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SEPARATOR SELECTION FOR HYDROCHAR PRODUCTION

Technology
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TIIVISTELMÄ

Tekijä	Henri Liias
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Tämän opinnäytetyön tavoitteena on vertailla erotusteknologioita, jotka soveltuvat hydrotermisesti käsitellyn biomassan ja prosessiveden erottamiseen sekä valita sopiva yleisratkaisu kyseiseen prosessiin. Tarkoitus on identifioida tärkeimmät suodatinlaitteiston valintaan vaikuttavat tekijät ja tehdä valinta niiden tekijöiden pohjalta.

Hydrotermistä hiiltämistä käsittelevien tieteellisten artikkeleiden, sekä kiintoaineden ja nesteiden erottelun teoriaa yhdistämällä tärkeimmät tekijät voidaan selvittää riittävällä tarkkuudella, jotta erotus teknologioiden rajaaminen muutamiin vaihtoehtoihin on mahdollista. Tästä rajatusta listasta vertailemalla soveltuvin vaihtoehto voidaan valita.

Mekaanista voimaa hyödyntäen prosessiveden määrä biohiilessä saadaan alenemaan energiatehokkaasti verrattuna veden haihduttamiseen. Eroteltavan biohiilen koostumuksesta johtuen suodattimen pintaan muodostuva kakku vastustaa veden kulkeutumista suodattimen lävitse, joten mekaanisen voiman tarve kasvaa. Tästä syystä hydraulisilla palkeilla laajennettavat suodatuskammiot valittiin soveltuvimmaksi erotusteknologiaksi.

Avainsanat hydroterminen, biohiili, suodatin, kakku

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ABSTRACT

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The objective of this thesis was to evaluate separation technologies for the separation of hydrothermally carbonized biomass from process water and to narrow the list of possible technologies to the most suitable one. With the identification of the most important properties affecting the separation process the selection could be made.

Scientific articles covering the properties of hydrothermally carbonized biomass combined with textbooks on solid liquid separation allowed the key properties to be identified to such accuracy that an overall view of the separation problem could be formed. This narrowed the list of different separation technologies so that the comparison was possible.

Mechanical dewatering of hydrothermally treated biomass as an energy efficient alternative to thermal drying allows a business case to be formed. The properties of the hydrochar increase the required mechanical pressure across the filter media for the separation to take place. Horizontal diaphragm filter press was chosen as a solution to the separation problem as the pressure difference across the media is high enough to produce relatively low moisture product.

Keywords Hydrothermal, hydrochar, filter, cake

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ABSTRACT

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1 INTRODUCTION

As the reduction of environmental impact resulting from the society's activities is central to ensure sustainable growth the reuse of waste is a growing trend. As no singular existing technology can replace fossil fuels or materials, it is necessary to look into a regionally available mix of alternative resources. As sewage waste is produced by humans and domestic animals all over the globe, it is a resource that is available today as well as in the future. However, the sewage sludge as it is found at the wastewater treatment plant or manure pits does not possess the required properties to be considered as a valuable resource so a process to enhance the properties of the sewage sludge is necessary.

A study into hydrochar production by Ramke shows that the hydrothermal carbonization process improves the dewaterability of organic waste from around 45% discharge to 67% discharge of the total volume, this is beneficial as the mechanical dewatering is essential for the process to be energy neutral or positive and to ensure economic and environmental feasibility. The figures are only to show that there is an improvement and higher dewaterability results are obtainable by specialized equipment. (Ramke 2009, 12)

This thesis will focus on the effluent from the hydrothermal carbonization reactor and how to separate the produced hydrochar from the process water. This is a necessary step for the process as the moisture content after the carbonization is around 90% and therefore it is too diluted to be utilized as intended.

1.1 Objective

The objective of this thesis is to find reliable and life cycle cost efficient means for the automated separation of hydrochar from process water and the conveyor technology for the transportation of hydrochar from the separator into the intermediate storage. The main aspects to be evaluated are the energy requirements and mediums, capital and operating costs, lifecycle and the quality of the end product. The influent flow is estimated to be 1208 t/a at 8000 h of operation and the process equipment should fit inside a semi-trailer. These constraints are to be taken into account when choosing the process equipment.

1.2 Methodology

Sludge properties are essential to be determined before the separator technologies can be evaluated. The particle size and size distribution, shape, porosity, specific surface, surface roughness and density are essential for the design. In addition, liquid characterizing parameters such as chemical composition, concentration of specific dissolved substances, conductivity, density, pH, temperature, surface tension or viscosity affect the design. When sufficient data about the process and the sludge have been defined, the different technologies and manufacturer types are compared and evaluated as defined in the objective. The comparison list will help to narrow the variety of technologies to find most suitable candidates. After the elimination the remaining technologies are compared further by capital and operational cost attained by contacting manufacturers. Then a proposition for the most suitable technology and its integration into the process is formed.

2 PROCESS, FEEDSTOCK AND HYDROTHERMALLY CARBONIZED SLUDGE

In this section the properties of the hydrothermal carbonization sludge that are most crucial to the filterability are listed to such extent that literature surveys allow without laboratory experiments and the process is explained with a cross section of the truck bed with the process equipment.

2.1 Requirements of the Separation

In this case the solids separated from the liquid are the valued product and the separation system must be chosen to suit this purpose. The separator is the last phase in the process chain prior to the conveyor to the intermediate storage. An acceptable yield of solids is 30 kg/h. Feedstock can vary in dry matter content depending on the state of the manure pit.

2.2 Process

Figure 1 shows the process equipment from left to right, feed tank, reactors and sludge tanks. The separator and additional equipment must fit between the sludge tanks and the back doors of the trailer.

Figure 1. A cross section of the trailer with the process equipment (Recomill Oy 2020).

