Lappeenranta University of Technology
School of Energy Systems
Mechanical Engineering
Master's Program in Mechatronics System Design

Andrei Nekrasevits

Investigating the combination of Ultrasound and Electrokinetics as Mechanisms to Enhance Sludge Dewatering

Examiners: Professor Aki Mikkola
Ph.D. R Scott Semken

Supervisors: Ph.D. R Scott Semken
Researcher Mojtaba Mobaraki

ABSTRACT

Lappeenranta University of Technology
School of Energy Systems
Mechanical Engineering
Master's Program in Mechatronics System Design

Andrei Nekrasevits

Investigating the combination of Ultrasound and Electrokinetics as Mechanisms to Enhance Sludge Dewatering

Master’s Thesis

2020

85 pages, 59 figures, 6 tables, 2 appendices

Examiners: Professor Aki Mikkola
Ph.D. R Scott Semken

Keywords: dewatering, ultrasound, electrokinetics, mechanical design, Solidworks

The aim of this thesis is to design an apparatus that will be used to experimentally investigate ultrasound and electrokinetics enhanced dewatering of the sludge. To understand the mechanisms behind this enhanced dewatering, theories touching the topic of sludge dewatering methods, ultrasound working principle, and electrokinetics phenomena are discussed.

In the practical part of the thesis Solidworks® is used to design the apparatus, which is then built by a prototype workshop. A series of experiments are conducted using assembled experiment setup to dewater chia seeds that are used as a substitution to the commercial sludge. The problem caused by the corrosion of the electrodes is briefly discussed and the potential solution to this problem is presented.

The experiment showed that using a combination of ultrasound and electrokinetics can dramatically enhance sludge dewatering compared to the conventional dewatering methods.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

F	Force [N]
P	Pressure [MPa]
D	Bore diameter [mm]

ACGIH 89	American Conference of Governmental Industrial Hygienists
AC	Alternating current
CCD	Central composite design
DOE	Design of Experiments
DC	Direct current
EEA	European Environmental Agency
EK	Electrokinetics
EU	European Union
HUED	High-powered ultrasound enhanced dewatering
MMO	Mixed metal oxide
OECD	Organization for Economic Co-operation and Development
TS	Total solids
US	Ultrasound
UWWT	Urban Waste Water Treatment
WWTP	Wastewater treatment plants

1 INTRODUCTION: MUNICIPAL SLUDGE MANAGEMENT ISSSUES AND A PROPOSED DEWATERING SOLUTION

1.1 Current state of sludge management

Sewage sludge is a by-product that comes from the treatment of industrial or municipal wastewater. The annual production of sewage sludge in the United States was reported to be around 6.5 million dry tonnes in 2007 (Venkatesan, Done and Halden, 2015), and in the EU-27 countries, that amount was 10.1 million dry tonnes in 2012 (Kelessidis and Stasinakis, 2012).

The management of sewage sludge is a much bigger concern in Europe due to various regulations and legislation that prevents the landfilling of sludge that contains heavy metal or pathogen amounts over a set limit. On top of that, the more environmentally friendly sludge disposal methods enforced in Europe require more advanced and costly dewatering solutions.

According to Eurostat (2019), the amount of municipal waste per capita that was generated in the European Union (EU) in 2017 was 487 kg, which is 1kg higher than a year before. Moreover, according to their previous data, this number has been on a small but steady rise for the past 10 years. Figure 1 represents more detailed information on municipal waste generation in the EU. It also shows that the most municipal waste was generated in Denmark (781 kg per capita) and the least in Romania (272 kg per capita). One of the reasons behind such variation is that municipal sludge reporting differs in the various EU countries (Eurostat, 2019).

Figure 1. Municipal waste generated in the EU in 2017 (Eurostat, 2019).

1.2 Sludge dewatering methods and current trends in sludge disposal

Sludge dewatering methods can be divided into mechanical and thermal dewatering. Mechanical dewatering systems include the belt filter press, press filter, vacuum filtration, and centrifuge. These systems are inexpensive and commonly used to dewater sludge. Thermal methods include thermal drying and thermal beds. They require a lot of energy to operate and are roughly between 300 to 500 times more expensive than mechanical methods (Wladimir, 2009). However, they can remove more water compared to mechanical methods.

Figure 2 shows a graph of sludge disposal methods on average throughout the EU in the years 2007 and 2017. The graph was produced using data on sewage sludge production and disposal collected by Eurostat and the Organization for Economic Co-operation and Development (OECD). From the figure, we can see that in recent years there has been a considerable shift from landfill disposal to other means. This is because of new laws and regulations from European Communities regarding treatments specified in the Urban Waste

Water Treatment (UWWT) Directive. The European Environmental Agency (EEA) has assessed the effectiveness of such policies on sludge management (EEA, 2017).

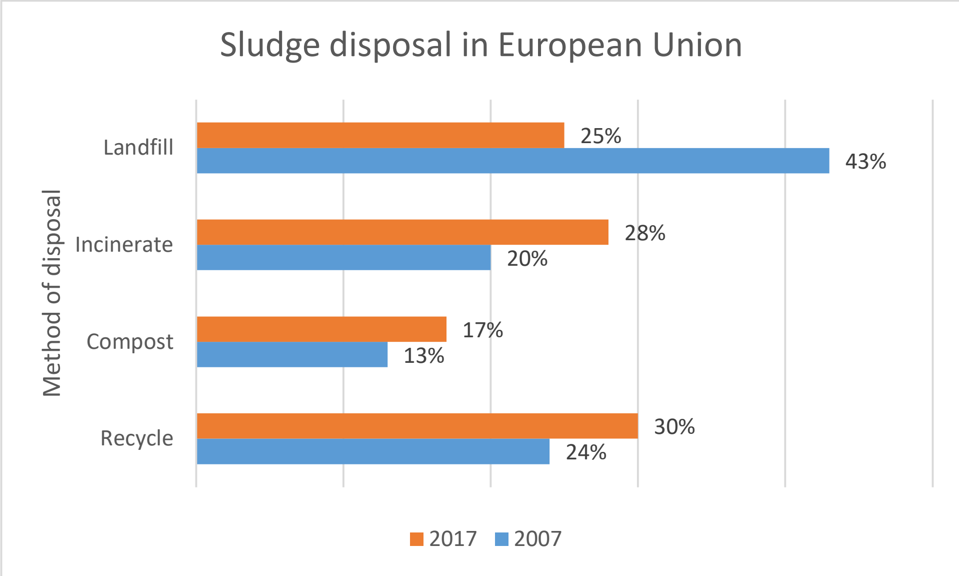


Figure 2. Municipal sludge disposal in European Union (Eurostat 2019, OECD 2019).

The disposal of municipal sludge varies from country to country. This depends on the ecological and political situation within the country. For example, the government in the Netherlands has adopted a policy of using sewage wastewater treatment plants (WWTP) as a source of energy and of valuable elements. Dutch Water authorities took this initiative in 1993 when they set up two sludge mono-incinerators. Since then, the amount of sludge incinerated in the Netherlands has risen significantly and has become their most used disposal method (Ruijters, 2018).

Another example is Switzerland. According to Phosphorus Platform archives (Nattorp, 2015), Swiss legislation has forbidden the landfill of organic matter since 2000, and they have not used sewage sludge in agriculture since 2006. Fahrni, H. published an article in 2011 about the ecological problems of sewage sludge disposal in Switzerland and why landfilling has been forbidden.

1.3 Importance of enhancing sludge dewatering

With current mechanical dewatering solutions, it is possible to achieve a total solid (TS) content of sludge that is between 30-45%, depending on the sludge type. The remaining 55-70% of the sludge mass is water, which is considered excess weight. Reducing the water content can significantly decrease the further processing costs of the sludge. For example, in landfilling, which is used to dispose of a quarter of municipal waste in Europe, higher TS content of the sludge can decrease logistic and handling costs. Moreover, since the mass of the sludge will be less, it will ease transportation and reduce the tax costs of landfilling.
Another sludge disposal method is incineration. Using data extracted from Eurostat, Table 1 summarizes information on sludge production and incineration showing the percentage of total production incinerated in different countries. The production and incineration numbers are given in thousands of tonnes. The table reveals that a large percentage of sludge in Europe is incinerated.

Table 1. Sludge incineration in some European countries (Eurostat, 2019).

Country	Incineration (Kt)	Production (Kt)	Percent of total production (%)
Germany	1149	1821	63,1%
Netherlands	320	344	93,0%
United Kingdom	229	1137	20,1%
Switzerland	188	195	96,4%
France	171	962	17,8%
Austria	118	239	49,4%
Belgium	89	157	56,7%
Poland	79	568	13,9%

The higher the TS content of the sludge, the easier and cheaper it is to burn. Some types of sludge can also contain considerable fuel power that can be extracted. However, with current dewatering methods, more energy is required to burn the sludge than the amount of energy produced (Ends report, 1993). In London, British water company Thames Water makes a loss burning their sludge for energy. However, the loss is balanced by a reduction in their costs of sludge disposal (The guardian, 2012).

Prior to incineration, wet sludge must be made drier. It often undergoes thermal drying, which reduces water content to a level suitable for burning. This process takes a lot of energy as water is evaporated (heat of vaporization). The less water the sludge contains at this phase, the better the energy return and the easier the burning. In previous work done at LUT during the PAKU+Herge project, it was established that at 60% TS content, the burning of sludge becomes adequately efficient, and energy recycling achieves a positive net enthalpy. This is represented in Figure 3.

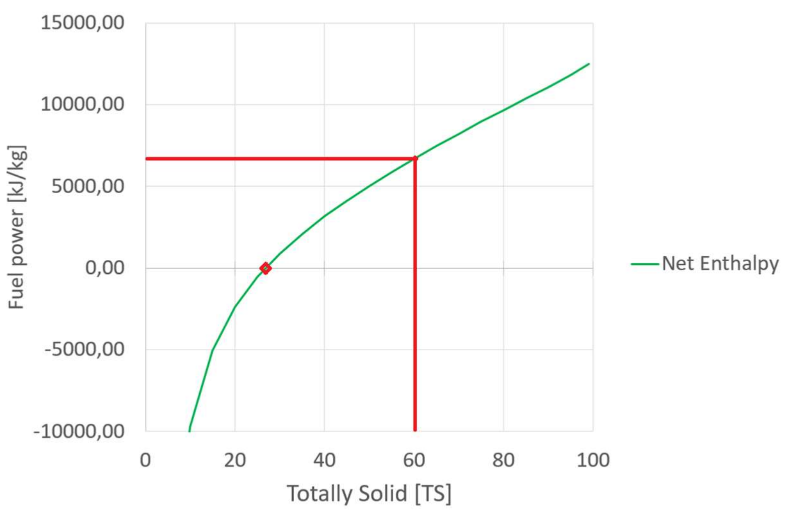


Figure 3. Relation of sludge fuel power to its TS (Nikku & Ritvanen, 2015).

1.4 Research done on the enhancement of sludge dewatering

Not much research has been done on using Ultrasound (US) to enhance sludge dewatering. However, there are many scientific and a few industrial cases of using ultrasonic transducers to enhance the dehydration of food or to separate particles in organic matter. Substantially more research has been done on electrokinetic dewatering enhancement.

The research work done as a part of this thesis is a continuation of a previous research conducted by Mojtaba Mobaraki (2016) where he learned that applying ultrasound could enhance the dewatering process. Figure 4 represents his findings on how the total weight of the test samples changed over time in ultrasonic and thermal tests. Results showed ultrasound to be more effective than drying and since it does not consume as much energy as heating it is also considerably more energy efficient.

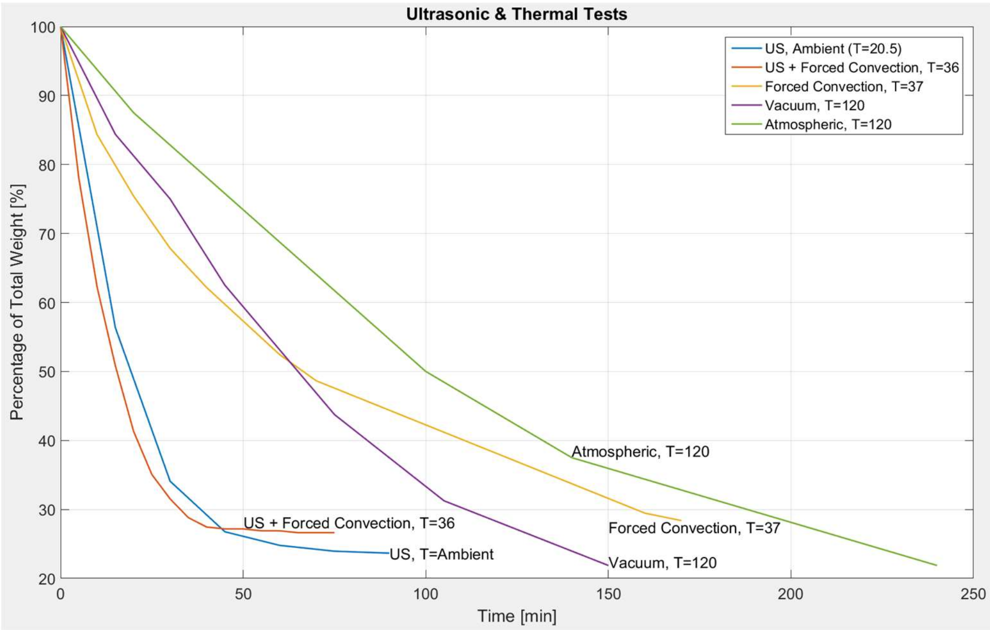


Figure 4. Results of ultrasonic and thermal tests (Mojtaba Mobaraki, 2016).

High-intensity ultrasound was applied to deliquoring by J. A. Gallego-Juárez and L. Elvira (A power ultrasonic technology for deliquoring) in 2003. In their experiments, a high-powered ultrasound emitter made direct contact with sludge cake on a rotary vacuum disk filter during the dewatering of a sludge suspension of water and fine particles of 1) TiO2 and 2) SZn. In each case, applying ultrasound increased TS content by approximately 10%.

Gallego-Juarez J.A. *et al*. has also done experiments on food dehydration. In 2007, they carried out an experiment on slices of carrots using airborne transducers. During the study, they developed and tested a new series of devices that showed promising results using US for vegetable dehydration. (J. A. Gallego-Juárez, E. Riera, S. de la Fuente, G. Rodriguez, V. M. Acosta, 2007)

The effect of different operating conditions for electrokinetics on wastewater sludge was investigated by Mahmoud, Olivier, Vaxelaire, & Hoadley (2011). Their experiments showed that applied electricity in combination with high pressure could yield results that require up to 25% less energy compared to thermal dewatering.

Sludge that comes from mine tailings is much harder to dewater than sewage sludge, and it is generally not cost effective using conventional methods. Research done by Lee, Shang, & Xu (2016) showed that electrokinetics can significantly enhance the dewatering of these tailings.

1.5 Benefits of applying Ultrasound and Electrokinetics to enhance dewatering

Mechanical dewatering methods are effective at extracting free water but struggle with water that is bound with the sludge particles. The application of high-power ultrasound combined with electrokinetics can help to break free some of the bound water and help push it out of the sludge. Ultrasonic vibrations induce cavitation, which can break down the bond between particles and ease the removal of water. Electrical flow through the sludge material induces fluid flow and pushes free water in the desired direction. In other words, electrokinetics acts as a pump, while ultrasound breaks down bonds between particles allowing more water to freely move in the material.

