}{3} + \frac{\theta}{4\tau}\right)$$

$$\tau I = \theta\left(\frac{32 + \frac{6\theta}{\tau}}{13 + \frac{8\theta}{\tau}}\right)$$

$$\tau D=\theta\left(\frac{4}{11+\frac{2\theta}{\tau}}\right)$$

These values calculated are then used in the mathematical expression of the PID controller which was shown previously. They are essentially inserted into this equation, which ultimately determine the controller settings in the equation.

5.3.1. Ziegler-Nichols Method

This method of tuning has the same principle of preventing the system from a state of instability, however, uses a different approach to the Cohen-Coon method. For this method, the control settings have to be input into the system, which it then relies in the systems response to the oscillations and deviations from the setpoint. It essentially assumes that the system that is wanting to be controlled is stable and there is no fluctuations at all and therefore has to induce fluctuations. This is because the proportional gain is increased until oscillations start occurring, meaning that it can cause for aggressive oscillations and lead to a brief instability in the system. The input parameters required for the closed loop Ziegler-Nichols equations are: Ultimate Gain value (KU), which is the proportional controller gain at which the constant amplitude cycle occurs and the Ultimate Period (PU), which is the period of one complete oscillation. The equations used to calculate the Proportional Gain, Integral Time and Derivative Time for a PID control loop are as shown below:

$$KC=\frac{KU}{1.7}$$

$$\tau I=\frac{PU}{2}$$

$$\tau D=\frac{PU}{8}$$

SimilartotheCohen-Coonmethod,thesecalculationsaretheninputintothePIDcontrolequationand acontrolloopisproduced,anddependingonthis,thecontrollersettingswillbedeterminedbythe controlequation.ThiswillbeaclosedloopZiegler-Nicholscontrolloop,meaningthattheoutputofthe systemwillbemeasuredandisusedtomanipulatetheinputfeedtobringhesystembacktostability.

Bothofthesetuningmethodscouldbeusedinanyofthecontrolloopsdiscussedearlier,including temperature,pressure,flowandlevelcontrol.Inmilkskimmingandanydairyprocessingforthatmatter, theimportantfactortoconsideristheirefficiencyinhandlinganysignificantchangesintheparameters ofthesystem.TheCohen-Coonmethodisoneofchoicebecauseitisfavourablewithsystemsthat havealongerdeadtime,thisisstatedbyNationalInstrumentsCorporationthatitprovidesbetterresults whenthecontrollerhasalargedeadtimerelativetothetimeconstant(NationalInstrumentsCorp., 2023).Thiswouldbepresentincentrifugalmilkskimmingastheskimmingprocesscantakeminutes, wheresimultaneouslymilkwillbefedintotheunit,whichwillcauseadelayinthedeadtimeduetothe timetakenforchangeincontrolsignalandresponsetothechangebeinglonger.TheCohen-Coon methodisalsoaffectedlessbythefluctuationsinthesystemparameters,whichwillbepreferredin suchasystemasthechangesinanyoftheseparameterswillaffecttheseparationefficiencyoftheunit andthereforethequalityoftheproduct.Therefore,withtheCohen-Coontuning,thereislesschanceof instability occurring on the separator.

Conversely,theZiegler-Nicholstuningmethodwillrelyonfluctuationsoccurringsothatitcanbeginthe controlloopandcalculatethecontrollersettings.Thistypeoftuningmayhavebenefitsinother industrieshowever,thefactthatitrequiresonoscillationsandhastoproduceinducedoscillations increasestheprobabilityofaddinginstabilitytothesystemmeaningthattherewillbemoreaggressive fluctuationsinthesystemparameters,whichwillcreateandangerousenvironmenttotheoperatorand personnel.Itwillalsoreducethequalityoftheproductduetotheaffectthatthesefluctuationshaveon theseparationefficiencyoftheunit.Thechoiceofthisbeingaclosedloopcontrolmeansthatitwill becomeorsensitivetochangesinthesystem,whenaddedontopoftheinducedfluctuationswillmean that more fluctuations will occur that will further negatively affect the optimisation of the separator.

Overall, the more suitable tuning method for the Tetra Pak H80, when it comes to dairy processing, would be the open loop Cohen-Coon method. This is mainly because there is less interference to the stability of the system than the Ziegler-Nichols method, which roots from its lower sensitivity to changes in the system and longer dead time, meaning that it will not affect the quality of the product as much as the Ziegler-Nichols method. In food and beverage processing, quality and safety of the product is paramount, therefore, when choosing the tuning method, these are the 2 factors that a must be considered and whether these tuning methods affect these factors. The Cohen-Coon method has shown to be the superior method of tuning for this process, therefore will be the chosen method.

5.4. HAZID

Table 3: Hazard Identification Study

Guideword	Hazard	Consequence	Safeguards
Process Fluid Release	Milk	Hot milk could cause for scalds if spilled Foodborne illnesses from the pathogens which can multiply in hot milk.	Regular Maintenance and inspections to ensure that the risk of these hazards occurring are minimised. Water rinsing could be added between the chemical cleaning steps in the CIP system. Isolation of each unit that requires a different chemical to clean, this will prevent the chemicals from mixing or reacting with one another. Could add backup fail-close valves to the system.
	Cream	Hot cream can cause scalds if spilled.	
	Nitric Acid	Poses threat to the human health due to it being corrosive and an irritant. Highly reactive with alkali and organic material, could cause for release of toxic gasses.	
	Sodium Hydroxide	Poses threat to the human health due to it being corrosive and an irritant. Sodium Hydroxide can release toxic gasses if heated, which can cause respiratory health problems.	
	Peroxyacetic Acid	If ingested, can cause nausea, vomiting and abdominal pain (ILO, 2015) Corrosive and irritant, can lead to respiratory health problems	
Utility Failure	Electrical Failure	Excessive power supplied to the centrifugal separator could overwork the centrifuge system causing for overheating of the system, could burn anyone in contact with components. Loss over the control system of the unit, which can lead to overpressure or overflow of the system, harming the personnel in close proximity. Exposed electrical instrument could cause for electrocution or personnel.	Backup generators to supply the system with electricity if there is a major electrical failure that compromises the system. Alarm systems could be implemented to indicate a loss of power so that the personnel can react as quick as possible to prevent any of the mentioned hazards.
	Pneumatic Failure	The opening and closing of valves could be inefficient or not function at all, leading to dangerous pressure fluctuations in the system. Could lead to over and underfilling of the separator, spilling the process fluids.	Alarms could be implemented to detect anomalies in process parameters that arise from electrical failures. Designing a fast shutdown procedure, so that any

		The centrifuge parts could cause moving parts to harm operator personnel.	potential hazards can be eliminated before there is or a probability of damage to equipment or harm to personnel. Regular inspection and maintenance of every pneumatic component to ensure they are safely secured into place and are reliable. Spring return actuators can make sure pneumatic components return to normal operation during the failure (CPV Manufacturing, 2022).
Operations	Human Error	Incorrect use of manual components, such a manual parameter controls or the manual valves	Have multiple people with responsibility over the manual valves. Multiple People in one control room. Working hours and breaks at reasonable times to reduce exhaustion of operators. Regular training sessions are given to the operator. Practice drill are frequently undergone so that the operator is well trained. Automated control systems could be integrated to the system as this will overcome most problem regarding human error.
Equipment failure / Defects	Pipe Failure	Hot fluid leaking can scald the operator and harm them, this can include personnel in close proximity. Lead to other components in the system sustaining damage. Contamination of the system due to leakage, bacteria growth excels in warm environments with high nutrients, which milk at 50°C possesses.	Frequent cleaning of pipes. Frequent inspection of the integrity of the piping connections and its material.
	Pressure control failure	Damage to key components such as the pump and valves, or even the separator itself.	Pressure alarms integrated at important locations where the

			pressure control is at most importance. Inspection of the pressure control systems that have been integrated and its individual components. Pressure Safety Valves added to the separator to eliminate any excess pressure build-up in the system, if the pressure control is inactive.
	Level control failure	Hot fluid leaking can scald the operator and harm them, this can include personnel in close proximity, this would be in a case of overfilling. Damage to components inside the bowl of the separator due to centrifugal forces could cause wear and tear, or aggressive vibrations from the unit can harm operator, this is for a case of underfilling.	Level alarms are integrated into the system to alert the personnel of any negative anomalies in liquid levels in the separator. The level control systems integrated should be frequently inspected including all of its components. Train the personnel to be able to identify any deviations from the optimal level and the importance of level control in the system. Emergency shutdown protocol developed to mitigate the effects of such a scenario occurring.
	Flow control failure	Can directly lead to a failure of control of all the parameters discussed, potentially leading to one of the other hazards being discussed in other parameter control failures. Overfilling due to overflow can rupture components, which can lead to harming the personnel.	Flow alarms could integrated into the system to alert the personnel of any deviation of the flowrates from optimal in the separator. The flow control systems integrated should be frequently inspected including all of its components. Train the personnel to be able to identify any deviations from the optimal flowrate in all the inlet and outlets and the importance of flow control in the system.