Hydrothermal carbonization process is a chemical process that converts organic compounds into structured carbons that can be used in a variety of applications, such as brown coal substitute for power plants and soil fertilization. The process is in fact an imitation of the naturally occurring process of brown coal formation. The influent is lead into a reactor and heat is applied increasing the pressure and temperature inside the reactor. Typical temperature ranges for the process are from 200 °C to 260 °C. At this temperature the water is kept under the water saturation pressure, so the water remains in liquid phase. The feedstocks organic matter is converted to hydrochar by a chain of chemical reactions that include hydrolysis, dehydration, decarboxylation, aromatization and recondensation. The hydrothermal carbonization process is desirable over other conversion methods, such as dry pyrolysis as the yield of hydrochar is higher and the chemical properties are closer to natural coals compared to the hydrochar produced by pyrolysis. Hydrothermal treatment also allows for water content in the feedstock to be as high as 95% (Libra, Ro, Kammann, Funke, Berge, Neubauer, Titirici, Fühner, Bens, Kern, Emmerich 2014, 71-106)

2.3 Feedstock Properties

The hydrothermal carbonization process in question is a continuous process with a mass flow of approximately 150 kg/h. The dry-matter content is estimated to be 20% w/w. The source for the feedstock is a manure pit of a swine farm. The particle size distribution of wet swine manure collected from a commercial swine farm listed in Table 1. (Masse 2004)

Table 1. Particle size distribution (Masse 2004).

Particle size of total solids	Percent in size categories
<0.45 µm	20%
0.45-10 µm	30%
10-50 µm	20%
50-250 µm	7%
250-1000 µm	5%
>1000 µm	18%

Values in Table 1 are examples, the exact particle size distribution can only be determined by sampling the manure of the farm in question. The d_{50} particle size distribution based on this chart is 10 µm as 50% of particles are smaller than 10 µm and it is presented in Figure 1 below.

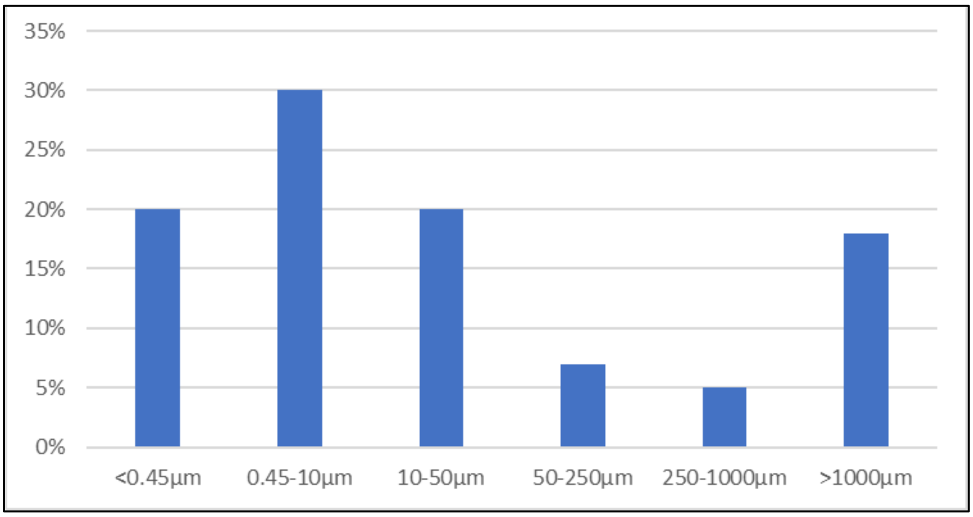

Figure 2 Chart of size distribution (Masse 2004).

2.4 Effects of Hydrothermal Carbonization Process to the Feed Properties

A study of the effects of hydrothermal carbonization process temperature on swine manure characteristics was carried by Song et al. and the results were that the particle size is reduced as the reaction temperature increases with notable differences on surface roughness starting from 180 °C as the decomposition of hemicelluloses and celluloses in swine manure takes place. (Song, Zheng, Shan, Wu, Wang, & Christie 2019)

Similar results were observed by Niinipuu et al. (2020) in their study on the impact of hydrothermal carbonization on the surface functionalities of wet waste materials for water treatment applications. The study of surface area and morphology with sewage sludge, bio sludge, fiber sludge and horse manure shoved that the surface area increased, and the particle size decreased with the increasing temperature of the hydrothermal carbonization process. (Niinipuu, Latham, Boily, Bergknut, & Jansson 2020)

2.4.1 Particle Size Effect on Filterability

The Reynolds number is used to measure the ratio of inertial forces to viscous forces and values of Re < 0.2 in solutions with fine particles usually presents difficulty of separation. Terminal settling velocity is used to gain a general perspective of how a slurry will perform in sedimentation and values under $1.11 \cdot 10^{-4}$ m/s are generally unsuitable for gravity separation. (Gertenbach & Cooper 2010)

$$Re = \frac{\rho u x}{\mu} = 2.73 \cdot 10^{-4} \tag{1}$$

where: ρ is density of liquid (g/m^3)
u is particle-fluid relative velocity (m/s)
x is particle size (m)
μ is dynamic viscosity of fluid (Pa s)

$$u = \frac{x^2(\rho_s - \rho)g}{18\mu} = 2.73 \cdot 10^{-5}\ m/s \tag{2}$$

where: ρ_s is density of particle (g/m^3)
g is gravitational constant (m/s^2)

For calculation the average particle size is determined to be $d_{50} = 10$ µm after the hydrothermal carbonization process. The particle size is squared in the latter formula for calculating particle-fluid relative velocity so it has a large impact to the Reynolds number and thus should be determined by laboratory experiments to have certainty. The density of particles was estimated to be 1500 kg m^{-3} using averages derived from studies of biochar skeletal density. The gravitational constant used for calculation was 9.81 m/s^2, density 998.21 kg m^{-3} and viscosity $1.002 \cdot 10^{-3}$ Pa s of water at the temperature of 20 °C was used. (Brewer, Chuang, Masiello, Gonnermann, Gao, Dugan, Driver, Panzacchi, Zygourakis, Davies, Christian 2014, 176-185; Liu, Dugan, Masiello, & Gonnermann 2017)

2.4.2 Specific Resistance of Hydrochar Cake

Specific cake resistance measures the filterability or dewaterability, the higher the value, the larger pressure difference across the media is required for a constant filtering rate. Initial resistance is caused by the filtering media and as the filter cake grows on the surface of the filter media the resistance increases as the filtrate has to pass through the accumulated cake as well as the filter media. The value is inversely proportional to the square of the particle size and a 50% decrease in particle size causes the specific cake resistance to grow by a factor of 4. (Tarleton & Wakeman 2005, 148)