1.6 Motivation for this research

This work is done as a part of the High-powered Ultrasound Enhanced Dewatering (HUED) project. The idea behind HUED is to develop a novel method of dewatering municipal sludge for WWTP and other industrial companies that are not satisfied with their current sludge dewatering methods.

Our marketing team has conducted a series of interviews with local Finnish companies. Experts on dewatering from these companies said that promising potential applications for this technology in Finland exist in the municipal wastewater, food, and bio sludge industries. Burning these sludges can yield energy, but they are hard to dewater and require chemicals in the process. By applying ultrasound to enhance their dewatering, it would simplify the dewatering process, since no chemicals would be needed, which leads to savings chemical costs. Also, without the added chemicals, many of these sludges could be more easily used in subsequent processes. Moreover, weight will be reduced by the more effective dewatering, which dramatically lowers disposal transportation costs.

1.7 Objectives of this research work

The objective of this research work is to design an experimental apparatus for applying ultrasound and electrokinetics to enhance dewatering, which can answer the following questions.

1. Is it possible to dramatically enhance dewatering by adding ultrasound and/or electro kinetics?
2. Can this method of enhanced dewatering be practically applied and scaled up to industrial sizes?
3. How dry will the sludge be after applying this enhanced dewatering approach?
4. What is the estimated cost per kg per %TS of this enhanced dewatering?
5. What would be the estimated relative cost of an enhanced dewatering system?
6. Batch or continuous process?
7. Which option will be more efficient using transducer in before dewatering, during dewatering or after dewatering?

2 THEORY: SLUDGE DEWATERING, ULTRASOUND, AND ELECTROKINETICS

2.1 Dewatering process of sewage sludge

Sewage sludge is the byproduct of the municipal wastewater treatment. Even though it represents only 1-2% of the treated wastewater volume, its disposal costs account for 40-60% of wastewater treatment plant costs. The reason behind such high costs is that the sewage sludge dewatering is a highly complex and costly process that consists of three main stages: thickening, conditioning, and dewatering. (Andreoli, Fernandes and von Sperling, 2007)

2.1.1 Sewage sludge water content

Sewage sludge, resulting from the wastewater treatment process, has a water content of 95-99%. Such a high percentage of water results in low energy content of the sludge and complicates disposal. To safely and economically dispose of the sludge or use it as a fuel, its water content must be significantly decreased. (Mahmoud *et al.*, 2013)

The water content of sludge can be divided into free water and bound water, which can be distinguished into three more types. Figure 5 shows all four different types of water that reside in a sludge

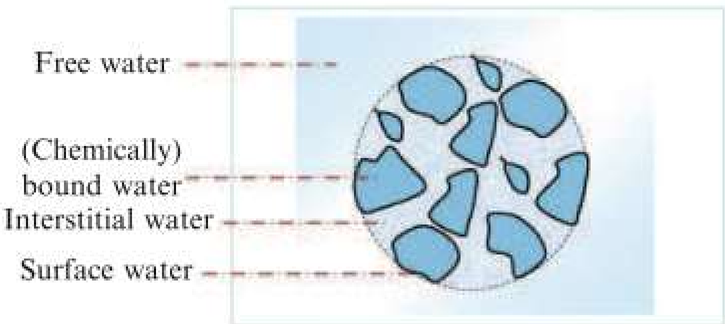


Figure 5. Four types of water in sludge. (Mahmoud *et al.*, 2013)

Free water, which is around 70-75% of total sludge volume, is not attached to the sludge particles. Free water can easily be removed by mechanical means. (Forno and Gronchi, 2015)

Interstitial or capillary water is bound and trapped within the sludge flocs. This water can be removed by using mechanical dewatering to break the floc. (Forno and Gronchi, 2015)

Surface or vicinal water[1] forms multiple layers of water to attach to the surface of the particles and form a strong hydrogen bond, which cannot be broken by mechanical methods. (Forno and Gronchi, 2015)

Intercellularly and chemically bound water resides inside the particle and can only be removed by a thermo-chemical destruction of the particle structure. (Forno and Gronchi, 2015)

2.1.2 Thickening

The main purpose of a sludge thickening process is to reduce the volume of the sludge by removing the free water. After thickening, a sludge with initial TS of 2% can increase its total dry solid content to 5-8%, which results in 60% or more volume reduction. This process considerably minimizes the sludge load on downstream processes. (Andreoli, Fernandes and von Sperling, 2007)

The most common sludge thickening processes include gravitational thickening, dissolved air flotation, and rotary drum thickening (aesarabia.com, 2019).

Gravity thickeners have a similar design to the sedimentation tanks. They mostly have a circular shape with rotating paddles. Thin sludge is pumped continuously into the thickener where sludge sinks in the tank and then is compressed by its weight, becoming concentrated

---

[1] water near surfaces

and thicker. Figure 6 displays a schematic representation of a gravity thickener (aesarabia.com, 2019).

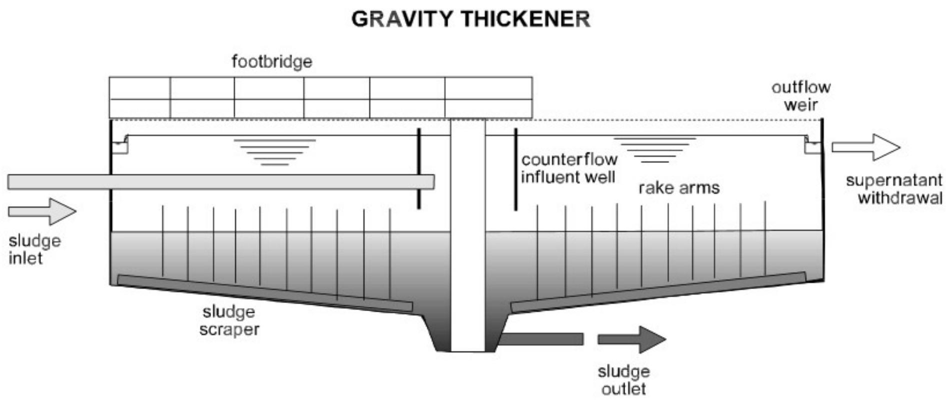


Figure 6. Gravity thickener (Andreoli, Fernandes and von Sperling, 2007).

In the dissolved air floatation thickeners, the solid particles are attached with the air bubbles, making their specific gravity lower than the water and allowing the particles to float. The air is kept under high pressure, and when it enters the tanks, where the pressure is significantly lower, small air bubbles are formed that attach to the sludge particles and carry them to the surface where they are collected by the skimmer (Andreoli, Fernandes and von Sperling, 2007).

2.1.3 Conditioning

Sludge conditioning is used to prepare a sludge for the dewatering process by applying different chemicals or various other means, including thermal treatment. The main purpose of conditioning is to change the size of the sludge particles as well as their distribution in the solution. A sludge solution that has a large number of small-sized flocs shows bad dewaterability since fine flocs tend to clog pores, and they have a bigger specific surface area. Dewatering this type of sludge is more complicated. Therefore, dense flocs of bigger sizes are preferred for easier dewatering (Andreoli, Fernandes and von Sperling, 2007).

2.1.4 Mechanical dewatering

Conventional dewatering methods mostly include mechanical processes. The main ones are presented with their brief description below.

Vacuum filtration

Dewatering systems with vacuum filtration apply vacuum on a rotating drum with a filter cloth making solids gather on its surface. A blade later separates the accumulated solids from the drum surface. Vacuum filter systems consist of a rotating filter drum, vacuum pump, filtrate tank, and a scraper blade. Apparatus construction is represented in Figure 7. Today, such systems are rarely used in sludge dewatering (Forno and Gronchi, 2015).

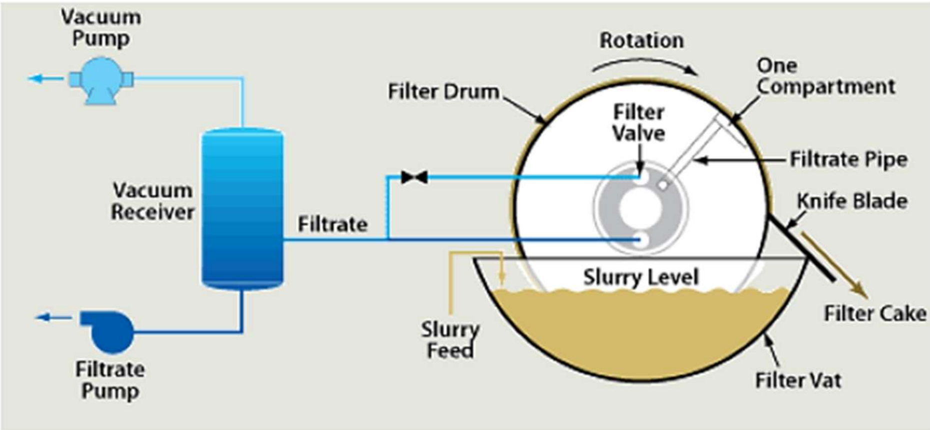


Figure 7. Rotary vacuum filter dewatering scheme (Forno and Gronchi, 2015).

Plate filter press

The plate filter system has multiple consecutive filter plates that are filled with sludge at a high pressure of up to 170kPa. After all the gaps between filter plates are filled, a hydraulic piston is used to compress the sludge into cake. The cross section of the plate filter system is shown in Figure 8. It is a batch process, so it is slower than the other continuous methods, however, since it operates at high pressure it can provide a sludge with higher total solid content.

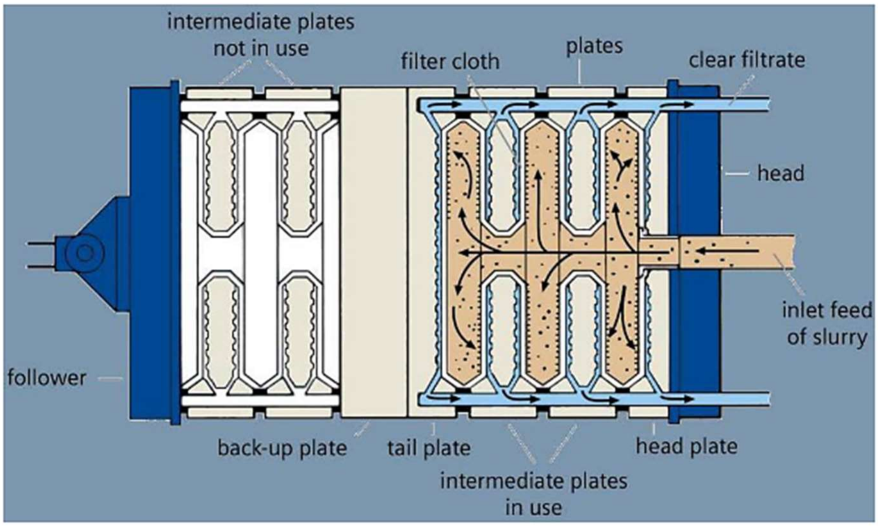


Figure 8. Plate filter press (Forno and Gronchi, 2015).

Belt filter press

The belt filter press is the most commonly used dewatering system because of its low operation cost and high continuous throughput. **Figure 9** illustrates the construction of a belt filter press showing that it is divided into three different zones: preliminary drainage, low-pressure, and high-pressure (Andreoli, Fernandes and von Sperling, 2007).

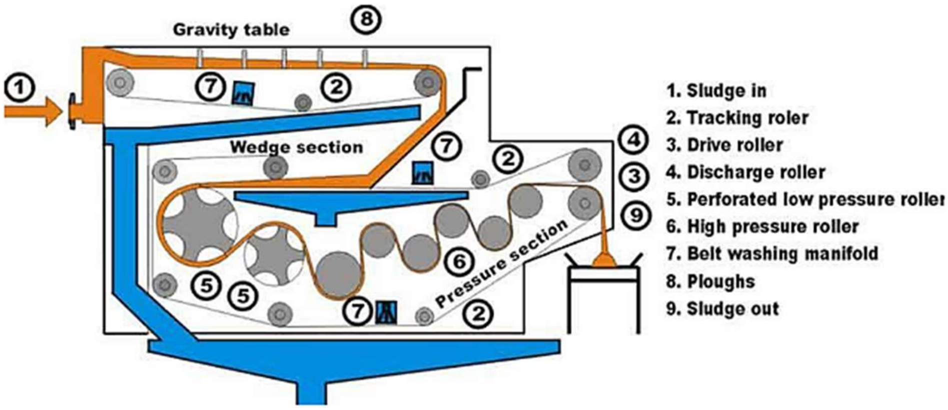


Figure 9. Belt filter press (Forno and Gronchi, 2015).

In preliminary draining, gravity removes most of the free water. Then the conveyor passes sludge to the low-pressure zone or wedge section. Under low pressure from the upper and lower conveyor belts, any remaining free water is removed from the sludge. The high-pressure zone is composed of closely spaced rollers of varying diameter. The rollers apply high mechanical pressure on the sludge to extract interstitial water (Andreoli, Fernandes and von Sperling, 2007).

Centrifuge

The centrifuge dewatering process uses a centrifugal force to separate solid particles from the sludge liquids. This force is produced from the rapid rotation of the cylindrical bowl. The removed liquid flows to one side, where it is being collected and discharged. Solid particles are pulled to the other side of the drum. This dewatering process is illustrated in **Figure 10** (Forno and Gronchi, 2015).

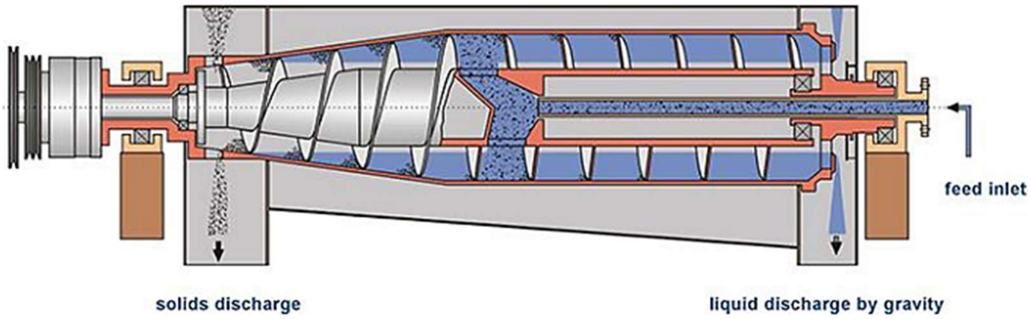


Figure 10. Centrifuge (Forno and Gronchi, 2015).

2.1.5 Drying

Thermal drying processes are used for sludge that has already undergone prior mechanical dewatering and has TS content in a range of 15% to 30%. It is an effective process to further reduce sludge moisture content, and it can result in a final solid content of 65-95%. However, it requires a lot of energy for operation as wastewater in sludge is turned into steam (Andreoli, Fernandes and von Sperling, 2007).

Figure 11 illustrates the thermal drying process. Sludge is placed into a hermetically sealed container to which heat is applied that evaporates wastewater, turning it into steam. The evaporated moisture is collected in the condenser and then sent for treatment (Andreoli, Fernandes and von Sperling, 2007).