			Emergency shutdown protocol developed to mitigate the effects of such a scenario occurring.
	Temperature control failure	Can lead to the milk temperatures exceeding the required level for the process, which could overheat the system leading to pressure build-up. If any spillage occurs, the hot process fluid can scald the personnel in close proximity.	Temperature alarms are integrated into the system to alert the personnel of the deviation of optimal temperature in the separator. The temperature control systems integrated should be frequently inspected including all of its components. Train the personnel to be able to identify any deviations from the optimal temperature in the separator and the importance of temperature control in the system. Emergency shutdown protocol developed to mitigate the effects of such a scenario occurring.
External Hazards	Fire	Peroxyacetic Acid can be flammable at temperatures above 40.5°C Bursting at any part of the system could be violent and lead to fire.	Fire alarms are to be added to the system and these are to be inspected frequently. Emergency shutdown protocol developed to mitigate the effects of such a scenario occurring. Sprinklers should be added close to the equipment to supply the site at which fire has occurred with water to eliminate any fire.

5.5. LOPA

LOPA (Layer of Protection Analysis), is a risk assessment method that analyses scenarios of serious consequences, such as major accidents, and assesses the risks that come with these scenarios. Once the analysis is done, it can be compared to the company's risk tolerance. If failed to reach the level of risk tolerance set by the company, then extra countermeasures are provided to ensure that the assessed risk will not occur, or that the probability of the scenario occurring is highly improbable.

The risk is calculated as a function of likelihood and severity, which are multiplied together to assess the consequences of the selected hazard. It then uses order-of-magnitude estimates for determining the likelihood. The order-of-magnitude value uses figures such as i.e. 0.1, 0.01, 10-3 yr-1 not precise figures such as e.g. 43.2 x 10-4 yr-1 (IChemE, 2019). The severity is analysed qualitatively in reference to the Risk Matrix.

There are some specific definitions used in LOPA studies to make it easier to communicate the depth of the risk in engineering, these make sure that the information about the risk is detailed enough to prevent it from occurring, however, it must also be easily interpreted by other engineers, so that the dangers and countermeasures of this risk are well understood by all personnel viewing the LOPA study.

5.5.1. Terminologies

Initiating Event (IE): This is the failure in the system that will trigger the sequence of events that lead to the risk identified. This is the event that if not countered by the control measures that are integrated into the system, will lead to a hazardous outcome.

Independent Protection Layers (IPL): These are the control measures that are put in place to prevent the initiating event, so that the hazardous outcome does not occur. It does so without be affected by the initiating event or by the action of the other independent protection layers determined. Probability of

Failure on Demand (PFD): this is the probability of the IPL failing to control the potential hazard from initiating and give the required protection when it is needed in these scenarios.

Enabling Conditions: These are the conditions needed for the initiating event to occur and start the hazardous outcome. They do not directly cause for the hazardous outcome but are required for the initiating event to start. Safety Integrity Level (SIL): It is the risk reduction after the safety component is

added to counter the hazard under the stated conditions required for the hazard within a period of time.

Safety Instrumented System (SIS): These are essentially a designed safety control systems that undergo safety instructions specific to the hazardous scenario.

Risk Reduction Factor (RRF): is the inverse of PFD, it is the probability of failure of the SIL when it is on low demand.

Safety Integrity Levels (SIL): a discrete performance measure that indicates the range of maximum acceptable probability of failure of a SIF (Torres-Echeverria, 2016).

Safety Instrumented Functions (SIF): This is a function that is given by the SIS to prevent the hazardous scenario.

5.5.1. Analysis

1. Hazardous Scenario:

   High-Pressure steam or hot process fluid due to failure of the unit seal, this can harm the operator of the unit or severely damage the equipment.

   Tolerable Risk Criteria

2. It is stated by the ALARP principle, which stands for ‘as low as reasonable possible’ that in the UK, the tolerable risk would be between 10-4 yr-1 and 10-6 yr-1 (Health and Safety Executive, 2023).

3. IE and Frequency of IE: IE: Seal failure in the piping or the Tetra Pak H80 centrifugal separator

   degrading from corrosion from fluid flow.

   Frequency: 10-1 yr-1 , which is a value used by companies for use in LOPA (Marszal, 2011).

4. Enabling Conditions:

-
- The process fluid, milk or cream, exceeding 650 kPa in the separator of the piping.
  The process fluid, milk or cream, exceeding 54°C.

- The cleaning liquid in the CIP could be corrosive and cause for prematurely degrade the material of the seal.

5. IPLs and their corresponding PFD values:

- Pressure Safety Valve - (PFD1 = 0.01)
- Pressure Control Loop - (PFD2 = 0.1)
- Temperature Control Loop - (PFD3 = 0.1)
- Regular Inspection of all listed safety measures.- (PFD4 = 0.01)
- Automatic Shutdown of System - (PFD5 = 0.001)

6. IPLs and their corresponding PFD values: This calculation is done by looking at the relationship

   between the PFD and the RRF values
   and see that they are inverse of one another, as seen in the equation below (Torres-Echeverria, 2016):

$$RRF = \frac{1}{PFD}$$

   Therefore:
- Pressure Safety Valve - (RRF1 = 100)
- Pressure Control Loop - (RRF2 = 10000)
- Temperature Control Loop - (RRF3 = 10000)
- Regular Inspection of all listed safety measures.- (RRF4 = 100)
- Automatic Shutdown of System - (RRF5 = 1000)

7. Total Risk Reduction Factor:

$$Total\ RFF = RRF1 + RRF2 + RRF3 + RRF4 + RRF5$$

$$Total\ RFF = 100 + 10000 + 10000 + 100 + 1000$$

$$\therefore Total\ RRF = 21200$$

8. Company Risk Acceptance:

   The target RRF was decided to be <106, comparing this range to the TRRF, it can be seen that this value lies within this range.

$$TRRF \leq 10^{6}$$

   This concludes that the risk reduction is withinthecompany requirements and that the IPLs that have been put into place can provide therequired risk reduction in the risk of harming personnel and extensive damage to equipment.Thisalso means that then number of IPLs and mitigation components added to the system areenough and no extra countermeasures are needed, preventing the company from spendingfinances on extra unnecessary layers of protection.

All of these steps were taken for the other hazard scenarios in Table 4, where the LOPA undergone is presented in a table with all the necessary information to conclude all the values calculated, the calculations for the next 2 hazard scenarios are found in the Appendix. Table 4: HAZOP Study for Multiple Scenarios

Hazard	IE	IE Frequency	IPL	RRF	PFD	SIL
Seal Failure	Degrading due to corrosion	10-1 yr-1	Pressure Safety Valve	100	0.01	1
			Pressure Control Loop	10000	0.0001	N/A
			Temperature Control Loop	10000	0.0001	N/A
			Regular Inspection	100	0.01	N/A
			Automatic Shutdown	1000	0.001	2
Overheating	Failure of Temperature control system	8.76 x 10^{-6} yr-1	Temperature control loop	10000	0.0001	N/A
			Integrating Cooling System	100	0.01	2
			Interlocks in the unit	10	0.1	1
Overpressure	Failure of Pressure Safety Valve	10-1 yr^{1}	Rupture Discs	10000	0.001	N/A
			Second PSV	1000	0.001	2
			Pressure Control Loop	10000	0.0001	N/A

There are some IPLs that do not have a corresponding SIL values. This is because the SIL values usually have some association to SIS and SIF, these are components designed to counter the risks that the hazard brings. The SIL value is a numerical representation of the risk reduction that the SIF components bring to the system. It can also be seen that not all IPLs can be classed as SIF, as control loops, inspections and rupture discs do not have SIL values, which explains why a SIL value is not applicable to some IPLs in Table 4.