A study of filterability of hydrothermally carbonized primary sewage sludge and synthetic faeces was carried by Danso-Botaeng et al. (2015). Using measured values for the specific cake resistance between $5.43 \cdot 10^{12}$ and $2.05 \cdot 10^{10}$ m kg^{-1} for cold filtration of primary sewage sludge, $1.11 \cdot 10^{12}$ and $3.49 \cdot 10^{10}$ m kg^{-1} for cold filtration of synthetic faeces, and $3.01 \cdot 10^{12}$ and $3.86 \cdot 10^{10}$ m kg^{-1} for hot filtration of synthetic faeces, the study indicates that the specific resistance decreases with the increase of reaction time and temperature without a significance change between hot and cold filterability of synthetic faeces. The separation method was a vacuum filter. (Danso-Boateng, Holdich, Wheatley, Martin, & Shama 2015)

Another study into specific cake resistance of hydrochar was carried by Waldmüller et al. (2020). using a pressure filter for the separation. The study concluded a resistance of $4.5 \pm 2.2 \cdot 10^{15}$ m^{-2} that is considerably higher than in the study performed with a vacuum filter. This was explained by the penetration of finer particles into the filter cloth, causing the resistance to increase. The pressure filtration as a process also causes the cake to be more densely packed and this also increases the cake resistance. Pressure filters are studied further in Chapter 4. (Waldmüller, Herdzik, & Gaderer 2020)

Vacuum filtration is generally suited for solutions with a specific cake resistance under $7.1 \cdot 10^{10}$ m kg^{-1} and pressure filtration for cake resistance values exceeding this value. (Holdich 2007)

The magnitude of specific resistance can be used to group different feeds by relative ease of filtration. (Tarleton & Wakeman 2005, 116)

Table 2. Ease of filtration in respect to the specific resistance.

Ease of filtration	Specific resistance (m kg^{-1})
Very easy	$<10^9$
Easy	10^{10}
Moderate	10^{11}
Difficult	10^{12}
Very difficult	$>10^{13}$

3 COAGULATION, FLOCCULATION AND SLUDGE CONDITIONERS

Coagulation and flocculation are an important aspect of wastewater treatment as they are used to increase particle size, thus easing the separation process of suspensions. Therefore, the chemical pre-treatment is crucial to the operation of wastewater plants and processes where separation is a key step. (Bratby 2016, 5)

Sludge conditioners are used in suspensions to enhance deliquoring. These substances or chemicals can also be used to strengthen the flocs before the deliquoring phase. (Tarleton & Wakeman 2005, 129)

3.1 Coagulation and Coagulants

Coagulation is defined as a process where a system is transformed from a stable to an unstable state. An example is the boiling of an egg where the protein coagulates as heat is applied. Mechanical force can be used as means for coagulation as agitation of suspension causes it to destabilase. Shear forces affect the suspended particles by delivering energy to them and cause formation of larger flocs if the solution environment permits it. Energy input to suspended particles must be greater than the potential energy barrier that opposes coagulation. As the agitation can only be increased to a certain level before the floc start to break, chemicals that reduce the opposing force to coagulation are used. (Tarleton & Wakeman 2005, 130)

Most common coagulants are metal coagulants and polymers. Metal coagulants are in two general categories, aluminium and iron based. Other chemicals are hydrated lime and magnesium carbonate. Aluminium and iron are used widely because of the low cost and availability as well as their effectiveness as coagulants. Al^{3+} and Fe^{3+} are especially effective in increasing the ionic strength of the solution. The benefit of increasing the ionic strength is that it reduces the range of repulsive forces between the particles. This is caused by the compression of the double layer. (Bratby, 2016)

3.2 Flocculation and Flocculants

Flocculation is the realized effect of the change of state in the system. Flocculation increases the rate of floc formation and influences the properties of the formed flocs and sets the final concentration of destabilised particles. This effect is enhanced with the use of substances or chemical additives called flocculants. (Bratby 2016, 7)

The flocculation takes place in two stages, first is called perikinetic flocculation that is caused by thermal agitation and it follows the Brownian motion that sets the upper limit for the floc size. This phase is completed in seconds as the upper limit to the floc size is reached. The second stage called orthokinetic flocculation is caused by velocity change in different layers of the liquid. The change in velocity can be caused by multiple different changes in the suspension or environment, such as mechanical agitation or differential settling velocity within the settling basin. The time of flocculation combined with the velocity change in the different liquid layers sets the rate and extent of floc formation and floc breakup. These are the most important design parameters for a flocculation basin. (Bratby 2016, 316)

3.3 Design Parameters

Important parameters that govern the efficiency of coagulation-flocculation process are numerous. When these parameters are defined the process can be tested. The testing phase is generally done so that one parameter is altered at a time to find the optimum. The governing criteria is the application of which the suspension is being treated. In this application the quality of the effluent is not the main concern but the effect on sludge parameters such as specific resistance. The use of low-cost techniques to increase the floc size can lead to faster processing times and lowered moisture content of final product. The recovery of very fine particles <1 µm also improves the efficiency of the process.

4 MODERN SEPARATOR AND CONVEYOR TECHNOLOGIES

As Table 1 states, 70% of total solids in the studied swine manure are <50 µm and after the hydrothermal carbonization this percentage will only increase as the biomass degrades. The decrease in particle size increases the surface area of the solids by the cube of the diameter and thus increases the area where water is in contact with solids causing the difficulty of separation presented by the small Reynolds number. The separator technology selected for the evaluation should be able to effectively separate particles in that range. The most suitable filter is often the technology that effectively separates the solution to a desirable degree with the minimum overall cost. The desirable moisture content is important as it determines the need for thermal drying after the filtration and as evaporation is always quite energy intensive compared to dewatering via mechanical pressure it can increase the operational costs. The following list of separation technologies was selected for further evaluation as they can separate particles of required size and are able to produce relatively low moisture cake. The technologies selected are batch types as the flow of feed is relatively low.