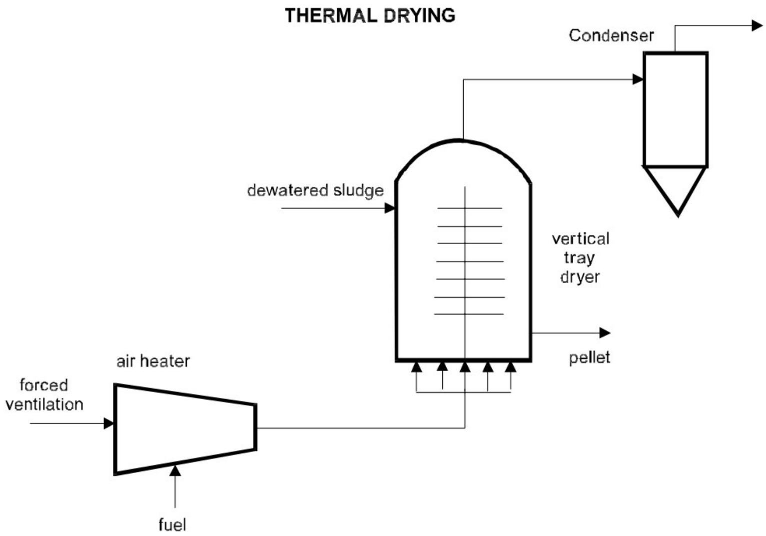


Figure 11. Thermal drying of sludge (Andreoli, Fernandes and von Sperling, 2007).

2.1.6 Electro-mechanical dewatering

Compared to other commonly used dewatering methods, electro-mechanical dewatering is a relatively new but promising process that has not yet been fully researched. Unlike mechanical dewatering, which is superior in extracting free water but struggles with bound water, and thermal drying, which can effectively remove bound water but at a much higher cost, the electro-mechanical process allows an effective and cost-efficient way of extracting both free and bound water from the sludge (Green Advanced Technology Dynamic venture company, 2016).

Current applications of this method represent a belt filter press that is enhanced by adding electricity to it. The top belt acts as anode and attracts solid particles, while the bottom layer acts as the cathode, which attracts liquid. This process is illustrated in Figure 12. The combination of pressure and electric field significantly increases sludge dewaterability yielding 45-50% total solid content (Forno and Gronchi, 2015).

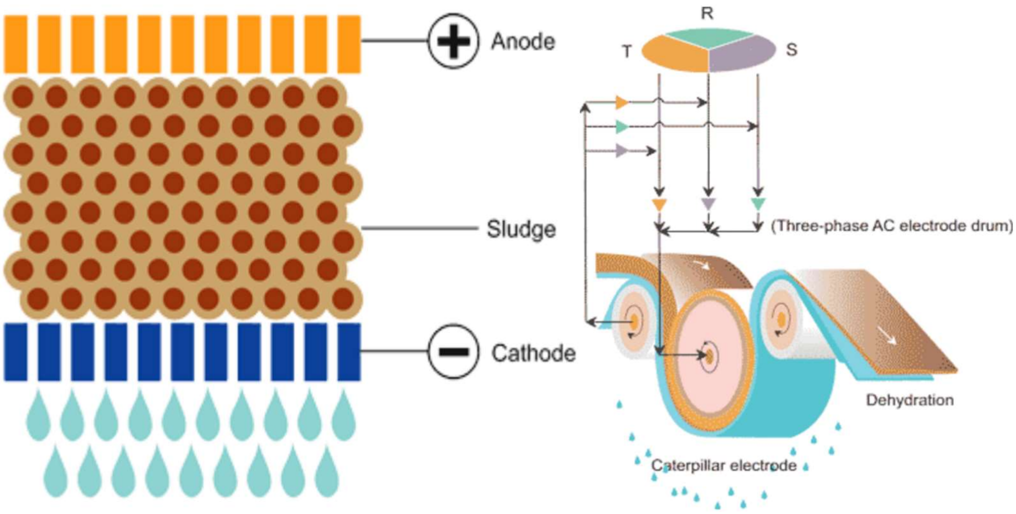


Figure 12. Electro-mechanical dewatering process (Green Advanced Technology Dynamic venture company, 2016).

2.1.7 Summary

The summary of the presented methods can be found in Appendix 1. It has compact information on the advantages and limitations of the above methods, as well as their outcome TS content.

2.2 Ultrasound mechanisms that help dewatering

2.2.1 Sonochemistry

Sound is a vibration that is transmitted through a medium, which can be gas, liquid or solid. Based on frequency, it is divided into audible and inaudible sound, *i.e.*, infrasound and ultrasound, and can range from 20Hz to 100GHz and higher, which is represented in Figure 13 below (Lévêque *et al.*, 2018).

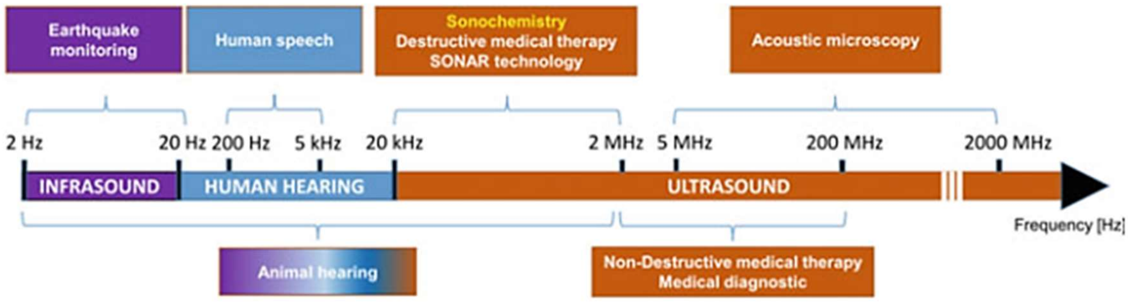


Figure 13. Sound range (Lévêque *et al.*, 2018).

Sound waves can be used to cause chemical and/or physical changes in matter. The science that studies these effects is called sonochemistry. Even though such changes can be induced by the sound of any frequency, the ultrasonic range offers optimal operation conditions. (Lévêque *et al.*, 2018).

Ultrasound used in sonochemistry is divided into two frequency ranges. Power ultrasound, which ranges between 20 and 100 kHz, is the lower end of the ultrasound range. Power ultrasound induces more physical change. The higher end of ultrasound frequency range, between 200 and 2000 kHz is where chemical changes are most predominant (Lévêque *et al.*, 2018).

The main cause of the physical changes is the cavitation phenomena that ultrasound produces. Cavitation occurs even at frequencies well above what is normally used in sonochemistry and only stops occurring at 5MHz and above, which is the range used for diagnostics. The different frequency ranges of ultrasound are shown in **Figure 14** below (Mason, 2014).

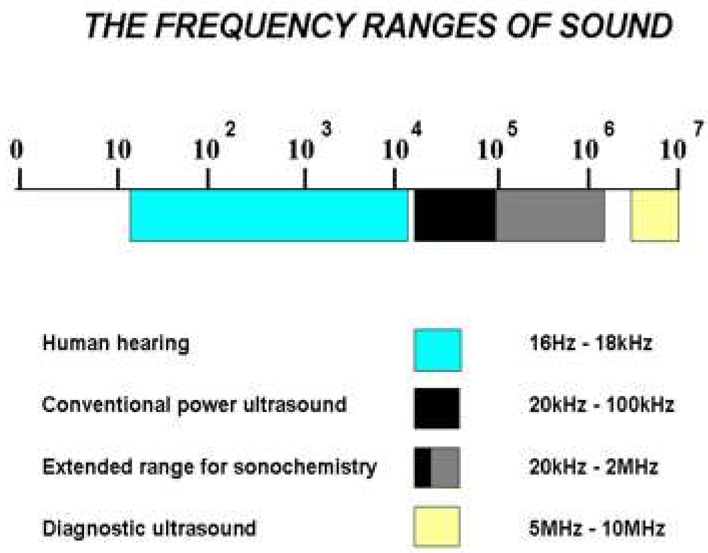


Figure 14. Different ultrasonic ranges (Mason, 2014).

2.2.2 Resonance frequency

Resonance frequency is defined as the frequency at which the system has vibrations with the highest response amplitude. In ultrasonic systems, the resonant frequency of the system should equal the natural frequency of the piezoelectric transducer. This way the most efficient electromechanical conversion can be achieved (Cracknell, 1980).

2.2.3 Cavitation

The first mention of the cavitation phenomena was in 1754 when Swiss mathematician L. Euler, in his theory of water turbines, speculated about the formation of microbubbles in turbulent flow. However, Sir Charles Parsons and Sydney Barnaby are credited with discovering cavitation in 1893 during their investigation on the sea-trial failure of a high-speed British Royal Navy warship. Their investigation revealed that the ships propeller blades could not reach full speed or attain continuous motion, because microbubbles were forming on the propeller surface that were causing vibration and damage (Li, Brennen and Yoichiro, 2015).

As mentioned before, ultrasound can induce chemical as well as physical effects in materials. The chemical effects are radical reaction and sonoluminescence, which are static based. Physical effects include acoustic streaming and shockwave production, which induce mixing. These effects are presented in **Figure 15** (Lévêque *et al.*, 2018).

The rapid changes in pressure due to ultrasonic vibration results in the formation of bubbles that rapidly expand and contract at high frequency. When the pressure amplitude passes the cavitation threshold, the bubble collapses producing shockwaves (Lévêque *et al.*, 2018).

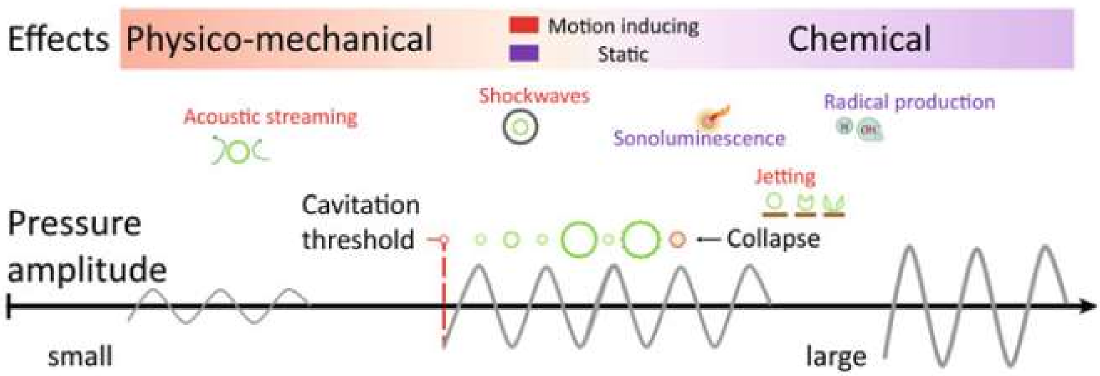


Figure 15. Physical and chemical effects that are induced by the ultrasonic vibrations (Lévêque *et al.*, 2018).

2.3 Elements of the ultrasonic equipment

To get positive work from applying ultrasound, a combination of several ultrasonic components is required. They include a generator (which produces electric energy of high frequency), a transducer (which transforms electrical energy into mechanical vibrations), a horn (which increases the amplitude of the vibration and is in direct contact the material), and possibly a booster (if even higher vibration amplitude is required).

2.3.1 Ultrasonic generator

The ultrasonic generator is a key component in any ultrasonic system. Its main purpose is to take the electrical energy from the power line, convert it to the required frequency, voltage, and current, and then send it to the ultrasonic transducer. The electric current in the power line usually has a voltage between 100V to 250V and a frequency of either 50Hz or 60Hz. To drive an ultrasonic transducer, a current of much higher voltage is required. Besides that, the current must be transmitted at the ultrasonic frequency, which is 20 kHz and higher. The conversion of electric current is illustrated in Figure 16 below (ctgclean, 2018).

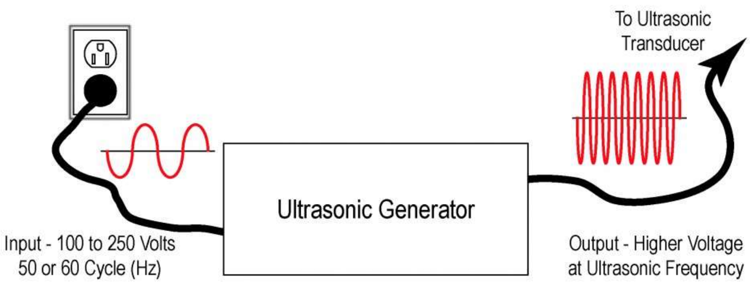


Figure 16. Electric current conversion from the power line by the ultrasonic generator (ctgclean, 2012).

Early models were made up of just a simple frequency generator coupled with a power amplifier. Today's ultrasonic generators are capable of not only sending electrical energy to the ultrasonic transducer, but also of receiving feedback so frequency and power output can be efficiently adjusted to achieve optimal system performance. Modern ultrasonic generators are shown in Figure 17 below (ctgclean, 2012).

Figure 17. Ultrasonic generators (ctgclean, 2018).

2.3.2 Ultrasonic transducer

The ultrasonic transducer is a device designed to convert a supplied source of energy into high-frequency vibration. Based on the energy source used, ultrasonic transducers can be divided into three categories: gas-driven, liquid-driven, and electromechanical (Mason, 2014).

Gas- and liquid-driven ultrasonic transducers are quite simple and are rarely used in industrial applications. Moreover, they are limited to low frequencies. Electromechanical transducers are more popular and versatile. Electromechanical ultrasonic transducers can be divided into magnetostrictive and piezoelectric, which is shown in Figure 18 below (Berg, 2013)

Magnetostrictive ultrasonic transducers produce a high-frequency mechanical vibration using a magnetic material that can produce a cyclic change in its size when the oscillating magnetic field is applied. Vibrations that are produced by such means have an elliptical pattern of oscillations. Power dispersion occurs along the whole surface of the material (Berg, 2013).

Piezoelectric transducers, on the other hand, produce high-frequency vibrations by applying an oscillating electric field to a material that can exhibit the piezoelectric effect (accumulation of internal strain resulted from applying an electrical field). Such materials include quartz and ceramics. Vibrations have a linear pattern causing power dispersion to be more active on the lateral sides (Berg, 2013).

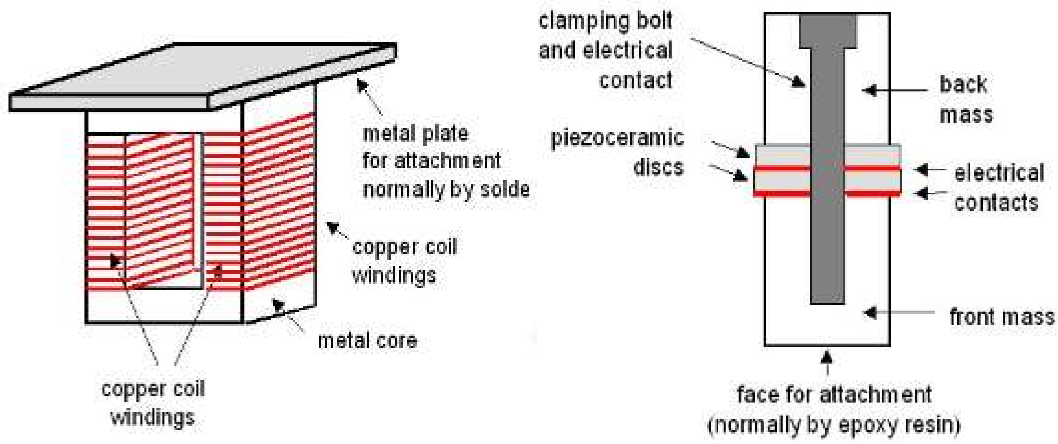


Figure 18. Magnetostrictive (left) and piezoelectric (right) transducers (Mason, 2014).

Both have their advantages and limitations, so the choice varies on the field of application. Magnetostrictive ultrasonic transducers, for example, have some restrictions on device geometry and are mostly used in applications requiring low-frequency range, such as ultrasonic machining and cleaning. Piezoelectric transducers are more versatile and can accommodate more varied geometry shapes that can change the ultrasonic wave depending on the chosen application. Figure 19 demonstrates two different shapes of the piezoelectric transducers. Moreover, they can be used in the entirety of the frequency range (Berg, 2013).