The total RRF values from the analysis undergone was: 21200 for the seal failure scenario, 10110 for the overheating scenario and 21000 for the overpressure scenario. After assessing the determined risk acceptance range and other industry guidelines when undergoing the analysis, the target RRF values for all of these fatal scenarios lied within the acceptable range set by the company. From here, a recommendation would be to review the LOPA analysis and renew the table is necessary and enforce a strict monitoring and maintenance of each of the stated IPLs in the analysis. In the long run, this will be effective at mitigating any of the initiating events of the scenarios and prevent any major incidents regarding the separator.

In conclusion, a Layer of Protection Analysis was undergone on a Tetra Pak H80 centrifugal separator to assess the effectiveness of the countermeasures integrated into the system, and to obtain a numerical value to conclude the safety of the system after the IPLs are applied. This value is the total RRF value.

5.6. Start-up and Shutdown Procedures

At the start of every shift in a working day, the whole plant will undergo a start-up before the process begins. This makes the transitions from no production to a full-scale production smooth, whilst achieving the efficiency that is required from the process. In terms of a Tetra Pak H80 separator, this is important as having a start-up procedure enables to system to reach optimal conditions to achieve the desired separation efficiency without causing any damage to the components or the separator itself. The shutdown procedure is the opposite of this process, it ensures that the separator goes from full-scale production to no production at all, without damaging any part of the system, so that when the start-up is required the next day, there are no setbacks from damage to components.

5.6.1. Start-up Procedure

a) CIP Activation

As stated multiple times, the most important factors in food and beverage processing is the safety and quality of the product. The safety of the product is ensured by preventing contamination in the system. The different chemicals in the CIP system provide a clean system in their own respective ways. As already discussed, Nitric Acid prevents mineral deposits can cause for scale and fouling, Sodium Hydroxide can remove the fats combining and prevent saponification. The Peroxyacetic Acid, or Peracetic Acid, acts as the sanitiser and eliminates any micro-organism that could contaminate the system and jeopardise the product safety.

The CIP system works in the order of:

1) Pre-rinsing, where water flushed through system to remove solids.
2) The water exiting the system is directed to a wastewater stream.
3) Alkali concentration adjusted to required levels and flushed through the system.
4) Secondary water rinsing to eliminate any residue alkali in the system, this is done to prevent the next stage leading to a neutralisation reaction in the system and producing by-products that could contaminate the product.
5) Acid concentration adjusted to required levels and flushed through the system.
6) Final water rinsing stage to remove any chemical residues.

b) Testing for equipment functionality

Testing for the functionality of the equipment is important as it ensures that any problem that may arise with the system components can be detected before the actual dairy processing can begin, which can reduce potential failure of the system and reduce the downtime.

Leak Testing:

This is done by closing the pressure safety valve and the inlet and outlet streams of the Tetra Pak H80, after this, the system is pressurised with gas to monitor the rate of pressure loss in the system. If any gas leak is detected, then the bolts are tightened between piping or component connections, or replaced if the leak detected is due to irreversible damage to a component. This is an important test as it shows how critical maintaining the pressure of the system at 650 kPa is for optimal performance of the separator and to keep the separation efficiency at 95%. The loss of pressure will also mean a higher energy consumption to maintain the system pressure at 650 kPa, the increase in energy demand will lead to an increase in OPEX.

This could also affect the system temperature as pressure and temperature are proportional to one another. The higher temperatures arising from pressure fluctuations can create environments where the bacterial growth is optimal and therefore significantly reduce the product quality to the point where it will be classed as unsafe to consume.

c) Utility and Service Systems Check

The utilities and service systems can now be activated, the checklist provided for this process includes: electrical systems turned on, which is followed by fire, process, and water potable systems (Hall, 2012).

d) Activation of Pumps

The pumps are turned on to raise the pressure of the system to 650 kPa, this is achieved by the pumps forcingair to travel around the system.

e) Heating of the System

f) Feed Flow into System:

From here, the milk can start to flow from the pasteuriser in the stage before skimming in the process, V-1 is opened and the raw milk is allowed to enter the bowl of the Tetra Pak H80 centrifugal separator. Pump-XX is then turned on to force the fluid around the system, starting the production process.

5.6.1. Shutdown Procedure

a) The flowrates aregradually reduced to 0.

This is done by slowly closing the valves. This ensures that the changes in the conditions inside the system are gradual, which enables any potential damage to the system are mitigated. Sudden flowrate drops will lead to the violent vibration of the separator, which put the operators and personnel in danger. It can also cause for any moving parts or components to be thrown from the centrifugal force of the separator. It also leads to a gradual decrease in temperature of the system, eliminating the possibility of thermal shock. Thermal shock occurs when a material undergoing sudden changes in temperature develops internal stresses and strains that may cause cracking and eventually failure (Oluseyi Philip Oladijo et al., 2021).

The gradual changes in the conditions allows for better observation of the changes occurring in the system, making it easier to detect any significant fluctuations in the process conditions, which gives an understanding to the operator to deal with any interruptions during normal operation.

b) Systems turned off:

Valvesused to open the system and start-up the process are gradually closed.

c) Full closure of the feed valve, nothing is entering the system, however, some of the unit still have milk or cream in them.

d) Pumping out remaining process fluids:

The leftover fluid and debris in the system has to be flushed out to prevent contamination upon start-up. Thewaste stream is connected to the outlets, where the closed gate valves will open up and direct the leftover fluids to the stream. A complete emptying of the stream must be achieved, with nothing presentuntil the next start-up.

e) System is brought to atmospheric pressure, which will lead to lower OPEX as the system pressure does not need to be maintained during the time periods that it is not operational.

5.7. Cleaning and Maintenance

The Tetra Pak H80 is a high quality centrifugal separator used in dairy processing. In this context specifically, it is used to skim the raw milk that has been pasteurised in the stage before in the fractionation process to produce Whey and Casein powder. These powders are consumer products, meaning that the product must be safe and eradicated from any harmful micro-organisms or contamination before it reaches the consumer. For the production to remain a high quality and deemed safe, the process must run at a consistently high efficiency with minimal interruption, meaning that the downtime must be reduced as much as possible, which stems from component failure in the system. To prevent these issues from occurring, a thorough cleaning and maintenance of the system is vital. Therefore, the main factors influencing the maintenance and cleaning are identified and mitigated.

5.7.1. Factors that affect cleaning and maintenance:

Fouling: Fouling is the accumulation of the organic material in the inner surface of the pipes forming a solid layer over it and can clump and clog. This can lead to an inefficient process and lead to fluctuations in the flowrate through the pipes, even causing blockades. This can be caused by :

- Fluid Viscosity:

Viscous fluids are more likely to deposit solids on the inner pipe surfaces, with a slower flowrate, further enables for solids to settle. Fluids with higher viscosity will have higher concentrations of particulate matter, organic and inorganic material, therefore, if the milk has higher viscosity, it will likely have a higher composition of the stated material. This increases the amount of this matter settling and accumulating in the inner surface of the pipes. A study published by the Journal of Dairy Science deducted that the protein aggregate formation was increased in the presence of increased shear stress applied during the processes, which could be the shear stress applying onto the proteins in the milk composition and denaturing them. The relationship between viscosity and shear stress in the Tetra Pak H80 can be assessed in the equation below:

$$\tau=\mu\left(\frac{du}{dy}\right)$$

Where: τ = Shear Stress (N m-2)

From a mathematical perspective, the viscosity is the proportionality factor between shear stress and shear rate. The equation shows that viscosity and shear force are directly proportionate and higher viscosity will mean higher shear forces acting on inner surface of the pipes.