In Figure 3, a generalized equipment selection guide is presented in respect to the particle size and required filtration pressure. (Anlauf 2019, 39)

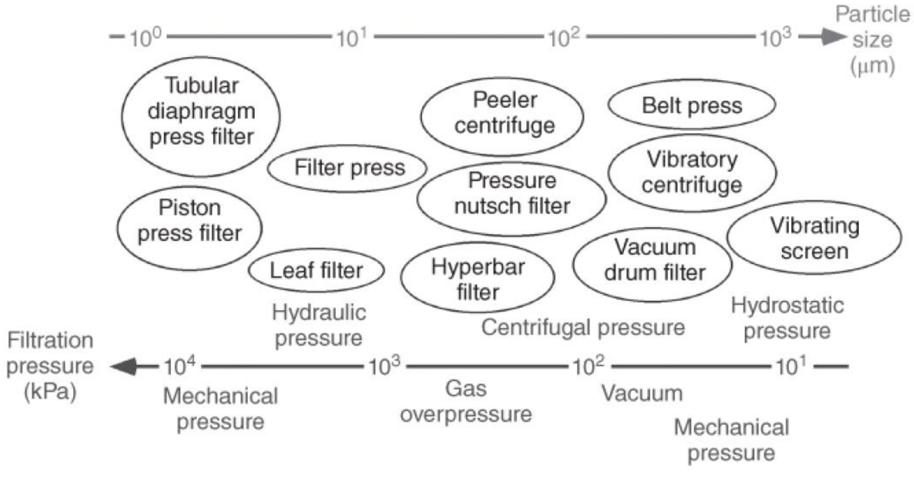

Figure 3. Particle size and required filtration pressure (Anlauf 2019).

4.1 Nutsche filter

The Nutsche filter is a batch type filter built in a cylindrical pressure vessel as seen in Figure 4. The filter media is a planar leaf at the bottom of the vessel. The feed is let into the vessel and pressure up to 800 kPa is applied inside the vessel so that the feed is forced through the filter. This starts the cake formation and it is continued until the cake formation phase is complete. The cake is discharged by rotating a plough that is lowered by hydraulic cylinder, an opening on the side of the vessel is opened to allow the discharge. The vessels can be installed with heating and cooling jackets and electric heaters. Convection drying where hot pressurized gas is blown through the solids can be used to reach moisture content of up to 0.1% w/w. Due to the design of the process it is necessary to compare the filtering area *A* to the bulk dimensions of the process equipment. This type has very low fraction as the element is one sided at the bottom of the vessel, so $A = 1\ \text{m}^2$ requires a vessel that needs area larger than $1\ \text{m}^2$. (Tarleton & Wakeman 2007, 37-38; Mayo, 2014)

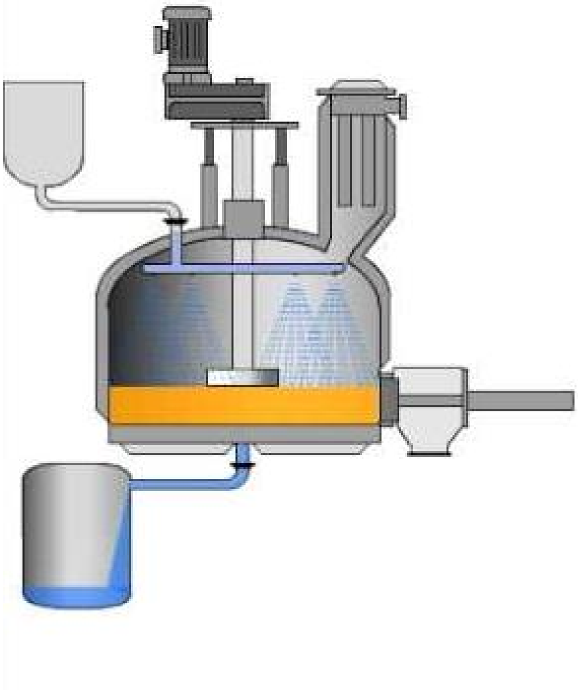

Figure 4. Pressure Nutsche filter (Heinkel Drying and Separation Group 2015).

4.2 Multi-element Leaf or Candle

A multi-element pressure filter is a cylindrical pressure vessel that has, depending on the type, either horizontal or vertical porous elements which hold the filter cloths inside the vessel. A horizontal multielement leaf filter with the pressure vessel opened is presented in Figure 5. The filtration takes place on the outside of the cloths due to increased pressure up to 500 kPa and filtrate is channelled through the elements and out from the vessel via piping. The filter elements can be flat squares, rectangular or circular. A candle formation is also possible with the elements in a tubular form. Sufficient spacing is left between the elements to enable cake formation. After the cake formation is completed the vessel is opened and cake discharged, smaller installations open the end of the vessel to enable removal of the whole element. In a more frequent process, the cakes are removed with the elements in place by vibration, rotating blades or liquid sluicing for wet discharge. Horizontal elements can also be discharged via centrifugal force forcing the cake off the leaves. (Tarleton & Wakeman 2007, 38-39)

Figure 5. Horizontal element leaf filter (National Filter Media 2021).

Vertically mounted vessels are economical in floor utilization but require adequate spacing vertically if the cake discharge is done by raising the leaves out from the vessel and during cloth cleaning, as seen in Figure 6. Horizontal leaves are desirable for processes where washing is required, feeds settle rapidly or if the equipment is used for varying feeds, this type increases the installation costs as the filtration takes place only on the upper surface of the leaves, thus reducing the total surface area for cake formation. Feeds with settling velocities under 3 cm/s are effectively filtered with rectangular vertical filters but have decreased washing performance as the cake is drawn of the cloth due to gravity. If washing is not required then tubular candle formation is usually used, in this formation the cake forms on the tubular outer surface. Horizontally mounted vessels utilize more floor space but require less height especially if the elements are withdrawn for discharge or washing. Washing abilities are also reduced as the cake tends to fall off the filter surface. This type has a moderate fraction as the element is two sided with multiple leaves inside of the vessel, however the required space for the discharge reduces the fraction. (Tarleton & Wakeman 2007, 40)