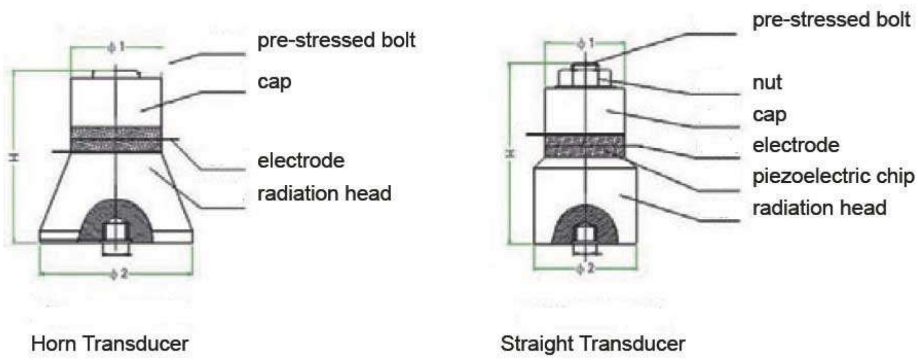


Figure 19. Two different structures of piezoelectric ultrasonic transducers (Bjultrasonic, 2012)

The frequency of the ultrasonic transducer affects its output amplitude - the lower the frequency the higher is the amplitude. However, even at a low frequency of 20 kHz, the ultrasonic transducer produces an amplitude of around 20 microns. To do any useful work, the output of the transducer must be amplified by a booster or a horn to increase the amplitude of vibration.

2.3.3 Ultrasonic booster

The main objective of an ultrasonic booster is to amplify the amplitude of the vibration produced by an ultrasonic transducer. It is placed between the transducer and the horn. The ratio between the amplitude the booster transmits to the horn and the input amplitude it receives from the transducer is called the gain of the booster. The different gain depends on the shape of the booster and is shown in Figure 20. Ultrasonic boosters are made out of titanium or high strength aluminum alloy (Sonicitalia, 2017).

Figure 20. Solid mount boosters of various gain (Branson, 2016).

2.3.4 Ultrasonic horn

The ultrasonic horn represents a metal rod that can translate the acoustic energy from the ultrasonic transducer into the treated media, which can be either solid or liquid. Ultrasonic horns are designed for a specific working frequency, which dictates their length. Longer horns are for lower frequencies. Figure 21 shows horns of various lengths that are designed to resonate at a specific frequency.

Figure 21. Comparison of ultrasonic horn based on varied frequency (Dukane, 2010).

Ultrasonic horns also differ based on form. Some have a straight shape without any change in diameter across the length, while some have a rapid change in cross section. The steepness of this change affects the vibrational gains and can increase or decrease the amplitude of vibration at the tip of the horn. Figure 22 shows horns of different forms (Dukane, 2010).

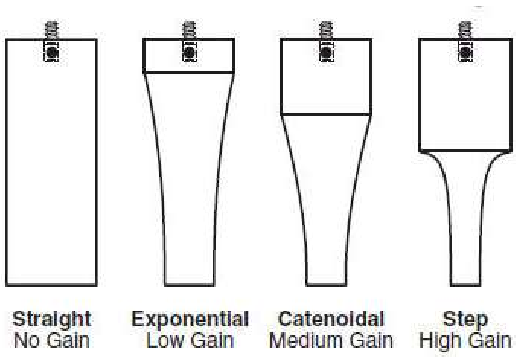


Figure 22. Comparison of ultrasonic horns based on form (Dukane, 2010).

An ultrasonic horn must transmit vibrations with as little dampening as possible and be able to withstand cyclic wear. Therefore, the horn material is chosen based on a combination of acoustical and mechanical properties. Commonly used horn materials are titanium and aluminum. Titanium has the best acoustical and mechanical properties and can withstand cycles of high amplitude change and wear. Horns, that do not have to undergo high amplitude changes and high stress, are commonly made our of aluminum, because aluminum is cheaper than titanium and has excellent acoustic properties (Branson, 2016).

2.3.5 Ultrasonic stack

A typical ultrasonic combination, or ultrasonic stack, consists of the ultrasonic transducer, booster, and horn. In some cases, the booster is not used. The transducer produces the vibrations and the booster usually increases the amplitude of the vibration. However, sometimes the booster will be used to decrease amplitude or have no effect at all, in other words, it will be a neutral booster. A neutral booster is used if transducer frequency will not change, but a mounting point is required so the system can be appropriately clamped and fixed in place. Lastly, the horn translates the vibration to the workspace. Figure 23 demonstrates typical ultrasonic equipment combinations (Dukane, 2010).

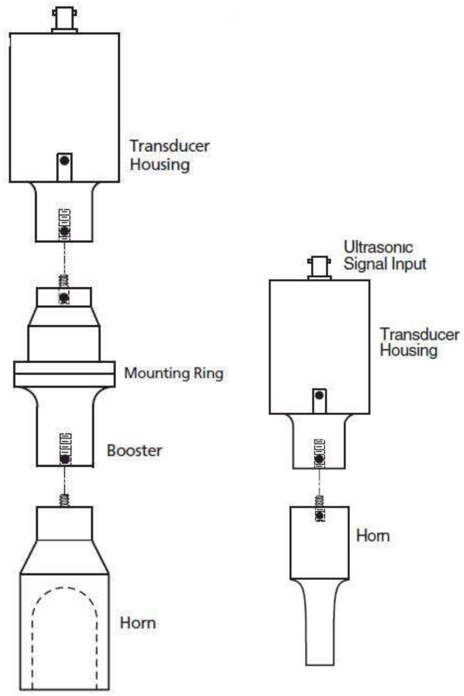


Figure 23. Two different configurations of ultrasonic stack (Dukane, 2010).

2.3.6 Ultrasonic vibration output amplitude

Ultrasonic transducers have different vibration outputs based on their structure and their operating frequency. Table 2 below shows the varied output amplitude from the typical transducers based on their frequency difference. As the table shows, the output amplitude directly from the transducer is quite small and must be amplified by the horn and potentially by a booster as well to do useful work (Branson, 2016).

Table 2. Output amplitude of transducers based on their resonant frequency (Branson, 2016).

Ultrasonic frequency (kHz)	Output amplitude (μm)
15	30
20	20
30	15
40	8

When an ultrasonic horn is excited at its resonant frequency, its length starts to increase and decrease in rapid successions producing longitudinal vibration. The middle point of the horn, which is its nodal point, remains still, having no motion there. The amplitude of this vibration at the output end of the horn produces useful work in the application and is measured as peak-to-peak displacement of the horn face. It is affected by the input amplitude as well as the horn's structure. The ratio of the output vibration amplitude at the endpoint of the horn to the input vibration amplitude is called gain. Figure 24 below shows how the output amplitude is calculated for the ultrasonic stack that consists of the 20kHz transducer, booster, and horn (Branson, 2016).

Figure 24. Vibration amplitude output in an ultrasonic stack (Branson, 2016).

The horn amplitude required for a specific application is dependent on the type of plastic, type of operation (e.g. welding, staking, etc.), part geometry, and joint design of that application.

Horns are made in several basic styles and amplitudes to meet the requirements of various applications. For example, a small high-gain bar horn might be used for welding a small rectangular part while a large slotted bar horn might be used for welding a large part requiring less displacement amplitude (Branson, 2016).

2.4 Electrokinetics phenomena that affect the dewatering process

In the electro-dewatering process, direct current is applied to sludge to force water extraction. This happens due to several electrokinetics phenomena: electroosmosis, electrophoresis, electromigration, and electrochemical reaction. Figure 25 shows them in the electro-dewatering process. All of these electrokinetic processes affect dewatering of sludge and are therefore discussed in more detail below (Forno and Gronchi, 2015).

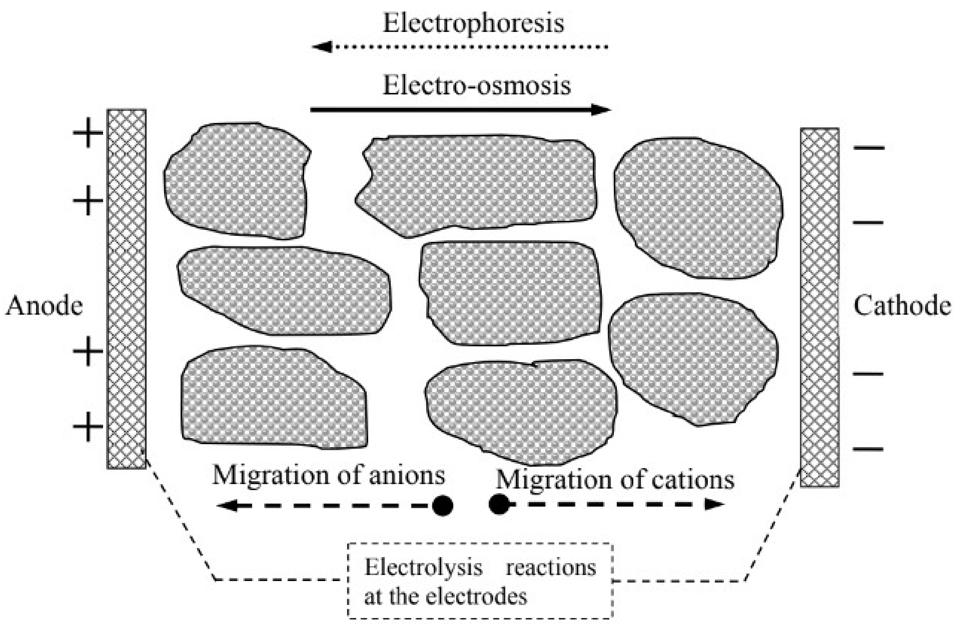


Figure 25. Electrokinetic processes in sludge dewatering (Tuan, 2011).

2.4.1 Electroosmosis

Electroosmosis is considered to have the biggest impact on the electro-dewatering process. It results in a flow of liquid under the influence of the electric field. Since water has a positive charge, it is forced to the cathode direction (Tuan, 2011).

Electroosmosis loses effectiveness with an increase of total solid content of the suspension, as there is less free water to easily move while an increase in solid content increases the resistance of the suspension (Tuan, 2011).

2.4.2 Electrophoresis

Electrophoresis is the movement of charged particles under the influence of the electric field. Usually, sludge has negative zeta potential and therefore negative sludge particles are strongly pushed in the anode direction by an electrophoresis process (Tuan, 2011).

At the beginning of the electro-dewatering process, sludge has bigger water content and solid particles can still freely move in the suspension. As water content is removed, it becomes harder for particles to move until they are fixed in their position. At this point, electrophoresis has no impact in the dewatering process (Tuan, 2011).

2.4.3 Electromigration

Electromigration is defined as the movement of ions when the electric field is applied in the suspension. Cations move from the positively charged anode in the direction of the negatively charged cathode. The movement is vice versa for anions (Tuan, 2011).

While ion migration can occur during electro-dewatering, it is most important in the removal of contamination from metal, and there is little research available on its effect in electro-dewatering (Tuan, 2011).

2.4.4 Electrochemical reaction

Corrosion and oxidation reactions occur at the surface of the electrodes due to the electrical field. They reduce the effectiveness of the electro-dewatering and depend on the material of an electrode (Tuan, 2011).

The reduction of water at the cathode side produces hydroxide, while water oxidation occurs at the anode side, which results in the release of protons that are then transported to the cathode by electromigration and electroosmotic flow. This can cause a decrease in the pH value of sludge, which changes sludge potential and dewaterability. Moreover, the release of oxygen and hydrogen produces a resistive layer at the surface of both electrodes, which reduces contact between sludge and electrode (Tuan, 2011).

In electro-dewatering, the anode material is prone to corrosion due to oxidation. A possible solution is to use noble metals that cannot corrode, however they are too expensive for large-scale facilities. Another solution is to use titanium that is coated with mixed metal oxide (MMO). The cathode material is not prone to corrosion and normal stainless steel can be used without a problem (Tuan, 2011).

3 METHODS: INVESTIGATING THE PERFORMANCE AND ECONOMY OF US PLUS EK ENHANCED DEWATERING

3.1 Design requirements of the experiment setup to fulfill objectives of the research work

To investigate the effectiveness of applying a combination of US and EK to enhance the dewatering process, an experiment setup is built and tested. The requirements for the experiment setup were as follows. The setup must be able to apply high force to the sludge cake, to accommodate ultrasonic stacks of varied length and size, and to apply electric potential across the sludge cake.

In previous testing, relatively low US frequencies (15, 20, and 30 kHz) showed the best effect in the dewatering process, so they were used in this experiment as well. The literature research revealed that in laboratory experiments, electrokinetic voltages were in the range of 10 V to 50 V. An electrokinetics power supply capable of voltages up to 50 V was selected for this setup.

A design of experiments plan is necessary to properly and most efficiently investigate the performance of US plus EK on sludge dewatering. Doing experiments following the experiment plan makes it possible to find what kind of effect each parameter in the testing had on the outcome of the experiment.

3.2 Design issues and considerations that must be addressed

Several problems were encountered in past experiments. One of these was overheating of the US transducer. Another was the noise level it produces. The following paragraphs focus on different issues that were considered during the design process for the improved dewatering experiment setup.

3.2.1 Node point

One of the crucial and important aspects of the ultrasonic equipment is the wave nodal points. They are the points at which no vibration occurs and therefore serve as the best points for holding the ultrasonic stack. Moreover, antinodes are where the vibration is at its highest and therefore any contact at that point needs to be avoided so that no damping, *i.e.*, loss of transmitted energy, occurs and so extra noise and wear on the system is prevented. Figure 26 shows the nodes and antinodes in an ultrasonic stack.

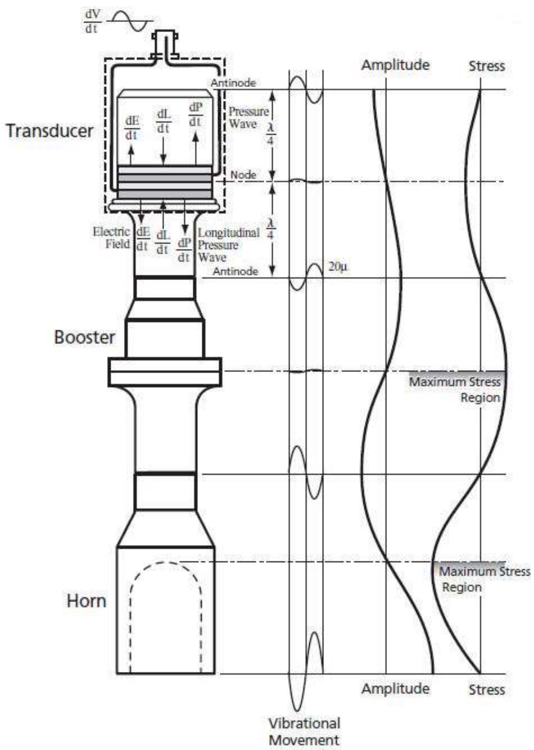


Figure 26. Nodal points of ultrasonic stack (Dukane, 2010).

3.2.2 Cooling

Previous testing revealed that transducers suffer from overheating that can lead to failure. Temperature measurements are shown in Figure 27. During a test, the transducer works for a prolonged period, generally more than half an hour. To achieve a good working condition that does not break the transducer during the test, an adequate cooling solution is required.