- Fluid Density:

  With density, it is known that dense fluids will settle more, which will increase the rate of build-up of the fouling to eventually decrease the cross-sectional area of the pipe or blocking it. A study was done to compared the density and fouling rate, using oil and water, the study showed that larger traces of oil fouling was detected in the walls of the piping after fluid constants (found in literature) and operational conditions established experimentally were applied to simulate and observe the density flow profiles along the upper and lower walls of a 2D pipe (Nuhu Ayuba, Ferreira and Toni Jefferson Lopes, 2022), which arrived at the conclusion that heavier fluids will have a higher tendency to settle, which can cause for the particulate matter in the high density fluid to settle, accumulate and clump, negatively affecting the process efficiency.

- Fluid Chemistry: This includes the pH and acidity of fluids and the chemical composition of milk.

  Chemical
  composition is the concentration of organic and inorganic material in the milk in such as sugars, fats, minerals and proteins, it can also be particulate matter (Guerrero-Navarro et al., 2020). In a study done on milk composition and fouling by University of Cambridge that β-lactoglobulin is reported to play a prominent role in the fouling process as it is a highly thermally-sensitive protein (Bansal and Habib, 2010). pH and acidity can also play a role because the acids can cause for corrosion of the material in the inner surface, releasing metal ions, or it can cause for the denaturation of the proteins, causing them to unfold. A study done on milk fouling stated that fouling is caused by both denatured and aggregated proteins and perhaps primarily influenced by the presence of the denatured proteins in the bulk (Bansal and Xiao Dong Chen, 2006).

- Fluid Temperature and Pressure: It is a known fact that the increase in temperature and

  pressure can increase the rate of
  reaction, in this context, is the rate of fouling. In a study, it was found that fouling starts to take place at temperatures between 75 °C and 110 °C. The deposits are white, soft, and spongy (milk film), and their composition is 50% to 70% proteins, 30% to 40% minerals, and 4% to 8% fat (Bansal and Xiao Dong Chen, 2006). This temperature range is also when proteins found in

milk start to denature, meaning that the protein structure starts to disintegrate. Thermal denaturation of whey proteins at the presence of calcium is believed to be the cause of fouling in dairy industry (Marwa Khaldi et al., 2018) meaning that this is the most common factor to cause fouling in dairy processes.

- Flow velocity: With low processing fluid flow velocities, the rate of fouling increases. This is

  because the slow

  fluid flow gives the solid particles and other organic matter the time to settle and accumulate on the inner walls of the piping or the separator itself, which can affect the cross-sectional area of the piping, which can then cause fluctuations in the flowrates of the inlet or outlet of the system. This will cause for pressure drop variations within the separator which will affect the separation efficiency of the unit, leading to lower quality products. If the fouling eventually leads to significant restriction onto flow or completely block the flow, it can also lead to damage to components and potentially put the operators at risk.

Corrosion:

Corrosion is the degradation of the material of the components and the separator in the Tetra Pak H80 system, which is caused by the flow of the process fluids in the piping, separator and the CIP system integrated. This is usually cause by the pH, water quality, material properties, temperature and pressure:

- pH of Process Fluids and Cleaning Chemicals: Chlorides, sulfates and nitrates cause corrosion

  by breaking down the protective barriers on

  the surface of the metal, opening the way to corrosion. Continuous addition of water increases the sulfate, chloride, and nitrate content of the water in a central system, thus making it more aggressive the longer it is used (Foltz, 2022). In this process, the system will be flushed with Nitric Acid, Sodium Hydroxide and Peroxyacetic Acid (Peracetic Acid) every start-up and shut-down, therefore this cleaning process being repeated every day before and after the process can cause for the degradation of the piping and the components of the system itself. This will decrease the lifespan of the equipment and lead to a higher frequency of maintenance runs, which in turn increases the downtime of the process, leading to lower daily yields.

- Water Quality: The quality of the cleaning water used in the start-up and shut-down procedures

  are also

  important, this is because hard water is high in dissolved minerals, largely calcium and magnesium. The minerals can lead to galvanic corrosion, which is an electrochemical process whereby one metal corrodes in preference to another metal that it is in contact with through an electrolyte. Galvanic corrosion occurs when two dissimilar metals are immersed in a conductive solution (TWI Global, 2023). The hard water in the CIP would act as an electrolyte solution, and the dissimilar metals are the metal cations found in water, Calcium and Magnesium, and the metal surface of the grade 304 stainless steel piping and separator, containing Chromium and Nickel. If this process is a regular occurrence, then this will lead to replacing and fixing of the components of the system, which will require more frequent maintenance and lead to greater downtime in the process, decreasing the amount of Whey and Casein produced. It will also increase the OPEX of the unit, which is not desirable.

- Material Properties: The material of choice for the piping and the separator were grade 304 and

  Super duplex

  stainless steel, respectively. With grade 304 stainless steel, it contains high amounts of Chromium around 18% (Thyssenkrupp, 2020). This can form a passive oxide layer on the inner surface of the piping, which can be compromised if there are highly acidic solutions flowing through it. Passive oxide layer is a thin layer of chromium oxide which, due to the chromium reacting with oxygen in the surrounding environment, develops on the surface layer of stainless steels with a Chromium content of above 11% (BS Stainless Limited, 2020). In this scenario, the passive oxide layer can be damaged, exposing the surface of the piping and causing for corrosion. With the Super duplex material in the bowl of the separator, it contains Chromium content of 24 – 30% (MONTANSTAHL, 2017), which is higher than the required level for passive oxide layer forming, leading to the same problems that arise with grade 304 stainless steel. Most stainless steel contains a minimum of 10.5% Chromium, therefore with any stainless steel, these problems could arise (Thyssenkrupp, 2022).

- Temperature and Pressure: The increase in temperature can increase the rate of corrosion by

  increasing the rate of reaction

  between the acidic and alkali cleaning components and the material of the piping and the bowl. Addressing the problem discussed in the previous factor, the passive oxide layers can fall and breakdown much quicker and the cleaning chemicals can further damage the material integrity of the piping and the bowl. Thermal pipe expansion and contraction can also occur in the material. Temperature changes cause an object or substance to change shape, area or volume. Pipes will generally expand when heated, and contract when cooled. This is caused by the molecular structure expanding due to the increased kinetic energy at a higher temperature – causing the molecules to move around more. The forces created by the thermal expansion can be large enough to cause pipe bowing and buckling, damaged pumps, valves, pipe clamps and fixings (Walraven Ltd., 2022).

Wear and Tear:

This is essentially the expected decrease in quality of the material due the numerous processes it has had to undergone throughout its lifespan, it is an inevitability. In the Tetra Pak H80 separator, this can happen due to exposure to acidic and alkali cleaning chemical, friction and temperature fluctuations. The reason for these factors arising must be identified before it can be effectively mitigated.

- Temperature and Pressure: Thermal Expansion and Contraction can lead to stress being

  applied to the material of the

  piping and the separator bowl. This will eventually lead to fatigue in the material, which can lead to excessive damage to the integrity of the material. If the temperature changes are sudden in the start-up and shut-down procedures, the thermal shock can also damage the pipe and bowl integrity and lead to cracks and leaks in the system, leading to decreased efficiency and higher energy consumption. The procedures are also undergone every start and end of shifts meaning that the system is constantly undergoing these thermal expansions and contractions, and increases the probability of thermal shock occurring.

  High pressure environments can also lead to increased stresses applied to the components in the separator and the piping material. The mechanical components such as the separation discs, control valves, etc. can experience this stress exerted during the process, which can eventually lead to irreversible damage to the components and may require replacements, meaning that more maintenance runs are needed to identify the issue before the damage occurs.

- Friction: Friction could be the most significant cause of wear and tear in the Tetra Pak H80

  separator.

  This could arise from 2 component surfaces scraping across one another, leading to gradual degradation of the material in point of contact. This can lead to damage to the equipment that may need frequent replacing, which will need to system to undergo maintenance to tackle to problem. This increases the downtime of the unit and decrease the yield of product. It can also cause for energy losses and also deform components such a the discs in the separator, decreasing the separation efficiency of the system. The amount of friction represents the energy losses in the system, typically as heat, which is why it must be mitigated.