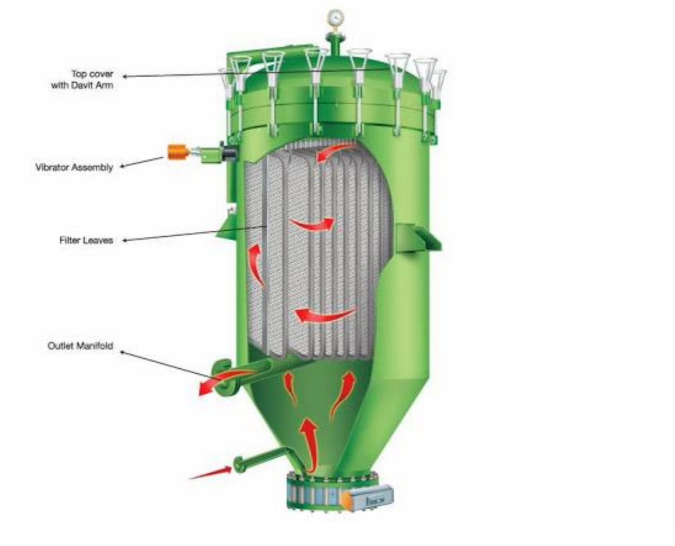

Figure 6. Vertical leaf filter (Aashiq 2013).

4.3 Filter Press

The basic filter press unit consists of a frame and a row of filter elements attached to the frame, as seen in Figure 7. Filtration takes place in the chambers formed by hollow intermediate frames and flat filter plates holding the filter cloths. The filtration chamber can also be constructed without the intermediate frames by recessed filter plates. The plates allow the cake to form and the optional operation of washing and gas deliquoring. The filter plates are sealed by applying pressure with a hydraulic ram on the other end of the support frame, when the hydraulic cylinder extends it forces the filter plates against the support frame and adequate pressure is formed between the filter plates to seal them. Feed is introduced through manifolds formed on the filter plate row by holes in the plates after the row is sealed. Pressure in the feed is increased with a suitable displacement or centrifugal pump and this starts the cake formation phase. Centre ported plates are typically used to pump feeds with higher solid content. Bottom ported plates are used when even cake formation is desired and top ported for suspensions that settle fast. Typical operating pressure is limited to 800 kPa, but special installations are available that allow pressures as highs as 7000 kPa. Fluid is discharged through the filtering cloth and allowed to fall into a collecting tray. When cake formation is complete, the hydraulic cylinder is drawn in to allow the filter plates to be separated, this is done either manually or automatically. Good properties for the cloths in respect to the release of the cake are important to ensure operational feasibility. Depending on the feedstock the cloths are washed after the cake release phase. The filtering area can be as high as 2000 m^2 but installations in the 50-1000 m^2 range are most typical. This type utilizes space most efficiently as the elements have filtering surfaces on both sides of the chambers. A press with 500 mm filter element consisting of 20 filter chambers has a filtering area of 10 m^2 and requires approximately 1.5 m^2 floor area. (Tarleton & Wakeman 2007, 41)

Figure 7. Filter press (ErtelAlsop 2021).

4.4 Horizontal Diaphragm Filter Press

The horizontal diaphragm filter press is a type of variable-volume filter press, similar to the filter press described previously but with an addition to membrane plates formed by flexible diaphragms between the filter plates presented in Figure 8. This type of filter is suited for the separation of suspensions where liquid is held inside the inherent porous structure of the solids. A usual way of operation is that the pumping is stopped when 80% of the cake volume is reached. This enables the chambers to be partially filled with the unfiltered feed. Then the membranes are inflated to increase the pressure up to 1600 kPa inside the filter chamber forcing the remaining filtrate out and pressing the cake to reduce the moisture content further. This operation is presented in Figure 9. Combined with gas deliquoring the cake moisture can be reduced up to 25% more than with the conventional filter press. Applying pressure to the cake also improves cake uniformity that can be of advantage in the following process steps. The installation, however, is significantly more expensive than the conventional filter press in capital and operational costs, but the value added by the reduced cycle time and improved cake characteristics justify the added expenses in cases where the separated solids are the value product. This type utilizes space most efficiently as the elements have filtering surfaces on both sides of the chambers. (Tarleton & Wakeman 2007, 43-45)

Figure 8. Diaphragm filter press (MET-CHEM 2021).

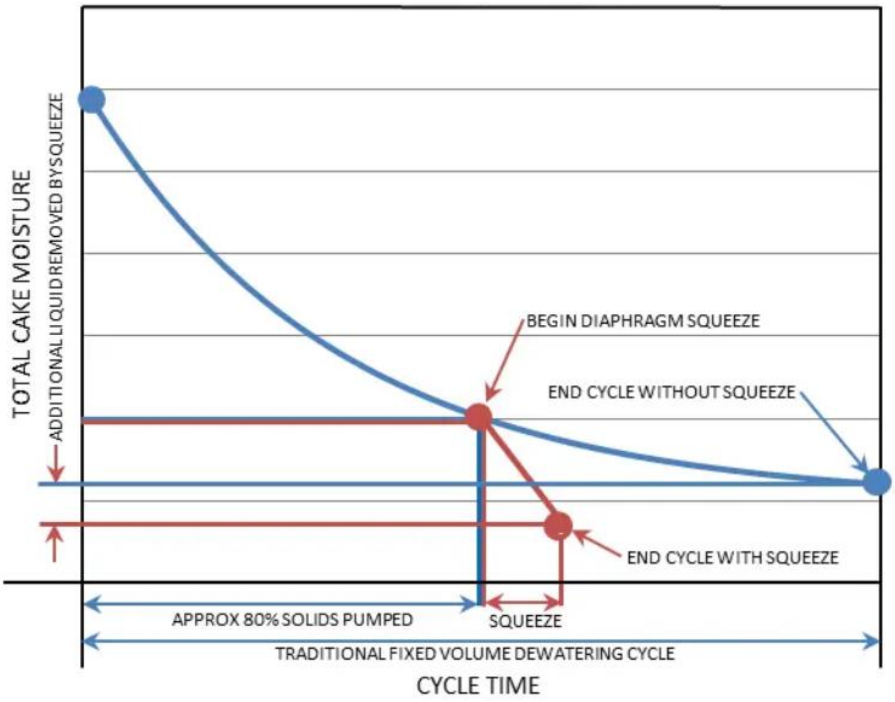

Figure 9. Diaphragm squeeze effect to cycle time and moisture content (Gethin 2019).