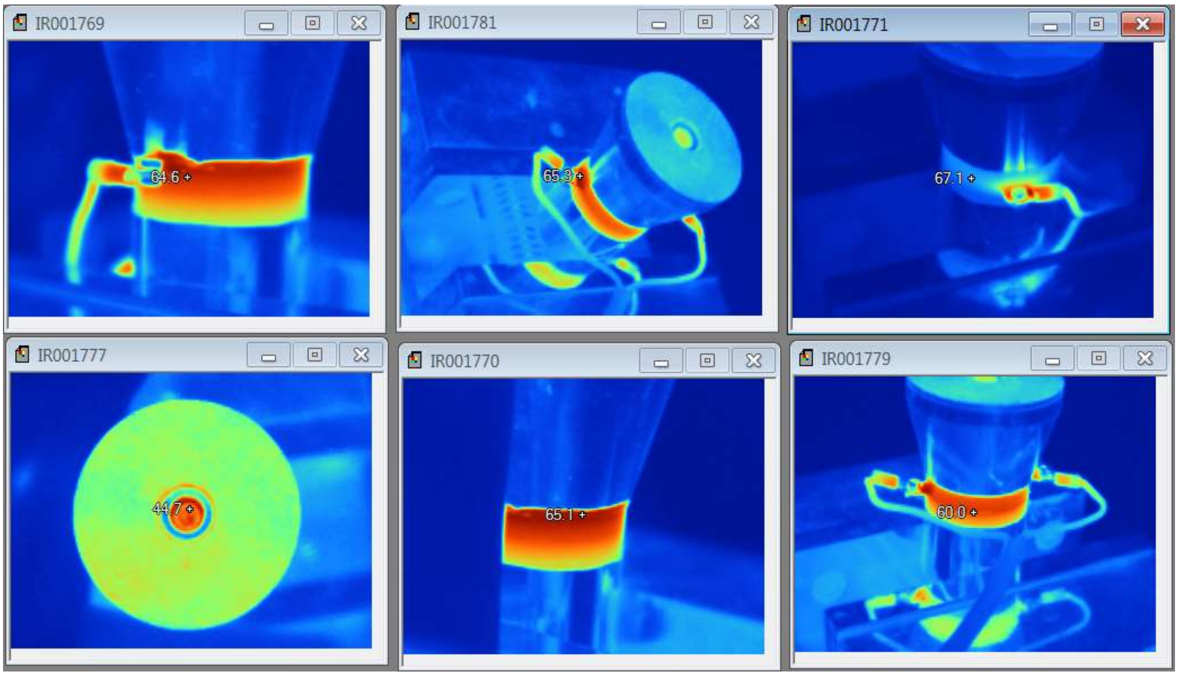


Figure 27. Temperature of the transducer.

3.2.3 Force

In previous experiments, the maximum force applied to the samples was around 1400N, which was achieved by adding weight discs to the top of the horn. However, that was only in simple pressure test and no significant force was used for the ultrasonic testing. Other research works indicate that increasing applied force positively affects dewatering when used together with ultrasound. The improved results from the higher force makes it possible to use less ultrasound to achieve similar results. To enhance a mechanical dewatering process by adding ultrasound, a new solution is needed for this experiment setup.

3.2.4 Area

To answer one of the questions of whenever such method of enhanced dewatering can be successfully applied and scaled to industrial sizes, horns of multiple sizes need to be tested. The apparatus must be able to use ultrasonic stacks of different frequencies and accommodate different area sizes.

3.2.5 Electricity

Electrokinetics has proven to be a valid method for sludge dewatering. It is mostly used together with mechanical dewatering, where force is applied onto the sludge, however adding ultrasound into the equation might show a significant improvement. Therefore, the manufactured apparatus must be able to supply electric current through the sludge and have proper insulation to prevent any short circuits.

3.2.6 Noise level

Ultrasonic equipment produces a high-pitched noise during its operation, which is unpleasant but harmless to human ears. However, at high power prolonged exposure to the noise can lead to noticeable discomfort. Using earmuffs and/or earplugs is highly recommended when dealing with ultrasonic equipment. During an accident condition that occurred in a previous experiment, one researcher sustained some temporary ear damage. Therefore, it was required to muffle the resulting noise.

A report published by the Canadian department of environmental and workplace health on the safe use of ultrasound included a table of exposure limits for airborne ultrasound set by different countries. These limits are summarized in Table 3. The USA recommended exposure limits were chosen as a guideline for this project work.

Table 3. Examples of Occupational Exposure Noise Limits in dB (canada.ca, 1991).

Frequency, kHz	Proposed by			
	Japan (1971)	Acton (1975)	USSR(1975)	USA (1989)
8	90	75	-	-
10	90	75	-	80
12.5	90	75	75	80
16	90	75	85	80
20	110	75	110	105

25	110	110	110	110
31.5	110	110	110	115
40	110	110	110	115
50	110	-	110	115

The noise level produced by a 15 kHz transducer at low power (20 W) was measured using sound meter as shown in Figure 28. Even at low power, the noise produced is already higher than the exposure limit for the selected frequency.

Figure 28. Noise level (dB) produced by a 15 kHz transducer at 20W.

3.3 Design process of the apparatus that is used to experimentally investigate US plus EK enhanced dewatering

The apparatus for the dewatering experiments was designed using Solidworks® and manufactured by the LUT Voima prototype workshop. Its construction is shown in Figure 29, and each part is described in detail in the following paragraphs.

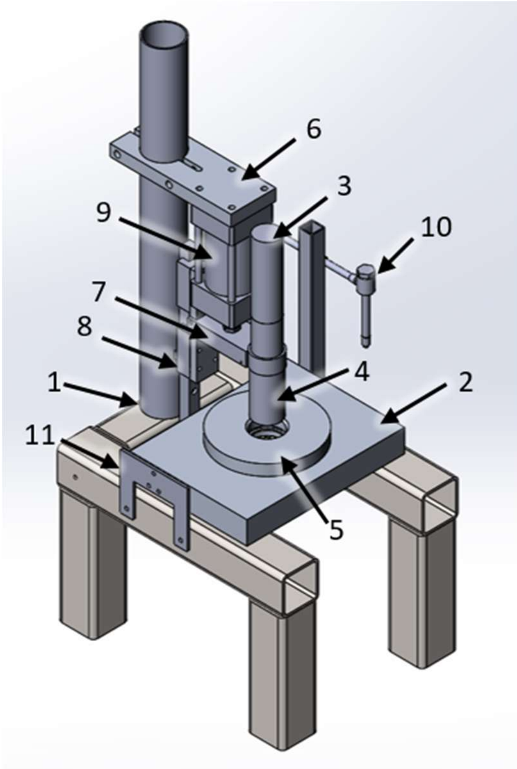


Figure 29. Solidworks® model of the apparatus assembly - (1) base support, (2) base, (3) transducer, (4) horn, (5) filler, (6) height adjustment, (7) nodal hold, (8) linear rail guide, (9) pneumatic cylinder, (10) vortex tube, (11) pneumatic control valve place.

3.3.1 Base support

The apparatus supporting structure consisted of seven rectangular tubes and one circular tube welded together as shown in Figure 30. Each side rectangular tube had three holes drilled into it for attaching pneumatics and cooling devices.

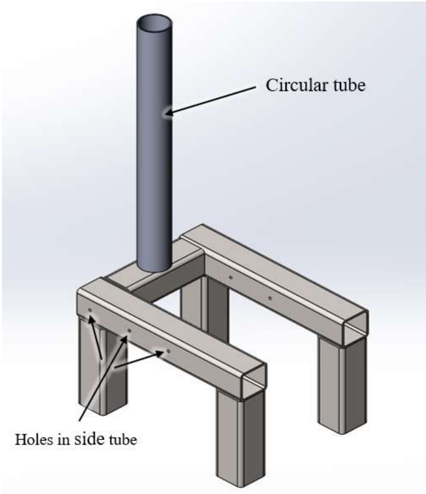


Figure 30. Supporting structure of the apparatus.

3.3.2 Base

To test horns of different areas, interchangeable components were needed. The base was to serve the purpose of accommodating such components. The base part can be seen in Figure 31 below. It has a section where different horn adapters could fit as well as a section where the filter plate could be placed and easily removed for cleaning needs. The bottom area was machined at an angle so that water could slide down easier. To prevent water from going sideways when exiting the base, a grove was made around the bottom hole.

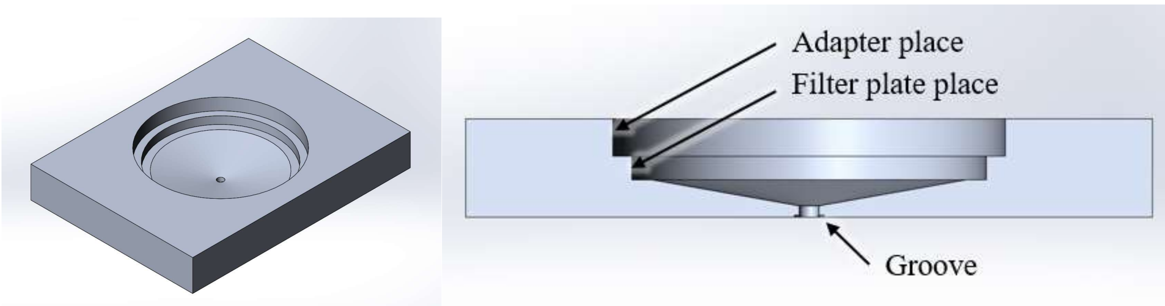


Figure 31. Solidworks® model of a base (left) and its cross-section view (right).

3.3.3 Transducers

Three sets of transducers were purchased for the experiment with frequencies of 15, 20, and 30 kHz. They can be seen in Figure 32 below. The transducers had diameters of 51mm, 50.2mm, and 30.5mm accordingly.

Figure 32. Transducers that were used in the experiments. From left to right 15 kHz, 20 kHz and 30 kHz (mmech.com, 2019).

3.3.4 Horns

Ultrasonic horns are generally made from titanium or aluminum material. The main difference is that titanium horns are more durable, but aluminum horns are considerably cheaper. For this experiment, the chosen horn material was aluminum alloy 7075, which has excellent mechanical properties for high-stress applications and is much cheaper than titanium.

The upper diameter of the horn, which will be connected to the transducer, must be the same diameter as its driving transducer. This way all vibrations from the transducer are transmitted onto the horn. To apply pressure to the sludge samples, force must be applied to the horn. It was applied to a shoulder of 2-4mm at the nodal point, which is at the middle of the horn. The lower part of the horn will be in contact with the sludge, and its diameter was mainly dependent on the size of the O-ring used to seal and guide the horn into the sludge. Horns with bigger areas had an additional section, with a thickness of 20mm. The three horn variations are shown in Figure 33.

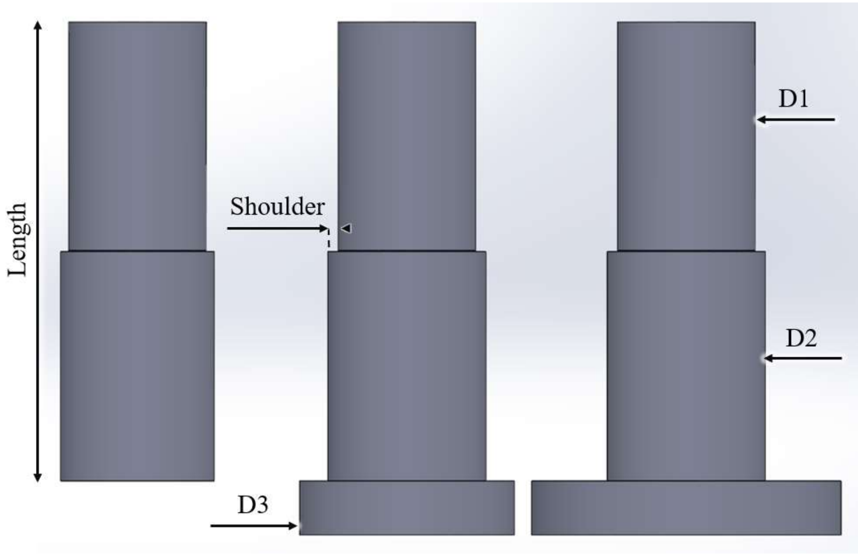


Figure 33. Three horn sizes.

Three horn surface areas were selected. Diameters were selected so that the surface area of each progressively larger horn was double that of the preceding smaller horn. O-rings of the following sizes were used for the three horn diameters: 56.52x5.33mm, 78.74x5.33mm, and 114.3x5.7mm.

The length of each horn depends on the material type used and the required frequency. Solidworks® Simulation module was used to determine proper horn length, which is shown in Figure 34.

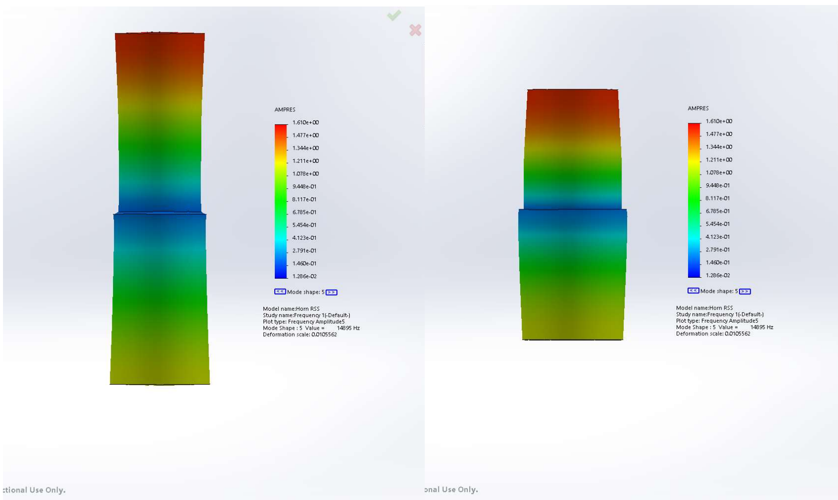


Figure 34. Horn frequency analysis in Solidworks®.

All horn dimensions are presented in *Table 4*. Drawings can be found in the Appendix 1.

Table 4. Horn dimensions.

Horn	Frequency	D1	D2	D3	Shoulder	Length
1	15 kHz	51 mm	56.9 mm	-	2.95 mm	170 mm
2				79.1 mm		
3				114.7 mm		
4	20 kHz	50.2 mm	56.9 mm	-	3.35 mm	145 mm
5				79.1 mm		
6				114.7 mm		
7	30 kHz	30.5 mm	56.9 mm	-	13.2 mm	100 mm

In total, seven horns were manufactured for testing purposes. They can be seen in Figure 35. Previous tests demonstrated the potential of the lower 15 kHz and 20 kHz frequencies so multiple horns of the three diameters were manufactured. On the other hand, because a 30 kHz transducer is quite small and does not provide a lot of power, only one horn was made for that frequency to compare the difference between the frequencies.

Figure 35. Seven manufactured horns.

3.3.5 Set screws for horns

The transducers used in the experiment had nonstandard fine threads in the transducer to horn mounting hole so custom set screws were required. For the 15 and 20 kHz transducers, the thread was M16x1.0, while for the 30 kHz, the thread was the standard M16x2.0. However, the manufacturer's thread information for the 20 kHz transducers was incorrect so the fabricated horns did not properly mount. The issue was fixed by fabricating a custom set screw with M16x2.0 thread on the transducer side and M16x1.0 thread on the horn side.

During the experiment, AC current in the transducer interfered with the DC current from the electrokinetics power supply. The two currents were isolated from each other by inserting a Mylar dielectric film between the transducer and horn faces and replacing all the set screws with nonconductive set screws fabricated from Torlon® PAI.