- Cleaning Chemicals: The CIP system is a chemical cleaning system that is flushed into the process during start-up and shut-down every working day, in intervals. This over time can lead to chemical corrosion dure to the acidic and alkali conditions during the cleaning. Any kind of excessive use of the chemicals can corrode the inner surface of the piping, the separator, or the control valves, which can decrease the lifespan of the equipment. The CIP system is also utilised at high temperatures and pressures, which can induce thermal and mechanical stress onto the components of the system. Mechanical damage can be indentations, scratches, components falling apart, etc. which means parts have to be fixed of replaced. Thermal stress can be caused from thermal expansion and contraction and thermal shock, this is the extreme fluctuations of temperature in the system, which leads to cracks and spills in the system, reducing the yield, and increasing the need for frequent maintenance. It can also lead to contamination of the system, as any exposures in the system can lead to harmful micro-organisms entering the system, bringing safety issues for the product.

5.7.1. Methods of Mitigation:

These are the necessary methods that need to be applied to the system to minimise the effect of these factors that affect the efficiency of process, quality, safety and yield of product. The main method for all of these factors would be the frequent maintenance runs to detect any problem in the system as early as possible so that it can be effectively solved and the process is affected as little as possible. Maintenance should achieve minimum downtime in the long run of the process, while cleaning should aim to achieve (Dairy Processing Handbook, 2015):

- Physical cleanliness – removal of all visible dirt from the surface
- Chemical cleanliness – removal not only of all visible dirt but also of microscopic residues that can be detected by taste or smell but are not visible to the naked eye
- Bacteriological cleanliness – attained by disinfection
- Sterile cleanliness – destruction of all microorganisms

With the mitigation methods suggested, these can be achieved and bring the product quality as high as possible.

Fouling:

With fouling, it will occur in any situation in a dairy process or any kind of food and beverage processing. The countermeasures put in place can only slow down the rate of fouling so that it can be detected and treated as quickly as possible. A method to approach this would be the creation of a cleaning plan, to do this, some factors could be put into consideration: cleaning agents, procedures and documentation of the cleaning to track the frequency of cleaning cycles. A cleaning procedure is already in place with the CIP system, which is already discussed on how there are intervals of cleaning agents and sanitisers, being flushed with water between each chemicals to prevent contamination or undesirable chemical reactions. The effectiveness of the chemicals used in the CIP system are already discussed and all have a specific purpose. Every cleaning at the beginning and end of the day or maintenance should e documented to accurately assess how frequently it is undergone and whether any changes need to be made to the frequency of maintenance runs.

A study on fouling in dairy processes was undergone and the most effective cleaning strategy was devised out of all of the experiments that were undergone. The results stated that the removal of proteinaceous dairy deposits is influenced by a variety of factors: temperature, fluid flow, chemical concentration, chemical type and the amount of deposit present. The complex inter-relationship makes the exact role of each difficult to determine. The force of water alone will not remove these deposits and expensive chemicals are required to remove the deposits. However, fluid motion is required: to bring the chemical to the deposit surface interface, provide shear to detach the particulates from the surface and to carry the detached deposit out of the system. Chemical removal dominates above 0.5wt% NaOH (for all flow rate) at temperatures of 50°C and above. However, the lowest flow rate at 30°C also appears to exhibit chemical removal for all concentrations. Physical processes dominate when the chemical concentration is low (or when the reaction is limited by low temperatures) and sufficient forces are applied from the fluid flow.

The pressure gauges and temperature sensors added to the inlet and outlet to monitor the effect of the fouling on the system parameters to see the magnitude of the fouling and how much it affects the process, this allows for early detection of any significant changes in the system caused by fouling. This is because the fouling on the walls of the piping will constrain the cross-sectional area of the pipes, which can be detected via changes in flowrate and other system parameters, which is why the transmitters in the control system are essential to detect these.

Pre-cleaning procedures could also be implemented, where some parts need to be manually cleaned. CIP components, like spray balls; and the valves, couplings, and sampling ports of CIP cleaned processing pipework also require regular disassembly and manual cleaning, to ensure the on-going efficiency and effectiveness of the CIP clean (Kheradia, 2015). These will not be cleaned by just the CIP system and may require individual treatment. To achieve this, personnel should be chosen to clean the parts so that it is effective and time efficient.

Friction:

Friction will occur in any process that includes moving parts which have probability of coming into contact. To ensure that this does not happen unintentionally, the sizing of the separator components must be done as accurately as possible, while allowing space between the components. Even after design, when it comes to assembling the unit, the parts should be checked if they align and all the dimensions are as calculated in the design. These misaligned parts will cause friction, especially in the bowl of the separator where the rotation to causes the centrifugal separation, otherwise excessive damage will be caused to the unit.

Adequate training must be given to operators and personnel to ensure that the operators have the knowledge and training required to assemble the unit within the correct dimensions. The information and data books can be given out for the operators to study before engaging with the separator. With this, the operators will make less errors with the manual components of the system and detect any hazards related to friction before it causes further damage.

The optimisation of the rotation speed of the separator could also eliminate any unnecessary fires or damages from excessive friction. The highest speed of rotation does not mean the highest performance, and very high levels of separation, around 95%, can be achieved with moderately high RPMs. A simpler method may be lubrication of parts, including the bowl, seals between components and the bearings in the moving parts. Lubrication is the applying of a substance that ultimately reduces friction, it is the cheapest and easiest way to mitigate effects of friction. This method can also counter wear and tear by decreasing the effects of friction and increasing the life span of the equipment. All of these methods applied will mitigate friction and therefore decreasing the OPEX of the unit and also lowering energy consumption.

Wear and Tear:

As already stated, the wear and tear is the inevitable damage to the components or piping over its time being used. Throughout the process however, there are some factors that can be controlled to minimise the unnecessary damages that may occur frequently. In the section before, lubrication was identified as a mitigating factor for both friction and wear and tear.

The methods that were used in mitigating the effect of friction also apply to the wear and tear. This is because fundamentally, to mitigate wear and tear, one must reduce the friction between component parts. The speed adjustment, alignment of components in the system, and operator training to identify traces of wear and tear in the system.

6. Conclusion

Throughout this report, the main goal was to design and optimize a Tetra Pak H80 centrifugal separator within industry regulations and codes. This was done to ensure that the operator runs at optimal performance and is designed to be safe, simultaneously. This in return will then decrease the OPEX of the unit and therefore the overall fractionation process. The Tetra Pak H80 was chosen due to being the most suitable separator for the skimming of milk as it already has proven to have high performance and efficient by Tetra Pak.

In every step of the design of the separator, there were main factors that were considered were the separation efficiency, desired fat composition in skim milk, and the capacity of the Tetra Pak H80. This was all done in the aim of maintaining the separation efficiency of 95%, as this is the determining factor of the quality of the Whey and Casein powder at the end of the fractionation process. The Tetra Pak H80 separator has shown to handle a wide range of flowrates while maintaining the optimal design parameters and separation efficiency. With this, the Tetra Pak H80 inherently has an Airtight Technology which allows for minimal air entering the system, preventing any further potential contamination of the milk in the system, adding an extra layer of security for the safety of consumption of the Whey and Casein powders. An in-depth optimization, including the design parameters such as temperature, pressure, flowrate and safety measures such as the incorporation of control loops, LOPA and HAZID resulted in an optimal yet safe separator, as promised by Tetra Pak in the H80 centrifugal separator data sheet.

The final design after the optimisation and the safety measures added had a processing flowrate of 61,800 kg hr-1, with cream fat content being 74.3% and skim milk being 0.01-0.05%. The design is capable of skimming the pasteurised milk down to these values for each stream whilst maintaining the Whey and Casein in the milk without denaturing the proteins. This high product quality with a wide range of flowrate and composition limits shows the adaptability of the Tetra Pak H80 to anomalous batches of milk, which varies frequently depending on the source and the conditions of the cows the milk was extracted from.