4.5 Tube Press

This tube press is constructed of two concentric cylinders, the permeable tube holding the filter is inside the outer solid tube that has been lined with a diaphragm made from elastomer. A series of tube presses can be seen in Figure 10. Feed is pumped between the filtering tube and the elastomer, when the chamber is filled, the cake formation starts by forcing the elastomer bladder to dilate by pumping water or some other hydraulic fluid inside the bladder. Pressures up to 100 bars can be reached and this reduces the moisture content of the cake superior to any other mechanical dewatering means. The cake is discharged by opening the bottom of the press and lowering the inner element holding the cake, then compressed air is used to create a pulse that causes the cake to fall off. Capital and operational costs can be relatively high, but the reduced requirement for thermal drying and short cycle times can make up for the costs. This type requires less floorspace but a lot of height to create efficient filtering area. Metso 500 series requires 3.5m height for a tube press with a filtering area of 1.35 m^2. (Tarleton & Wakeman 2007, 47-48; Metso Outotec Oy 2021)

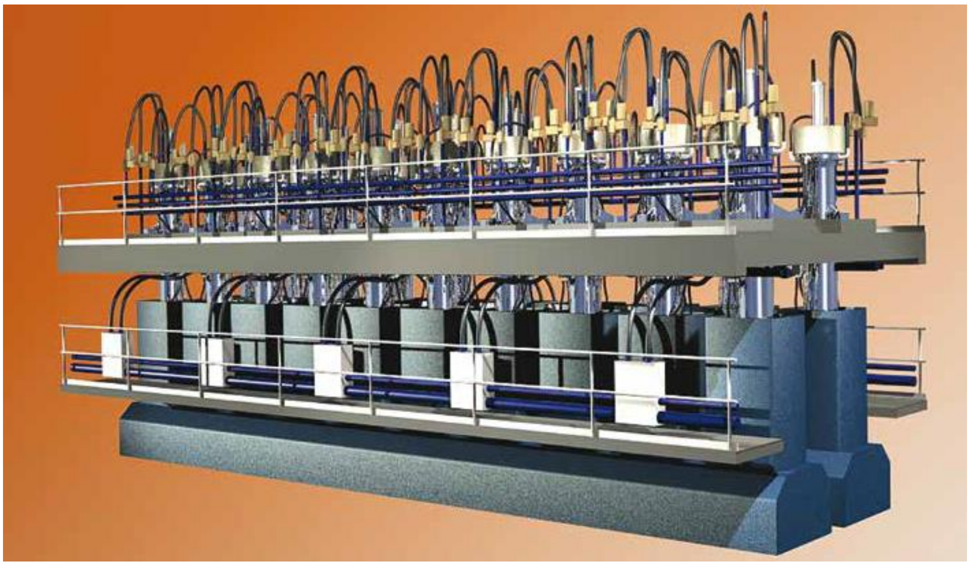

Figure 10. A series of tube presses (Metso Outotec Oy 2021).

4.6 Expression Press

The expression press is a type of filter used for filtering solutions that form compressible cakes. The batch unit has the filters arranged in a series of square or cylindrical boxes containing the filter cloth. The boxes are filled with the feed and a piston starts reducing the volume of the box causing the increased pressure to force the filtrate through the filtering cloth at pressures up to 40 MPa, leaving the cake formed from the solids inside the box. The cake is discharged, and the process starts again. The continuous unit as seen in Figure 11 has various types but the most usual is a conical axle with a variable pitch helical screw rotating up to 2 rpm, inside a cylindrical tube lined with the filter cloth allowing the filtrate to be discharged. Feed is filtered continuously by increasing pressure by rotating the screw and adjusting the cake discharge nozzle. This continuous type with a diameter of 1 m and a length of 8 m, can reach throughput of dry solids greater than 1 te h^{-1}. This throughput presents the equivalent of dry product, as the end-product has residual moisture of approximately 40%. (Tarleton & Wakeman 2007, 48)

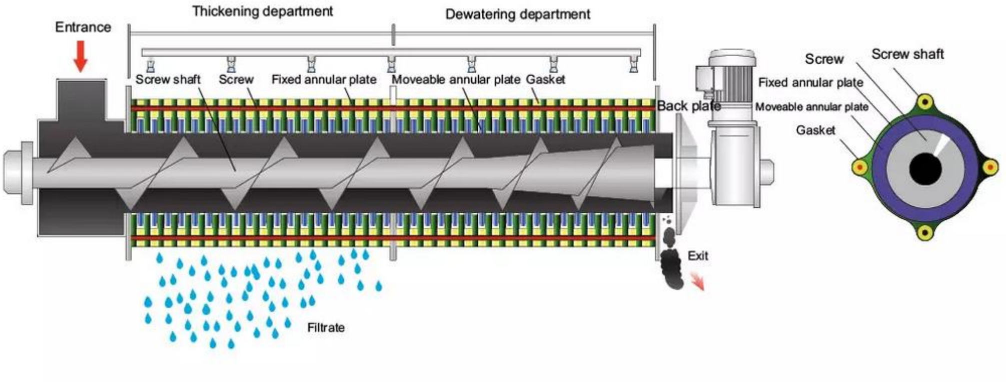

Figure 11. Screw type filter press (BOEEP 2018).

4.7 Basket Peeler Centrifuge

The basket peeler centrifuge has a rotating bowl lined with the filter cloth that allows filtrate to pass. The basket is mounted via a horizontal axle and the cake forms on the basket surface. Centrifugal force is induced by rotating the bowl and this forces the filtrate through the filtering media, allowing the cake to form on the surface of the filter. The separation driving force, relative centrifugal force can be as high as 2000. The formed cake can be washed and allowed to deliquour before the cake is discharged. A plough is lowered to scrape the formed cake to remove it from the basket. This design allows the basket to be kept in constant motion conserving time for the deceleration and acceleration. The smallest type offered by Andritz with a filtering area of 0.1 m^2 requires 1.1 m^2 and a centrifuge with 0.3 m^2 filtering area, as seen in Figure 12 requires 10.8 m^2. (Tarleton & Wakeman 2007, 19-20; Andritz 2021)

Figure 12. Basket peeler centrifuge (Andritz 2021).