Figure 36 shows the eight sets screw manufactured for the three different transducers. During testing, steel set screws were used when only ultrasound was powered on (no electrokinetics). The Mylar dielectric film and Torlon® PAI were used when ultrasound and electrokinetics were applied together. Both Torlon® 4301 and 4203 were used.

Figure 36. Set screws for ultrasound transducer horn pair.

3.3.6 Drainage plate

A drainage plate was needed to support the thinner and therefore more flexible mesh filter to prevent it from bending and allow water to pass through the system. It can be seen in Figure 37 below.

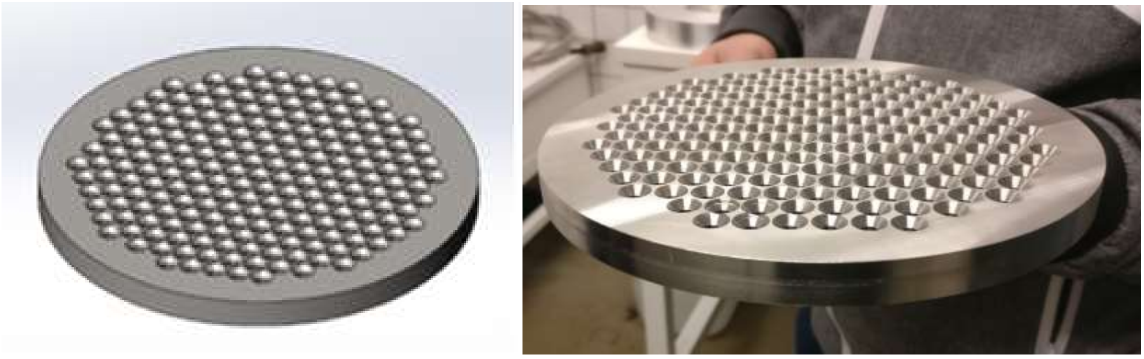


Figure 37. Filter plate as Solidworks® model (left) and as a manufactured part (right).

The plate was designed to withstand the maximum downward force planned for the experiment. The Solidworks® simulation module was used to determine the required plate thickness. The maximum testing force was chosen to be 1800N, but for extra safety, 2500N was applied in the Solidworks® simulation. The plate will see maximum stress when the smallest diameter 56.9mm horn is being used.

12mm stainless steel plate with a yield strength of $2.07*10^{2}$MPa was available from the fabrication shop. This yield strength was used for the analysis. The results are shown in Figure 38. The maximum predicted strain in the plate is $1.8*10^{-2}$mm and maximum stress is 4.8*10MPa, which meets the design requirements.

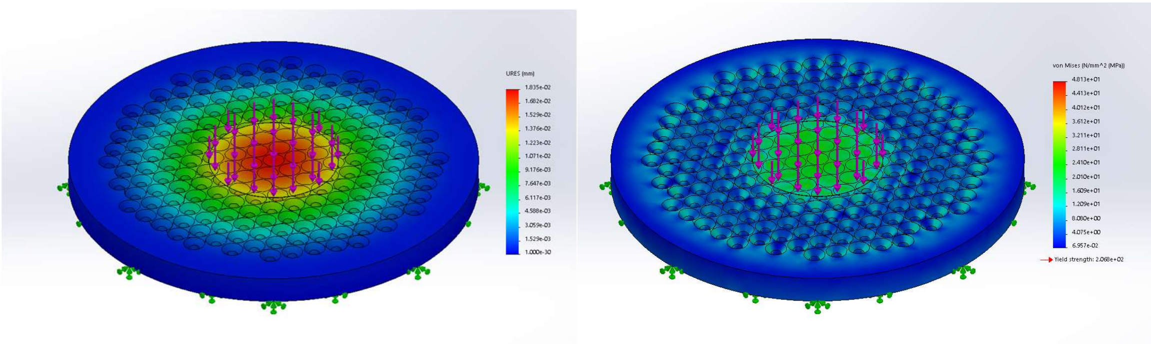


Figure 38. Filter plate strain (left) and (stress) analysis in Solidworks®.

3.3.7 Horn adapters

Horn adapters were made to accommodate horns of varied areas. The smallest of the batch can be seen in Figure 39. It has a chamfer on top to ensure easier insertion of the horn, a groove for the O-ring and an area on the bottom to accommodate the filter cup. To prevent leakage during testing, the filter cup area height was undersized so no free space would remain between the cup and filter under the weight of the horn adapter.

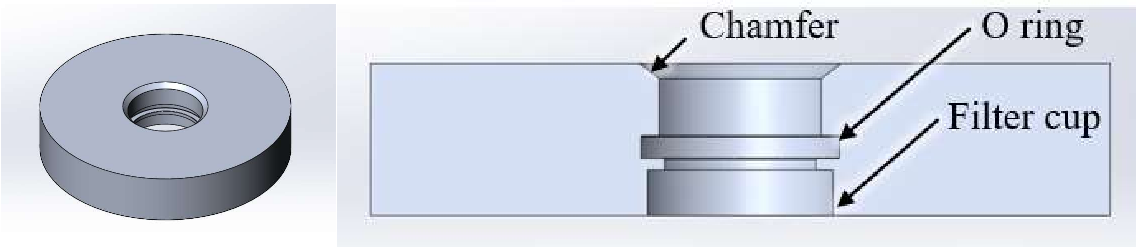


Figure 39. Smallest horn adapter Solidworks® model (left) and its cross-section view (right).

Because there were three horn sizes, the same number of horn adapters were needed. They were designed and manufactured to accommodate all horn sizes and properly fit the various O-rings diameters. The manufactured parts are shown in Figure 40.

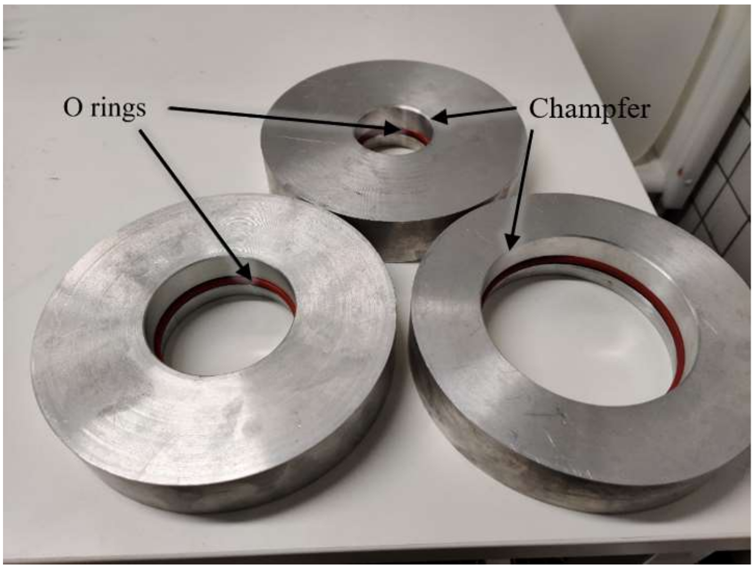


Figure 40. Three manufactured horn adapters.

3.3.8 Height adjustment

Horns had different length and were cut during the tuning process and therefore some sort of height adjustment mechanism was needed. Figure 41 shows a part that was used to hold a pneumatic cylinder and move up and down on the circular tube. The hole in the middle has an oval shape so that when the part is turned to the side it can easily slide up and down, but when it is turned to the front of the apparatus, it is locked down in its position and can be further tightened by the side screws.

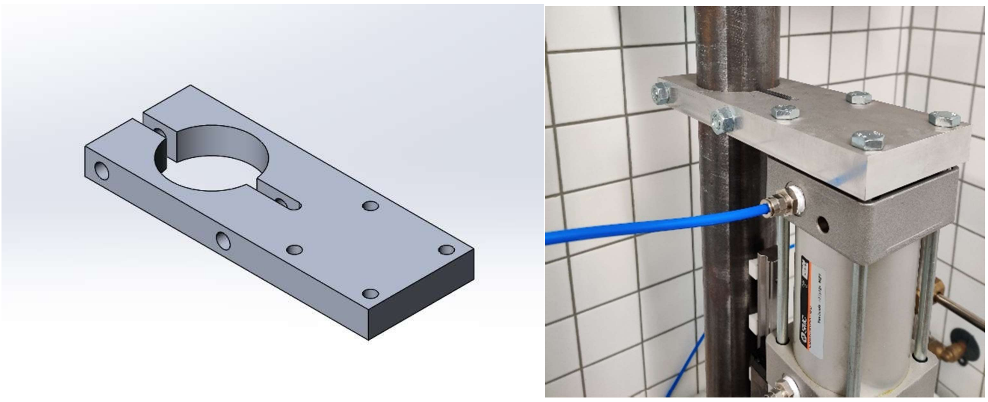


Figure 41. Height adjustment model in Solidworks® (left) and manufactured part (right) with pneumatic cylinder secured in position on the circular tube.

3.3.9 Nodal hold

Figure 42 shows a part that is used to transmit force from the pneumatic cylinder onto the horn. One end is attached to the rail guide, the middle section has a hole for attaching the pneumatic piston. The circular section at the other end is used to holster the ultrasonic stack and apply force on the horn's nodal point. It also has a hole on the side that is used to attach a cable for electrokinetics.

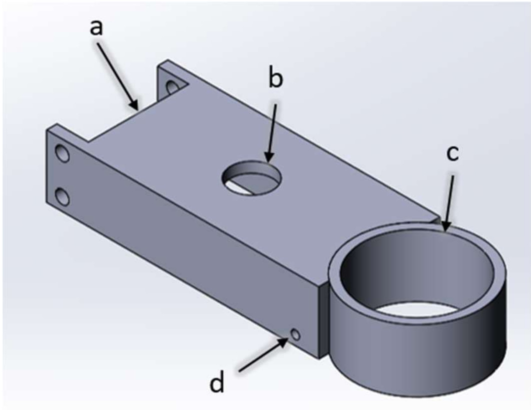


Figure 42. Nodal hold – (a) end that is attached to the rail guide, (b) hole for holding pneumatic piston, (c) circular section for applying pressure on the horn, (d) hole for attaching electric cables.

3.3.10 Rail guide

A linear rail guide was required to allow smooth and accurate power transmission from the pneumatic cylinder to the horn. The moment produced by the pneumatic piston on the nodal hold part was calculated to be 250 Nm, which is higher than one small SKF linear rail can sustain. Therefore, two carriages are used to uniformly distribute the moment force. An SKF® profile rail guide catalog was used to choose the proper part (SKF, 2013).

Since the apparatus base had a circular tube, it could not hold the linear rail on its own. Filler parts were 3D printed out of nylon to allow the rail to be properly attached and secured to the base. Figure 43 shows how the linear rail guide was attached to the apparatus frame.

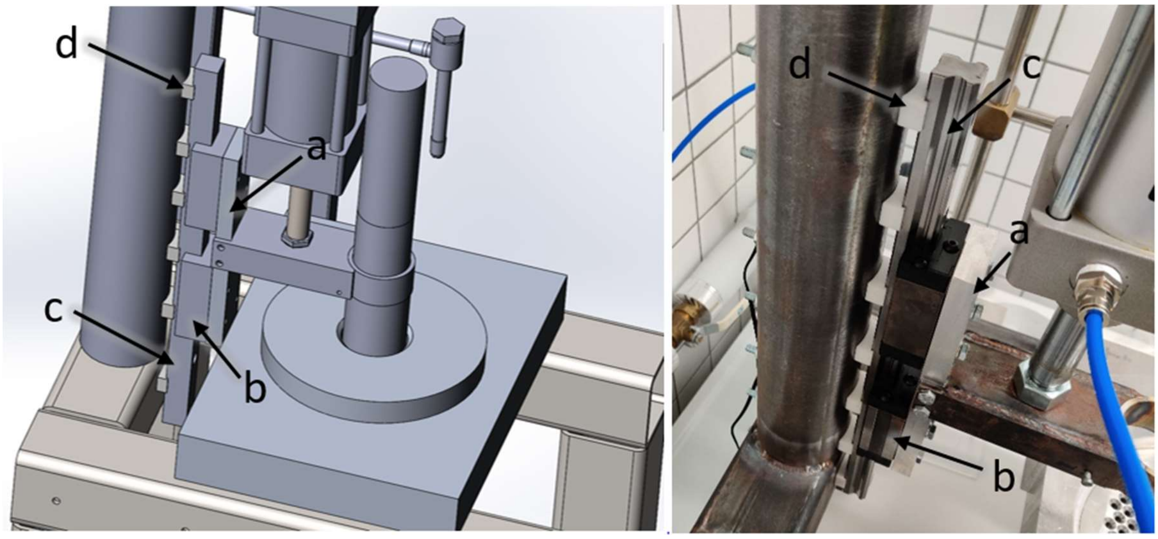


Figure 43. Linear rail guide system - (a) plate for attaching nodal hold and holding two linear rail carriages, (b) rail carriage, (c) linear rail, (d) 3d printed spacers.

3.3.11 Pneumatic cylinder

The pneumatic cylinder was chosen as an actuator for moving the horn and applying the force. The main criteria were that it had a suitable stroke and could provide force higher than 1400N, which was used in previous tests.

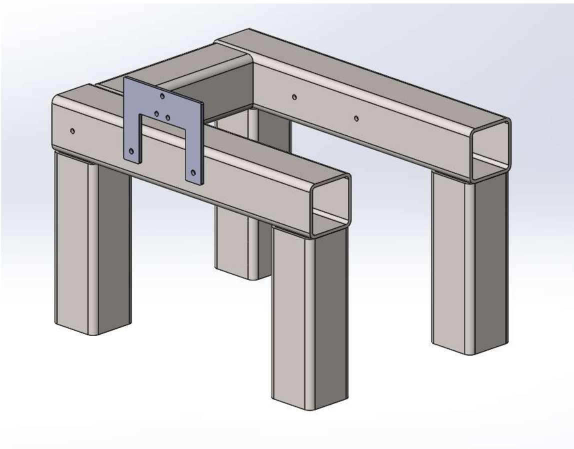
The chosen pneumatic cylinder had a bore of 80mm and stroke of 60mm. It is shown in Figure 44.

Figure 44. Pneumatic cylinder used for the experiment (maxodeals.com, 2019).

On the site of the experiment, the maximum available air pressure was 6 bar. Using Eq. 1, where F is the force, P is the pressure, and D is the bore diameter of the pneumatic cylinder, the 6-bar maximum pressure supplying the pneumatic cylinder can provide a force of 3016 N, which fits the requirements and leaves a room for future improvement.

$$F = P * \pi * \left(\frac{D}{2}\right)^2 \tag{1}$$

Control of the pneumatic cylinder is done using a 5/2 directional control valve that is attached at the side of the base support as seen in Figure 45. A system pneumatic diagram can be found in the Appendix 2.



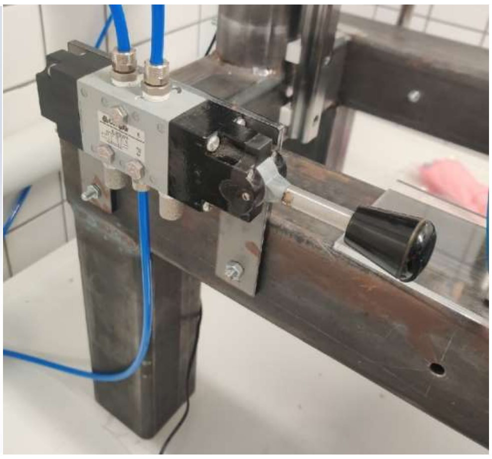


Figure 45. Directional control valve used to operate the pneumatic cylinder.