Safety and risk assessment of the Tetra Pak H80 was also undergone, which helped identify and mitigate any hazard from minor to fatal. The probability and severity of all the potential hazards were assessed and suitable countermeasures and control systems were implemented into the process to ensure that the operator and personnel are safe to engage the unit without having to feel unsafe. The LOPA analysis has also confirmed that all of the safety measures that have been implemented onto the 3 different scenarios have effective risk reduction, where the calculated total risk reduction factor was is within the company requirements, meaning that the IPLs can provide the safety required to ensure a safe working environment and minimize the probability of significant damage to any or multiple components of the unit.

There is also the scalability of the Tetra Pak H80, this design enables the unit to be able to be used in greater production rates if there is a future growth in demand of Whey and Casein powder. This is because the process parameters and the features of the separator add to the adaptability of this unit for any pasteurised milk supply or demand for protein supplements. This can be done due the maximum process capacity of the Tetra Pak Being 80,000 L hr-1, if the demand still cannot be met, another option would be to have more than 1 separator skimming vast amounts of pasteurised milk, which again, underlines the easy adaptability of the Tetra Pak H80 separator.

However, there was one main assumption that should be considered in a more detailed unit design, which would be the exclusion of the discharge outlet, which can be seen in Figure 1. This was neglected because this would add further complexity to the mass and component balances and other design calculations. The unit design aimed to be as adaptable as possible and therefore the complexity had to be reduced, the exclusion of the discharge port allowed for this, but should be taken into account in further design calculations of the Tetra Pak H80 centrifugal separator. It should be taken into account that this design is just a prototype and the performance of the separator was the only concern in this project. Therefore, in future designs of the Tetra Pah H80, the discharge port should be added for a more accurate design.

In conclusion, the Tetra Pak H80 centrifugal separator merges innovative design and up-to-date technology to produce a high performance separation of milk and cream reliably. As seen from the complexity of its design and optimization, this separator is a breakthrough in modern dairy processing. As technology implemented into the dairy industry develops, the Tetra Pak H80 will always remain a crucial unit to integrate into the fractionation process to ensure that the Whey and Casein powder produced will be high quality and safe to consume.

6.1. Specification Sheet

Table 5: Specification Sheet for the Designed Tetra Pak H80 Centrifugal Separator

Centrifugal Separator Specification Sheet					
Operation	Separate Cream and Milk in Raw Milk		Revision:		Status:
Unit	Tetra Pak Separator H80		Date: 02/05/2023		Completed
Process Data					
Flowrates			*Power Requirements*		
Inlet			Motor	26.9	kW
Unskimmed Milk	61,800	kg hr^{-1}			
			Operating Conditions		
Outlet			Pressure	650	kPa
Skim Milk	55,710	kg hr^{-1}	Temperature	50	˚C
Cream	3,090	kg hr^{-1}			
Capacity					
Min. Flowrate			7,000 L hr-1		
Max. Flowrate			80,000 L hr-1		
Min. Milk Fat in Skim Milk			0.3 %		
Max. Milk Fat in Skim Milk			0.01 %		
Volume			568.9 L		
Motor Power			6,000 –10,000 RPMs		
Material and Component Selection					
Bowl Material			Super Duplex stainless steel		
Pipe Material			Grade 304H Stainless Steel		
Agitator			Propeller Agitation		

Heating and Cooling System	Plate-and-Frame Heat Exchanger
Heat Source	Steam
Dimensions	
Optimal Process Fluid Depth	1.129 m
Width	1.028 m
Height	2.056 m
Inlet Diameter	51 mm
Outlet Diameter (Cream)	12.2 mm
Outlet Diameter (Skim Milk)	50.2 mm

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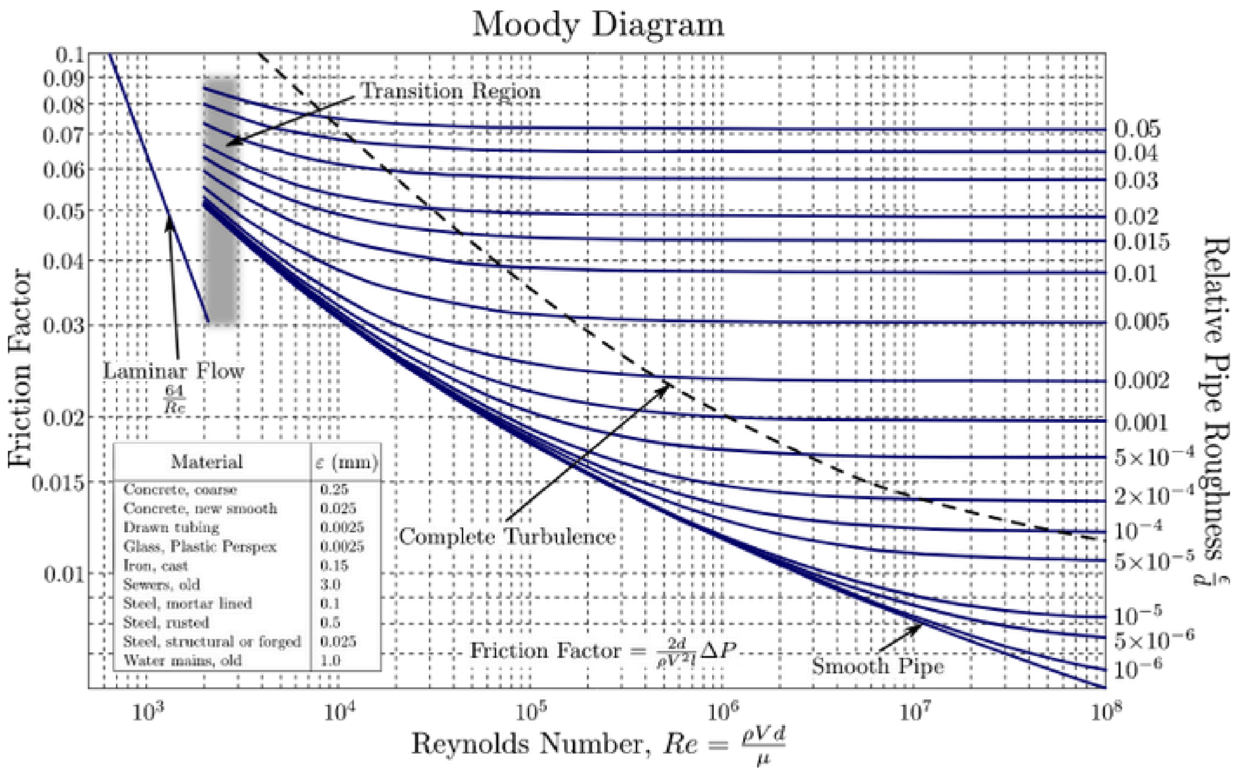
8. Appendix

Appendix 1:

Figure 11: Moody Diagram used to calculate the pipe lengths for inlet and outlet streams of Tetra Pak H80



Appendix 2: Calculations of the average lengths and diameters of the streams used in Figure 7

$$l_{Inlet\ Pipe} \approx l_{Outlet\ Pipe,SkimMilk} = \frac{(11.63+39.39+9.73)}{2} = 20.25\ m$$

$$d_{Inlet\ Pipe} \approx d_{Outlet\ Pipe,Skim\ Milk} = \frac{(0.1418+0.1255+0.1)}{3} = 0.1224\ m$$

$$l_{Outlet\ Pipe,Cream} = \frac{(5+5+10.73)}{3} = 6.91\ m$$

$$d_{Outlet\ Pipe,Cream} = 0.0122\ m$$

Appendix 3: Weight calculations for the unit

First of all, dimensions and properties of the components included in the total weight calculation are needed, which will be listed as:

Piping:

Table 6: Dimensions and Properties of the Piping in the Unit

	Inlet	Skimmed Milk Outlet	Cream Outlet
Inner Radius (m)	0.051	0.0502	0.0122
Outer Radius (m)	0.0536	0.05243	0.01274
Length (m)	20.25	20.25	5
Density (kg m-3)	7900 (Sandmeyer Steel, 2016)		