4.8 Conveyor Technologies

After the separation phase is complete the hydrochar must be transferred to intermediate storage awaiting transportation to the end use site. This transfer is best performed by a conveyor. Two types of conveyors are studied in this section and their properties regarding the process and product are assessed. As the conveyor only needs to penetrate the end of the truck bed, the distance for the transportation is short. A screw and troughed belt conveyor are compared for the application.

4.9 Screw Conveyor

The screw conveyor uses a metal strip rolled to a helix welded around the shaft, the properties of the handled material affect the design of the screw pitch and structure. The shaft can be a pipe, or a solid axle and it is driven by a motor usually mounted to the outlet side although some installations require the motor to be at the inlet side for accessibility and space requirements. Each revolution of the shaft forces the product to move along the face of the helix. The pitch determines the distance that the product moves per revolution. The standard pitch is measured to be equal to the outside diameter of the screw. The inlets and outlets are open and can be controlled by valves. The outer shell can be a full pipe or a semi-circular trough. A full pipe can be mounted to 0-90° angle and the troughed version is usually limited to 0-45°. The shaft rests on bearings on each end and when the length and product properties require a central bearing to stiffen the shaft. On light duty applications the screw can rest against the outer shell supported by bearings on each end. (Mcguire 2009, 145-147)

4.10 Troughed Belt Conveyor

The troughed belt conveyor is best suited for bulky loose materials where product orientation is not of importance. One flat and two inclined rollers force the belt to a trough shape, the duty specification determines the diameter and inclination of the rollers. Coal mine conveyors need to have rollers that have well-greased and sealed bearings that keep out the dust and debris, as a jammed roller can cause a fire hazard due to friction between the belt and the roller. The belt runs on the rollers supported by the roller frame that is bolted on the conveyor frame, on the underside belt runs on straight rollers that only support the belt as the trough shape is only necessary on the side where the product is transported. The loading of the product must be designed so that the material is loaded to the centre of the belt because the material loaded to one side of the belt forces the belt to run to the other side. This is usually achieved with skirt boards that guide the material until it settles and reaches full conveyor speed. The snub and return rollers can efficiently be used to track the belt to the centre when the conveyor is under 30 meters long. Sensors are used to stop the conveyor if the belt runs off too far of the centre. On a smooth belt the belt is cleaned with a flat scrape after the point where material naturally falls off at the end pulley. A grooved belt is cleaned with a rotating brush. Motors are mounted to the unloading end because the belt has greater area of contact to the pulley and it halves the amount of belt under tension. This reduces the cost and wear of the equipment. Drive pulleys are generally rubber coated to increase friction with grooves to allow debris stuck on the underside of the belt to navigate the pulley without puncturing the belt. The width of the belt is determined with product characteristics, such as the lump size, angle of repose and the angle of surcharge. (Mcguire 2009, 62-66)

4.11 Comparison list

This section summarises the information from the previous chapters to give an overall view of the technologies studied and help with the selection of the most suitable solution to the separation problem. Values are typical to the type of separator and can vary by manufacturer and customer specifications.

Separation method		Particle size Range (µm)		Solids %w/w in		Solids %w/w out (est.)
Nutsche filter		1	200	<1	20	60+
Multielement leaf	Horizontal element	1	100	<1	20	50+
	Vertical element	0.5	100	<1	20	50+
	Tubular candle element	0.5	100	<1	20	50+
Filter press		1	100	<1	30+	60+
Diaphragm filter press (horizontal)		1	200	0.3	30+	80+
Tube press		1	200	0.3	30+	80+
Expression press		1	200	10	80	60+
Basket peeler centrifuge		2	1000	4	30+	80+

		Area efficiency	Gas deliquoring	Driving separation force	Pressure max. kPa
Nutsche filter		0.8	Yes	Pressure	800
Multielement leaf	Horizontal element	3.3	Yes	Pressure	500
	Vertical element	3.3	Yes	Pressure	500
	Tubular candle element	3.3	Yes	Pressure	500
Filter press		6.7	Yes	Pressure	800
Diaphragm filter press (horizontal)		6.7	Yes	Pressure	1600
Tube press		2.3	No	Pressure	16000
Expression press		2.5	No	Pressure	40000
Basket peeler centrifuge		0.1	No	Gravity	(2000 RCF)

Figure 13. Comparison list.

The area efficiency is calculated by dividing required floor space of the separator with the filtering area.

4.11.1 Separator Comparison

For further evaluation, the filter press and horizontal diaphragm filter press were chosen based on the low moisture cake produced, high area efficiency and capability to achieve high pressure difference across the filtering media. These factors are important as the feed can be described as hard to filter due to the small particle size and the process equipment must fit in to the semi-trailer with the rest of the process equipment. These types of filters are highly customizable as the number of filtering plates and the dimensions of the plates can vary. The filter cloth material and properties can be customised.

4.11.2 Conveyor Comparison

The troughed belt for this application has a much greater amount of moving and wearing parts and the installation takes a larger effort to be weather resistant when compared to the screw type where the outer shell shields the product from elements. The accumulation of dust is also easier to control with the screw type as the inlet and outlet can easily be sealed. The screw type also breaks the hydrochar cake as it is forced through the pipe so that the storage space efficiency is improved as the product is homogeneous. The overall operational reliability is higher with the screw type and the need of automatization and maintenance is lower.

5 INTEGRATION TO THE PROCESS

With the suitable technologies narrowed down to the best candidates the integration to the process can be studied. The filter press and horizontal diaphragm filter press were compared for the process. Additional process requirements that depend on the type of filter selected were studied.

5.1 Selection of the Separator

The advantage of the horizontal diaphragm filter press compared to the filter press is that it reaches lower moisture content in a shorter cycle time as seen in Figure 9 where the initial moisture is reduced by filtration in both types at the same rate until 80% of the chamber volume is reached. Then the diaphragms are dilated, and the moisture content reduces rapidly to approximately 20% lower than the filter press can reach. The reduced moisture content increases the value of the product as less water is transported and the duty for additional drying is reduced. (Gethin 2019)

However, the disadvantage of the horizontal diaphragm filter press is the increased capital and operational costs due to the diaphragms in the filter plates. The capital costs are generally 20% higher with the membrane version. However, the estimated moisture content is 20% lower with the additional dewatering via diaphragms. Therefore, the horizontal diaphragm filter press is the most suitable candidate for the process.