3.3.12 Vortex tube

The vortex tube is a device that separates compressed air into cold and hot air flows, which allows it to quickly generate cold air of temperatures below -30°C. Figure 46 demonstrates its working principle.

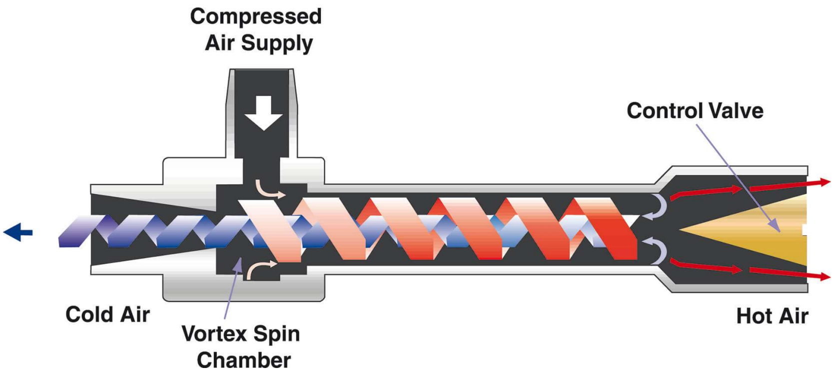


Figure 46. Operation principle of the vortex tube.

The original design of the vortex tube mount attachment had only one degree of freedom where the vortex tube could only rotate around its axis, and the hose was used to direct the flow. In the final design, the vortex cooler was attached to an adjustable tube that allowed horizontal and vertical position change, as well as rotation. Figure 47 illustrates both these designs.

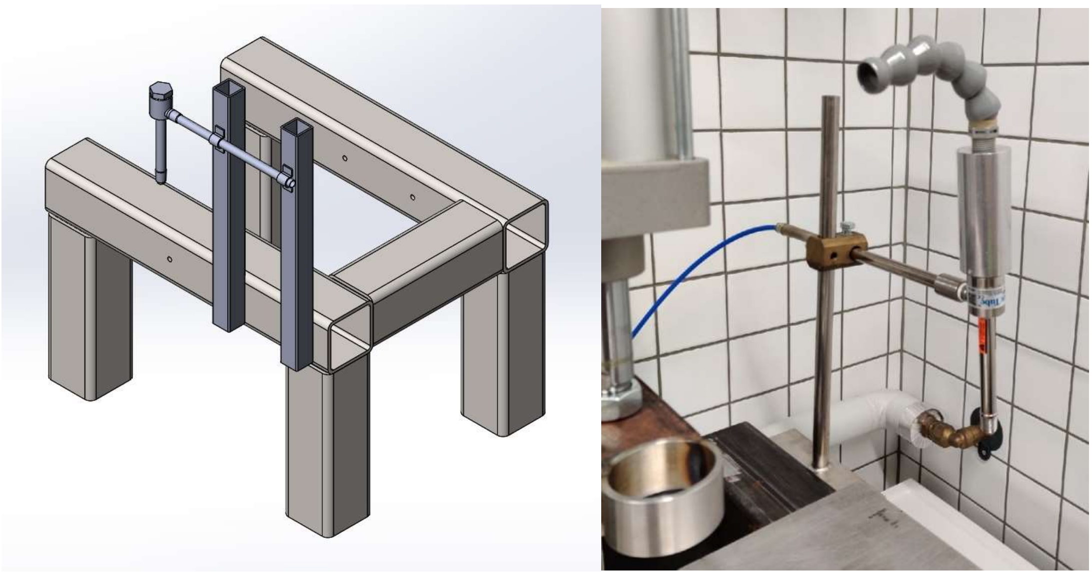


Figure 47. Initial design of cooling mount as Solidworks® model (left) and final version of cooling mount with vortex tube attached to the apparatus base (right).

3.4 Experiment plan to investigate US plus EK enhanced dewatering

The experiment was to follow the design of experiment (DOE) plan. The main purpose of the plan is to get good results in the least amount of experiments and reduce the uncertainty in model predictions, due to uncertainties in data.

3.4.1 Design of the experiment

It was chosen to first use a 2^k plan. It enables the estimation of a linear model plus interaction terms (k stands for the number of factors or variables in the experiment).

- Each factor gets values at two levels (±1)
- The design contains all combinations of the levels
- 2^k plan allows the estimation of the main effect and the interaction terms

To estimate the noise in the experiment, extra measurements are required. It was advised to perform several (3-4) repeated measurements at the same point. Most commonly, they are done at the center points. Noise level is then easily computed using STD (standard deviation). The experimental plan done using a 2^k experiment with 3 repeated measurements in the center is demonstrated by Eq. 2.

$$X = \begin{pmatrix} x1 & x2 \\ -1 & -1 \\ +1 & -1 \\ -1 & +1 \\ +1 & +1 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix} \tag{2}$$

CCD (Central composite design) is more complex and time-consuming but allows the estimation of a full quadratic model. It can be done after parameters are optimized using a 2k plan to get more detailed information on variable responses.

3.4.2 Parameters that affect the dewatering process

Many parameters can affect the dewatering process and therefore it is important to determine what parameters have a bigger impact and chose those that would be studied at first. It is also important to limit how many parameters will be varied at a given experiment set to avoid making an overcomplicated and time-consuming experiment.

Cooling

The temperature of the transducer affects the dewatering process. As a rule of thumb, at higher temperatures, the transducer becomes less effective and can break without sufficient cooling. The vortex tube used for cooling provides sufficient temperature control, and its energy consumption is negligible to the overall energy cost of the system.

Exposure time

A working transducer consumes a considerable amount of energy. In welding applications, the transducer is active only for a short amount of time during contact with the material. In research work done by Peng, Momen, & Moghaddam in 2017, they found out that using the transducer in intervals was almost as effective as continuous use, but was more cost-effective.

Exposure area

To know how much this process can be scaled before it loses too much of its effect, several horns with different areas have been manufactured. They will enable scalability testing.

Frequency

Previous experiments showed that lower US frequencies have a better impact on sludge dewatering. However, those experiments were done only with US and the effect of its frequency when US and electrokinetics are applied at the same time has not been fully studied, so it could be a good idea to vary frequency to determine if it will show different behavior in a combination with EK.

Power

The more power is applied to the transducer the more effective it will be, but on the contrary, more energy will be consumed.

Pressure

High pressure is used in conventional dewatering methods to remove water, and pressure affects the resonant frequency of the transducer-horn pair. However, too high pressure can force the sample to leak in the designed apparatus for dewatering. The pressure is supplied by a pneumatic cylinder and can be regulated by a pressure valve.

Voltage

Electrokinetics works by forcing the flow of water thought the suspension. Having a bigger voltage would increase the flow of water but would consume more energy. The power supply at hand can produce up to 60V to determine voltage effect on the dewatering.

Sludge type

The sludge that comes from various sources is different, so it is crucial to understand what type of sludge is more suitable to the designed setup work.

3.4.3 Designed plan for conducting the experiment

Three variables were selected for study in the first experiments:

- Frequency: Categorical variable with 3 levels [15 kHz, 20 kHz, 30 kHz]
- Voltage: Numerical variable with 2 levels [10 V, 30 V]
- Pressure: Numerical variable with 2 levels [1 bar, 2 bar]

The plan is based on 2^k, so that for each transducer a separate 2^2 plan is needed. Four repeated measurements have been added at the midpoint of variables. Then, the plan is as follows in Table 5. The time of the experiment is determined from the first experiment, which will run until water extraction ceases.

Table 5. Experiment plan for 2^k.

Label	Transducer frequency, kHz	Pressure, bar	Voltage, V
Ex1_1	15	1	10
Ex1_2	30	1	10
Ex1_3	15	2	10
Ex1_4	30	2	10
Ex1_5	15	1	30
Ex1_6	30	1	30
Ex1_7	15	2	30
Ex1_8	30	2	30
Ex1_9	20	1.5	20
Ex1_10	20	1.5	20
Ex1_11	20	1.5	20
Ex1_12	20	1.5	20

The experiments are done in two stages. At first, the testing is conducted based on a 2^k design with center-point replicates. If the center point values give an indication of quadratic behavior (values are larger/smaller than at the corner point, so cannot be linearly analyzed with 2^k) the design will be extended to the CCD plan, which allows quadratic analysis. The CCD plan is shown in Table 6. If the quadratic behavior is not observed then the results are analyzed using a linear model and based on it, new parameters are chosen for the next stage.

Table 6. Experiment plan for CCD.

Label	Transducer frequency, kHz	Pressure, bar	Voltage, V
Ex1_13	15	1,5	20
Ex1_14	30	1,5	20
Ex1_15	20	0,66	20
Ex1_16	20	2,34	20
Ex1_17	20	1,5	3,18
Ex1_18	20	1,5	36,82

4 PRACTICAL EXPERIMENTS

Experiments were carried out using the designed apparatus, which is shown in Figure 48 below. It is enclosed within an enclosure that dampens noise and protects against electrical hazard. Scales were used to weigh the samples and the extracted water. The other parts have already been described in detail in the previous chapter.

Figure 48. Experiment setup in the lab.

The ultrasonic vibrations are produced via an ultrasonic transducer that is supplied with ac current by the amplifier. Electrokinetic voltage is supplied by the DC power supply. Their connections are shown in Figure 49. The figure also shows the cross section of the dewatering area in the base.

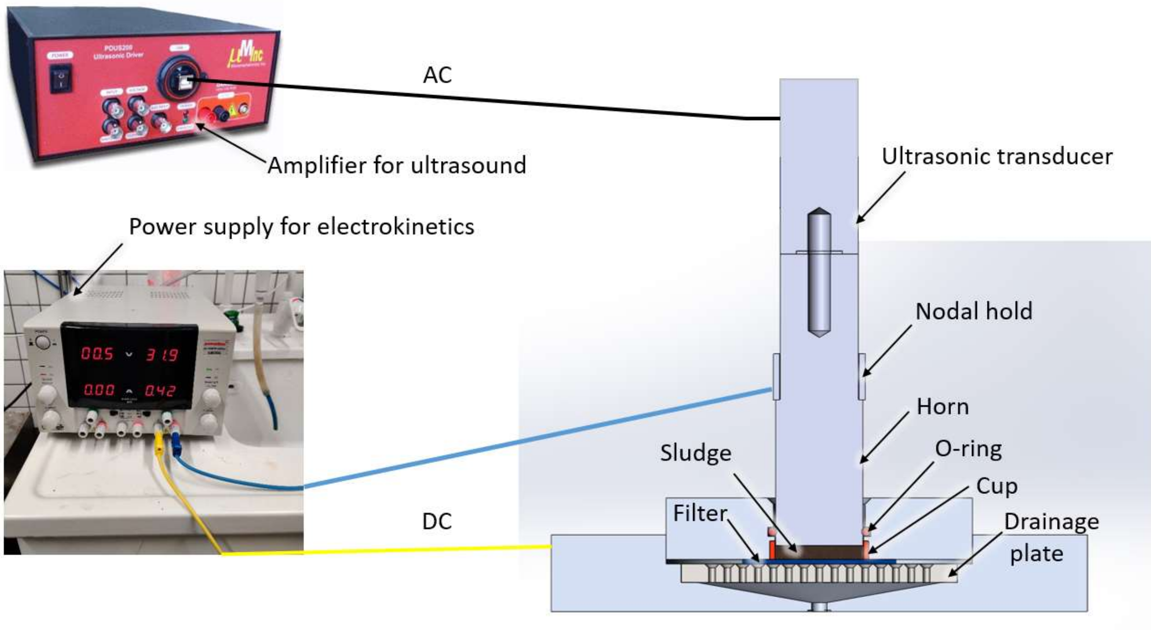


Figure 49. Cross section of the testing procedure.

A mixture of chia seeds and water was selected as a sludge substitute for the initial phases of the experiment to evaluate various parameters in the dewatering process. Chia seeds were chosen, because they are excellent at absorbing water. They can hold up to 10 times their weight in liquid.

Sample preparation

Chia seeds can quickly absorb water, and usually 1 hour is enough for mixture preparation. However, with a longer time chia seeds mixture would become more homogenous and therefore it was decided to wait 24 h for chia seeds to fully bond with the water. For sample preparation, 32 g of chia seeds (dry chia seeds have 6% water content) was mixed with 120 g of water to achieve a 20% TS content mixture.

4.1 Preliminary experiments

In preliminary experiments pressure, ultrasound and electricity were separately applied to the sludge to have a basis for comparison. Then, EK and US were applied in combination to see if better results would be achieved. A pressure of 1.5 bar, a voltage of 30 V, and a frequency of 15 kHz was applied to a sample with 20% TS. The results can be seen in Figure 50.

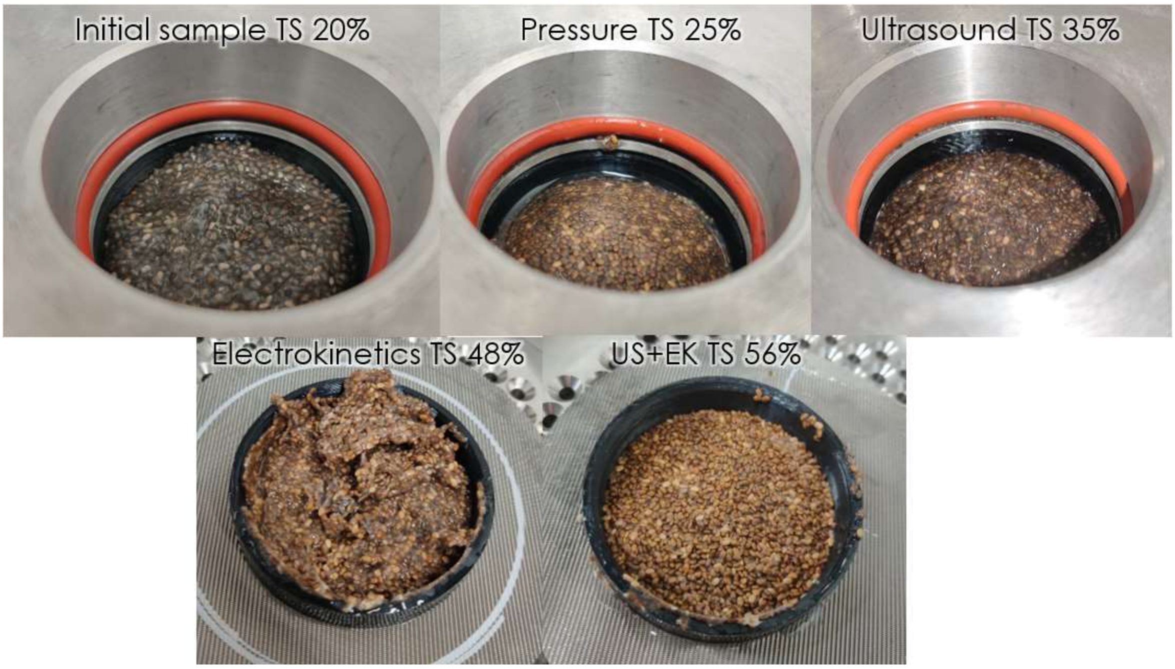


Figure 50. Chia seeds TS content after different dewatering method.

The results indicate that EK yields better results compared to the application of only US or only pressure. However, the combination of EK and US yielded better results overall. However, when applying EK, a problem occurred. Chia seeds would stick to the horn and had to be removed by scraping. That is why the "Electrokinetics TS 48%" image in Figure 50 shows a disturbed chia seed cake. Changing the direction of the current (switching the polarity of the voltage) at the end of the experiment made chia seeds detach from horn and therefore the sample looks uniform in the last result.