An example calculation is undergone for the inlet pipe. Volume calculation requires the volume of cylinder using the outer and inner diameters and subtract the smaller from the larger volume, in which this value will be the pipe material volume:

$$VMaterial = V_{Outer} - VInner = \pi(r^2outer - r^2inner)l$$

$$\therefore V_{Material} = \pi \times (0.05362 - 0.0512) \times 20.25 = 0.0173\ m^3$$

From here, the volume can be multiplied by density of grade 304H stainless steelto arrive at the weight of the pipe:

$$W_{Inlet\ Pipe} = V_{Material} \times \rho^{304H}$$

$$\therefore W_{Inlet\ Pipe} = 136.7\ kg$$

The same principle is applied to the outlet pipes, which give values of:

$$W_{Outlet-Skimmed\ MilkPipe} = 115.0\ kg$$

$$W_{Outlet-Cream\ Pipe} = 1.671 kg$$

Bowl: Again, with the bowl, the volume from the inner radius must be subtracted from the larger radius

and
multiplied by the density of the material, grade 2507 Super Duplex stainless steel, which has a density of 7800 kg m-3 (Sandmeyer Steel, 2016):

$$V_{Material} = V\ Outer - VInner = \frac{1}{3}\pi(r^2_{outer} - r^2_{inner})h^{bowl}$$

$$V_{Material} = \frac{1}{3} \times \pi \times (0.525542 - 0.5142) \times 2.056 = 0.00822\ m3$$

$$\therefore WBowl = VMaterial \times \rho G2507$$

$$\therefore WBowl = 64.13\ kg$$

Valves: Now that the weight of the piping and vessel are determined, the weight of the motor, valves and

pumps.
Therefore, using the weight of a Samson Type 3241 valve for control valves and the average valve weight table provided by Wermac:

$$\therefore W_{Valve} = W_{Control} + W_{Gate} + WCheck = 100 + 231 + 95$$

$$\therefore W_{Valve} = 426\ kg$$

Pumps:

There are a total of 5 pumps in the main system, being the Alfa Laval LKH-100 model. Which weights at 70 kg as stated on the data sheet of the component (Alfa Laval,2006):

$$W_{Pump} = 5 \times 70\ kg = 350\ kg$$

Motor:

The Siemens 1LA5 model is stated to be 78 kg.

$$\therefore W_{Motor} = 78\ kg$$

CIP System:

Appendix 4: Relationship between Fluid Velocity and Pressure Drop, including all the factors in performance evaluation

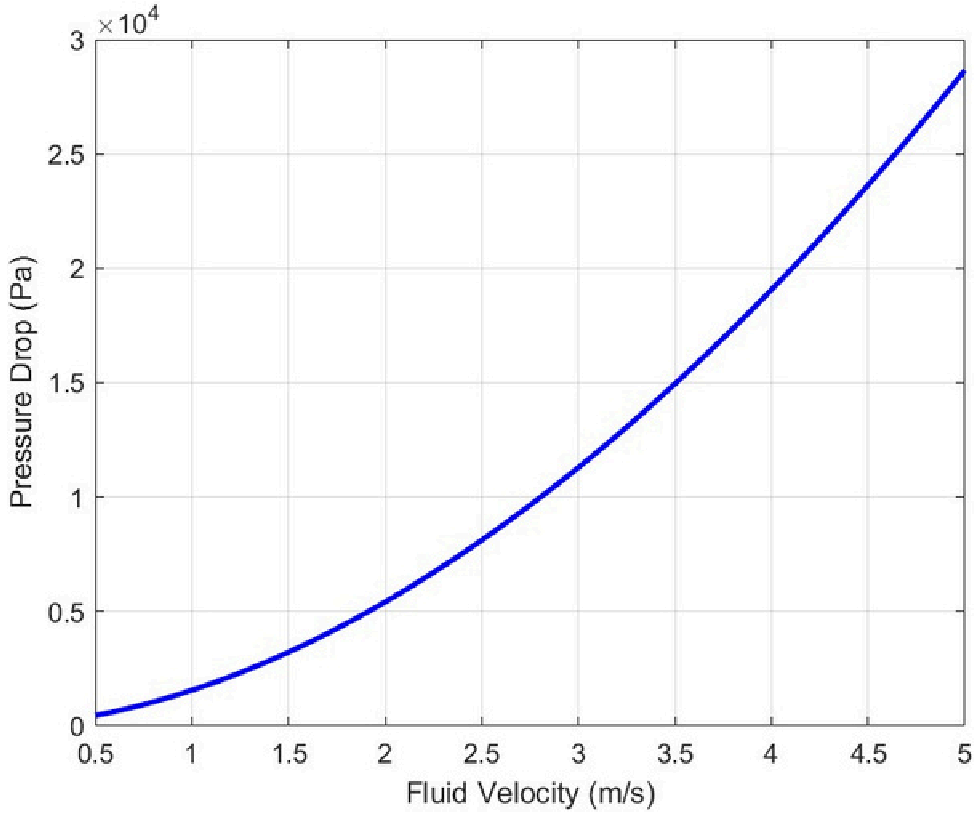


Figure 12: Relationship between Fluid Velocity and Pressure Drop, including fouling and non-Newtonian properties and constant piping dimensions.

The code for this is as seen:

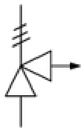
```
%This graph was produced due to the problems that came %with Figure 7. It was that the optimal dimensions for the %pipes to achieve this pressure drop was out of range of the graph and %showed unrealistic values, which had to be further investigated. For this, %a fluid velocity against pressure drop graph was produced to see of the %problem lied in the fluid velocity, which was concluded that it was the %problem.



%Optimal pipe parameters calculated as an average between Figures 5 and6
%and the unit design calculated parameters
```

```
d_pipe = 0.1224; % Pipe diameter (m)
L = 20.25; % Pipe length (m)

%Fluidparametersforraw     milkwasused.

rho = 1035; % Fluid density (kg/m^3)
v_range=linspace(0.5,15,    100); %Fluid velocities (m/s)

%Frictionfactorcalculation,theReynolds number

Re_range=rho*    d_pipe*v_range/(1.3 * 10^-3); % Reynolds number
epsilon=0.05/    1000; %Piperoughness (m)
f_guess = 0.02;

%  frictionfactorswerecalculatedusing Colebrook-White equation,as seen
%  inthePerformanceEvaluationsection.

f = zeros(size(v_range));
for k = 1:length(v_range)
    f(k)=fzero(@(x)1/sqrt(x)+2*log10(epsilon/(3.7*d_pipe)+
2.51./(Re_range(k)*sqrt(x))),f_guess);
end

%Oncethefrictionfactor     wasobtained, it was incorporated intot the
% Colebrook-White equation/

P_drop=f.*(L/d_pipe).*      (rho.*v_range.^2) / 2;

%Plot pressure drop against fluid velocity
figure;
plot(v_range, P_drop, 'b-', 'LineWidth', 2);
xlabel('Fluid Velocity (m/s)');
ylabel('Pressure Drop (Pa)');
grid on;

f(k)
```

Appendix 5: Legend for the P&IDs of the Tetra Pak H80 and CIP System

Table 7: P&ID Symbol Identification

P&ID Symbol	Component	Label	P&ID Symbol	Component	Label

	Centrifugal Separator	CS-		Gate Valve	GV-
	Pump	P-		Control Valve	V-
	Pressure Safety Valve	PSV-		Check Valve	CHV-
	Thermal Safety Switch	TSS-		Orifice	O-
	Resistance Temperature Detector	TE-		Globe Valve	V-
	Pressure Gauge	PG-		Normally Closed Valve Gate	CGV-
	Level Alarm	LA-		Level Transmitter	I- I-
	Pressure Alarm	PA-		Pressure Transmitter	TT-
	Temperature Alarm	TA-		Temperature Transmitter	TIC-
	Level Indicator and Controller	LIC-		Temperature Indicator and contorller	
	Pressure Indicator and controller	PIC-			