5.2 Feed Tank

The process is continuous so the hydrothermally carbonized sludge must be stored in a tank during the filtration cycle. The tank can also be used for the particle sizing where oversized particles accumulate at the bottom of the tank and can be flushed away via piping. A tank of 0.6 m^3 allows a filtration cycle time of four hours.

5.3 Particle Sizing

The feed has larger particles that can be processed with the filter press or the horizontal diaphragm filter press so the feed must be screened to match the equipment specifications. Various types of screens are available but for this application a cost effective and low technological complexity solution can be found from passive intake screen and static screen which are studied below.

5.3.1 Passive Intake Screen or Nozzle

The passive intake screen is a stationary cylinder with a trapezoidal mesh that allows only particles under specified diameter to pass through. The pump sucks the feed through the mesh and leaves the particles that are too large inside the tank. Low intake velocity reduces the larger particles from impinging the screen. A backflush via pressurized air or process feed can be used to clean the screen. (Pankratz 1995, 105)

Usually used in seawater intake for power plants, a smaller version can be utilized in the hydrothermal carbonization process to allow only correct size particles to the filter press.

Figure 14. Intake nozzle (UBO Wedge Wire Screen 2021).

5.3.2 Static Screen

The static screen consists of an inclined screen deck that sieves particles from the feed. Feed is led through the headbox that reduces turbulence at the back of the unit to the top of the screen via an overflow weir. Feed flows over the weir and accelerates downward passing the screen deck. Solids are separated from the feed as it cascades down the screen. Filtrate passes through the screen and is collected in the filtrate chamber and led to the filter press. Particles larger than the screen opening continue downwards and are eventually discharged from the lower edge of the screen. The installation does not have any moving parts and requires only the pumping of the feed to power it. The deck can be mounted with a straight, curved or three-slope screen. The screen is typically inclined from 45° to 60° angle and some versions have adjustable angle. Brush and spray cleaning systems are available for feeds that are prone to foul the screen. (Pankratz 1995, 168)

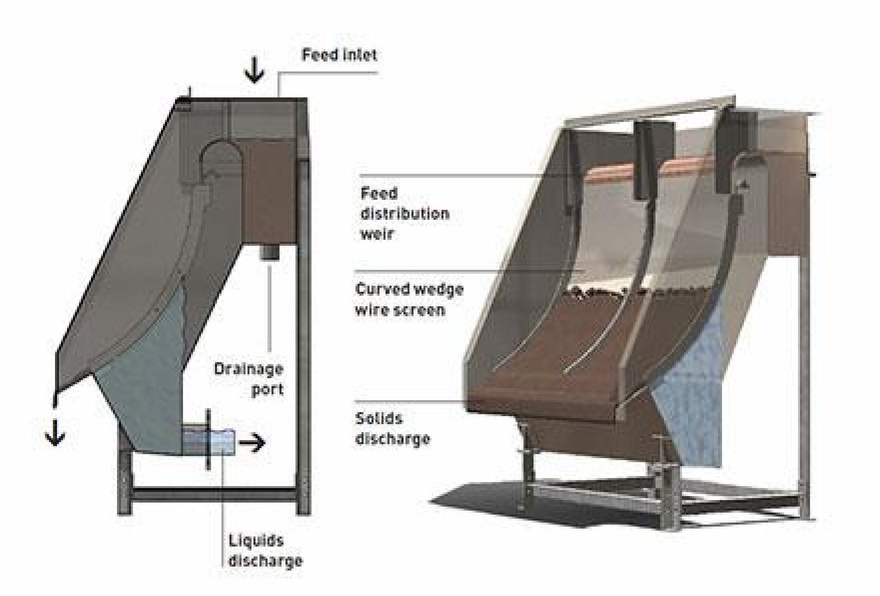

Figure 15. Static screen in operation (Optima International Ltd. 2021).

5.4 Installation

The filter press should be mounted on legs high enough to enable the screw conveyor to be mounted underneath it with an adequate distance to the plates to allow the filter cake to fall off the plates. For a 630 mm filter element a minimum of 1 m distance is required to the screw conveyor. A steel cone that guides the discharged cakes to the screw conveyor can be used to connect the screw to the filter. The feed tank coupled with the particle sizing equipment should be designed in a way that it utilizes floorspace efficiently and allows the piping to be easily flushed from the oversized particles that accumulate during the process.

6 CONCLUSION

Selecting a correct separation technology for the process is always difficult without extensive prior knowledge. Therefore, this thesis covers the basic properties of a few separators used in solid liquid separation where the goal is to form a low moisture cake. Based on the information provided, the design of the separation process can be taken further and tests can be carried out for the slurry to determine the important parameters such as the particle size and specific cake resistance for simulations and pilot tests to determine the suitability of the horizontal diaphragm filter press. The required properties of the feed and economic factors should be considered in the next phase of the design to determine the suitability of the selected equipment. The use of flocculants should also be studied further to see if specific cake resistance can be reduced so that the benefits are greater than the costs of chemicals or substances and the necessary equipment. It is important for a company selecting the separation equipment to gain necessary information about the separation problem and the separation equipment before contacting suppliers and manufacturers so that all available methods are considered, and the most feasible combination of technologies selected. It is also important to study suitable and cost-effective filter cloth materials that suit the sludge properties.

7 DISCUSSION

As this thesis was done as a literature survey, the selected literature affected the outcome. The book *Solid Liquid Separation: Equipment Selection and Process Design* by Tarleton and Wakeman provided a great deal of the information about the background of separation equipment and important design factors. Other important information was found from publications discussing the hydrothermally carbonized feedstocks and the produced hydrochar and its characteristics. The combination of the background information and published results allowed the comparisons between different separation technologies. However, as the data is gathered from tests done to various kind of hydrothermally carbonized feedstocks with varying process parameters, it is very important to do similar tests to the feedstocks treated by the company’s process and process parameters.

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