Appendix 6: MATLAB code for the 3D plot for pressure drop with no factors included (Figure 5)

```
%This graph is a simple translation of the Darcy-Weisbach equationonto  a
%3D plane which allows for visualisation of the equation ratherthan
%reading and understanding, this allows for technical and non-technical
%audiences to grasp a basic understanding of what this equationrepresents,
%which is the relationship between pipe dimensions and pressuredropin   the
%unit. This graph neglects non-Newtonian and fouling effects andlooks
%purely at the relationship in a perfect scenario.


%These are the chosen range of design parameters, as they include the
%calculated dimensions in the Unit Design section.


l_Pipe = [10, 20, 30, 40, 50]; % Example pipe lengths in meters
u_fluid = 2; % Fluid velocity in m/s
rho_fluid = 1035; % Fluid density in kg/m^3
d_pipe = 0.05:0.01:0.2; % Example pipe diameters in meters


%The calculation is then undergone


pressure_drops = zeros(numel(d_pipe), numel(l_Pipe));
```

```
for i = 1:numel(d_pipe)
    for j = 1:numel(l_Pipe)
        pressure_drops(i,j)=(rho_fluid * u_fluid^2) / (2 * d_pipe(i)) *
l_Pipe(j);
    end%Thecurrentcombinationofdiameter and length is checked to see if
it is close to 650 kPa

end


%Thisisthebaselinecode       requiredto start plotting the 3D graph to see
%therelationshipbetween      the3variables in the Darcy-Weisbach equation.


[X, Y] = meshgrid(l_Pipe, d_pipe);
surf(X, Y, pressure_drops);
xlabel('Length of Pipe (m)');
ylabel('Diameter of Pipe (m)');
zlabel('Pressure Drop (Pa)');


%Marker at 650 kPa and 0.1 m pipe diameter
pressure_marker = 650 * 1000; % Conversion of kPa to Pa
target_diameter = 0.1; % Pipe diameter (m)
hold on;
marker_color = 'r'; % Marker colour was chosen red to be easily identified.
marker_size = 30; % The marker size was also large so that the reader can
identify the optimal dimensions for pipes easily.


%Calculate the corresponding pipe length for the target pressure drop  and
diameter
target_length = (pressure_marker * (2 * target_diameter)) / (rho_fluid *
u_fluid^2);


%This adds the marker which will show the optimal point of the graph to
%achieve a pressure drop of 650 kPa.


plot3(target_length, target_diameter, pressure_marker, '.', 'Color',
marker_color, 'MarkerSize', marker_size);


hold off;


%Once the optimal point is found on the graph, the marker locationis
%generated and displayed in the code, this is what this line of codeis
%for.


fprintf('Marker location:\n');
fprintf(' Pipe Length: %.2f m\n', target_length);
```

```
fprintf(' Pipe Diameter: %.2f m\n', target_diameter);
fprintf(' Pressure Drop: %.0f Pa (%.0f kPa)\n', pressure_marker,
pressure_marker / 1000);
```

Appendix 6: MATLAB code for the 3D plot for pressure drop with non-Newtonian factors included (Figure 6)

```
%Thisisessentiallyidentical to the graph with no factors included, which
%meansthatonly   thepower  law and the required parameters for this law
%were required.


% Power-law parameters
k=0.1;%Exampleconsistency index (Pa*s^n)
n=0.8;%Exampleflowbehavior index


% Fluid velocity in m/s
u_fluid = 2;


% Fluid density in kg/m^3
rho_fluid = 1035;


%Examplepipediametersin     meters
d_pipe = 0.05:0.01:0.2;


% Example pipe lengths in meters
l_Pipe=[10,20,30,40,50];


pressure_drops = zeros(numel(d_pipe), numel(l_Pipe));


fori=1:numel(d_pipe)
    forj=1:numel(l_Pipe)
        r_inlet =d_pipe(i) / 2; % Inlet pipe radius (m)
        F_inlet =u_fluid * pi * r_inlet^2; % Flow rate at the inlet (m^3/s)


        %Calculatethe shear rate (du/dy)
        du_dy=  (4*F_inlet) / (pi * r_inlet^3);


        %Calculatethe apparent viscosity (µ_app)
        mu_app=  k*du_dy^(n - 1);


        %Update  thepressure drop calculation with µ_app
        pressure_drops(i, j) = (8 * mu_app * l_Pipe(j) * F_inlet) / (pi *
r_inlet^4);
```

```
    end
end


%Plot the updated 3D graph
[X,Y] = meshgrid(l_Pipe, d_pipe);
surf(X, Y, pressure_drops);
xlabel('Length of Pipe (m)');
ylabel('Diameter of Pipe (m)');
zlabel('Pressure Drop (Pa)');


%Marker at 650 kPa and 0.1 m pipe diameter
pressure_marker = 650 * 1000; % Conversion of kPa to Pa
target_diameter = 0.1; % Pipe diameter (m)
hold on;
marker_color = 'r'; % Marker colour was chosen red to be easily identified.
marker_size = 30; % The marker size was also large so that the reader can
identify the optimal dimensions for pipes easily.


%Calculate the corresponding pipe length for the target pressure drop  and
diameter                                                                 *
target_length = (pressure_marker * (2 * target_diameter)) / (rho_fluid
u_fluid^2);


%This adds the marker which will show the optimal point of the graph to
%achieve a pressure drop of 650 kPa.


plot3(target_length, target_diameter, pressure_marker, '.', 'Color',
marker_color, 'MarkerSize', marker_size);


hold off;


%Once the optimal point is found on the graph, the marker locationis
%generated and displayed in the code, this is what this line of codeis
%for.


fprintf('Marker location:\n');
fprintf(' Pipe Length: %.2f m\n', target_length);
fprintf(' Pipe Diameter: %.2f m\n', target_diameter);
fprintf(' Pressure Drop: %.0f Pa (%.0f kPa)\n', pressure_marker,
pressure_marker / 1000);
```

Appendix 6: MATLAB code for the 3D plot for pressure drop with all factors included (Figure 7)

```
%This graph shows the relationship between the pressure drop, pipe length
```

```
%andpipediameter,itisalreadystated in the report that the diameter
%frominletand   skimoutlet  aresimilar, therefore the assumption was
%d_inlet~d_skim_outlet.Withthisgraph however, the factors of fouling
%andnon-Newtonianfluideffectsareincluded


%Thesearethe   target_delta_P=determinedprocessparameters in the Tetra Pak for milk
l=linspace(10,   650000; % targetpressure drop (Pa)
d=linspace(0.05,0.05,500);50); % pipelength values (m)
                              %pipediameter values (m)
rho_fluid=1035;   %fluiddensity(kg/m^3)
u_fluid = 2; % fluid velocity (m/s)


%Variables  are  intialised  to  store  them.
Delta_P   =   zeros(length(l),   length(d));
min_difference   =   Inf;   optimum_l   =   NaN;
optimum_d = NaN;



%Thislineofcodewillcalculatethe        pressure drop for each pipe length
%anddiameterinthegiven      rangesin  theparameters section.
for i = 1:length(l)
    for j = 1:length(d)
        Delta_P(i,j)=(rho_fluid*u_fluid^2) / (2 * d(j)) * l(i);
        %Thispieceofcodeessentiallytries every combination of pipe

        %length  anddiameterontheDarcy-Weisbach equation to find the2
        %dimensionsthatcrossoverat650       kPa, the optimal separation
        %pressure
        ifabs(Delta_P(i,j)   -target_delta_P) < min_difference
            min_difference =abs(Delta_P(i,   j) - target_delta_P);
            optimum_l=l(i);
            optimum_d=d(j);
        end
    end
end


%Createa3Dplotofpressuredropagainst         pipe length and diameter
[X, Y] = meshgrid(d, l);
figure
surf(X, Y, Delta_P)
xlabel('Pipe Diameter (m)')
ylabel('Pipe Length (m)')
zlabel('Pressure Drop (Pa)')
grid on


%Mark the optimal point on the 3D plot
hold on
scatter3(optimum_d, optimum_l, target_delta_P, 'r', 'filled')
hold off
```

```
%Display the optimal pipe length and diameter
fprintf('Optimum l_pipe: %.2f m\n', optimum_l);
fprintf('Optimum d_Pipe : %.4f m\n', optimum_d);
```