4.2 Effect of a dielectric layer buildup on the results

When the electric current is applied to the chia seeds sample, a dielectric layer forms on the surface of the horn, which is the EK anode. Figure 51 shows three different horns: one that was never used before, one that was used in dewatering but was sanded, and one horn right after the dewatering process.

Figure 51. Dielectric layer on the surface of the three different horns.

The formation of this dielectric layer negatively affects the results of the dewatering and requires sanding to remove, which is troublesome and cannot be done constantly. The solution to this problem was using a layer of aluminum foil between the horn and the seeds, which acts as a disposable and sacrificial material. The results of the different approaches to horn cleaning are shown in Figure 52.

As can be seen from the results, the horn that had a buildup layer on the surface yielded poor results in the beginning. However, the end result was the same. Using aluminum foil produced results similar to the results for when the horn was sanded every 10 minutes. In the first test using aluminum foil, the spike at 40 minutes is due to the foil change. In the second test, the same aluminum foil was used throughout the whole test and results were a bit lower due to layer formation. Results indicate that using aluminum foil between the horn and the chia seeds helps to prevent horn contamination without affecting the results too much and therefore this method will be used in the planned experiments.

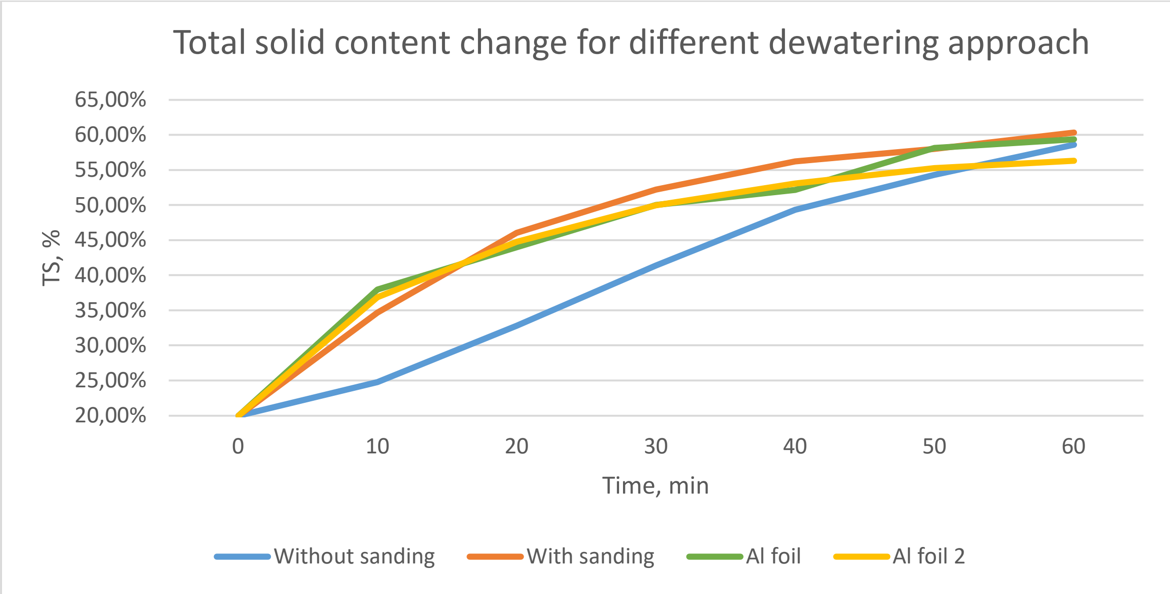


Figure 52. Effect of different approach on the TS content change of Chia seeds.

4.3 Experiment results for 20 kHz transducer

The first batch of the experiments for the 2k plan was done at the middle point of the chosen variables. Four identical experiments were carried out. This is to ensure that the dewatering process is consistent and does not have noticeable variation. The parameters were 20 V, 1.5 bar of pressure and 20 kHz. The results are shown in Figure 53.

The results indicate that the process is consistent and yields the same TS content with the same parameters. The first two tests and the last two tests were done with a difference of several days. Sample preparation was identical; however, the horn was in contact with the water that was coming out from beneath the aluminum foil, which contaminated the horn and, after 2 days, formed a dielectric layer negatively affecting electrokinetics. Nevertheless, the final TS content after dewatering was similar across all four tests. To prevent such contamination in the future, all upcoming tests were done on the same day to decrease the process deterioration over time due to horn contamination.

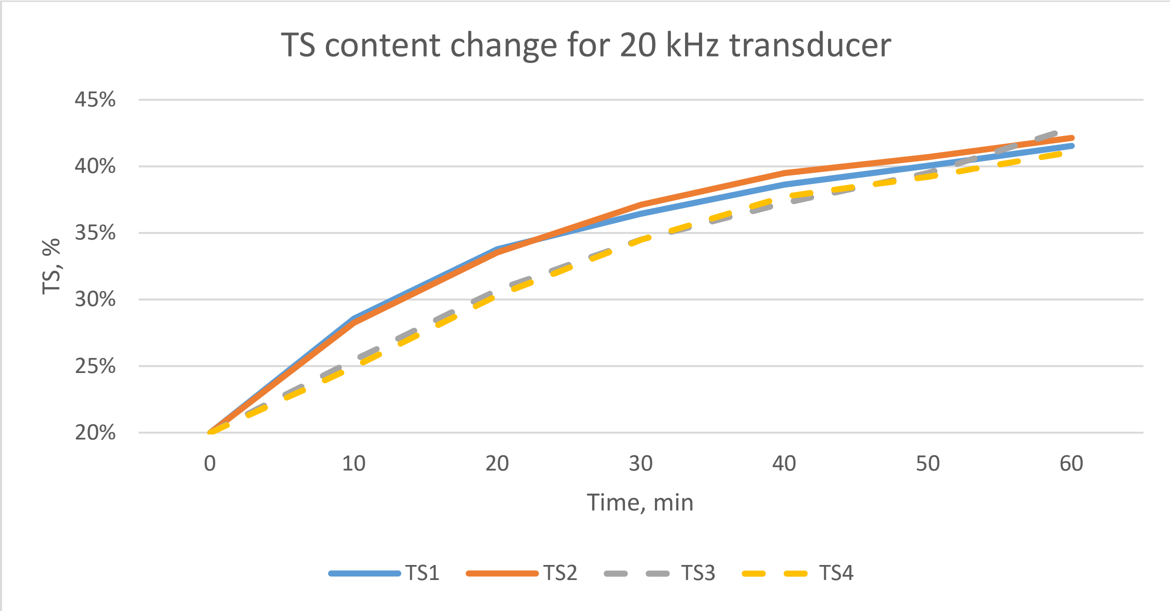


Figure 53. Four identical experiments using 20 kHz transducer to determine consistency of the dewatering process.

During the experiments, nonlinear behavior was observed and therefore extra tests were done using the CCD plan to investigate the quadratic behavior of the results. For 20 kHz, the extra tests are shown in Table 6 with labels Ex1_15 to Ex1_18, and the results can be seen graphically in Figure 54.

The results show that voltage has a bigger impact on the results than pressure. Low voltage leads to much worse TS content results than having low pressure. At the same time, higher voltage has a bigger spike at the beginning of the dewatering process but comes even with the high pressure at the end.

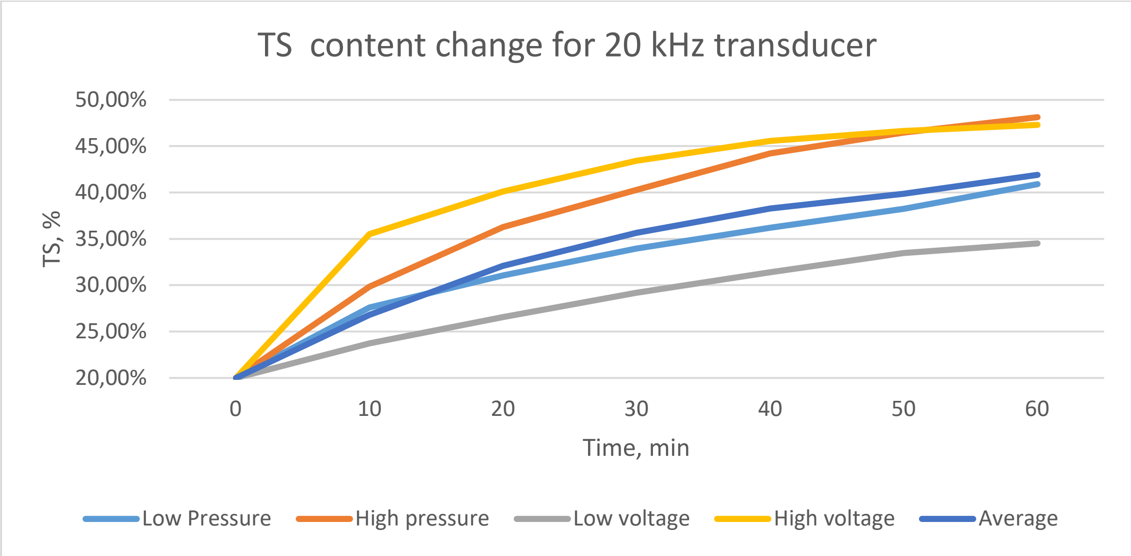


Figure 54. Experiments following CCD plan for 20 kHz.

4.4 Experiment results for 15 kHz transducer

For the 15 kHz transducer, four experiments were conducted at the corner points of the chosen variables: low pressure and voltage, low pressure and high voltage, high pressure and voltage, and high pressure and low voltage. The results for these parameters are shown in Figure 55.

The results show a similar trend as before. The voltage has a much better impact on the results than pressure. Both results where the voltage was high yielded better results than tests with low voltage. Pressure still shows a positive effect, so high voltage and high-pressure deliver the best outcome.

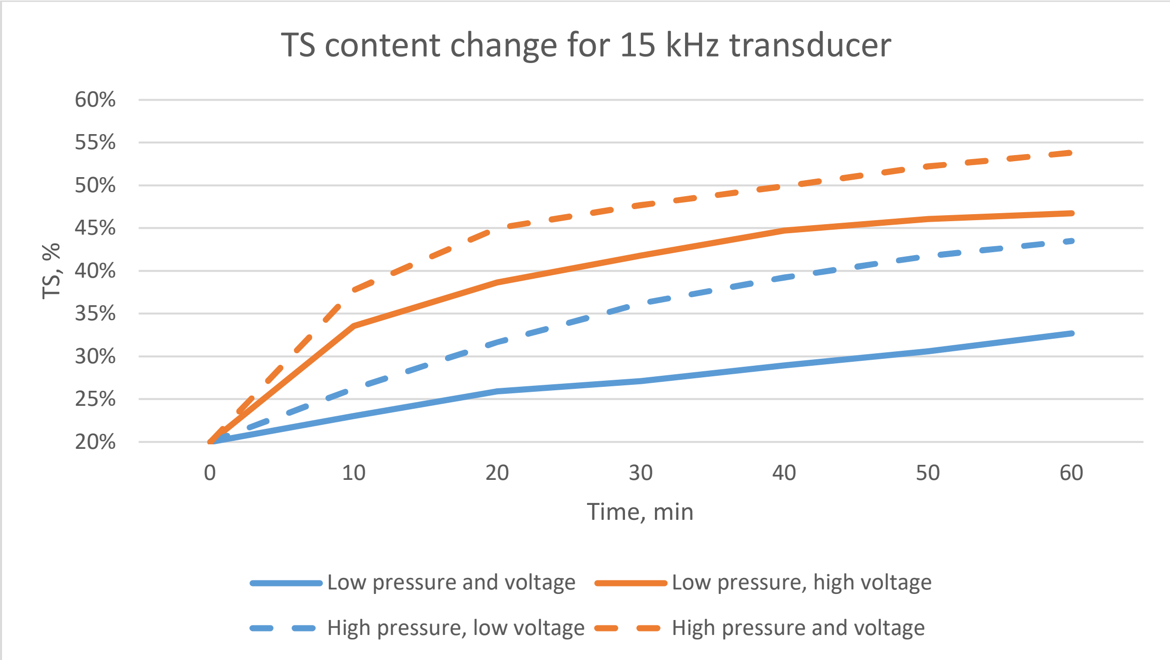


Figure 55. Experiments following 2^k plan for 15 kHz.

4.5 Experiment results for 30 kHz transducer

For 30 kHz, the experiment sequence was like that done for 15 kHz. The corner points of the parameters were tested. The results are presented in Figure 56.

The end results of the experiments for the 30 kHz transducers are the same as for 15 kHz. However, intermediate measurements show a different behavior. For example, in the first 10 minutes of high voltage, the results were the same for low and high pressure. However, the low-pressure curve drops after that and ends under the high pressure and high voltage curve. The high pressure and low voltage case shows poor results in the beginning but got a big spike in the last 20 minutes of the experiments. This might be because 30 kHz horn was smaller than 15 kHz horn and could not apply sufficient force on the sludge to compact it into smaller thickness cake that could manage to transmit such a low voltage current, so only ultrasound was helping the dewatering process in the beginning.

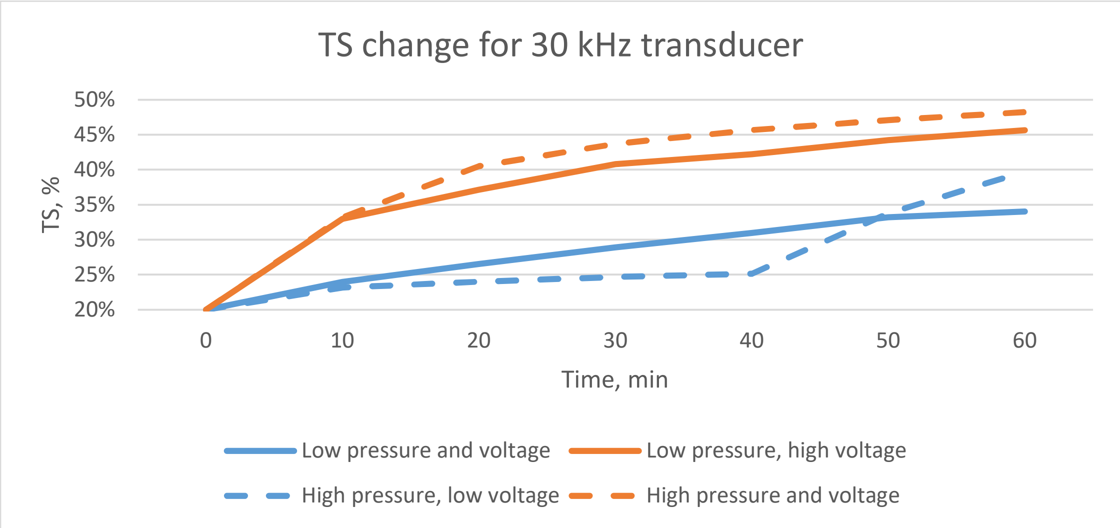


Figure 56. Experiments following 2^k plan for 30 kHz.

4.6 Further attempts at stopping process deterioration due to electrochemical reaction

In the preliminary test, it was discovered that the layer that forms on the surface of the horn leads to process deterioration. A temporary solution was to use aluminum foil. Although the foil leads to good and consistent results, it had to be changed constantly. A better solution is needed.

Aluminum has excellent acoustic properties and that is why it was choosing as a horn material; however, it is also an active material prone to oxidization. Adding a protective coating could help protect aluminum horns from an electrochemical reaction.

Two different coatings were used to see if they could prevent process deterioration. Each coating had two back-to-back 10-minute tests using a sample from the same batch using 20 kHz transducer and 30 V. Results are shown in

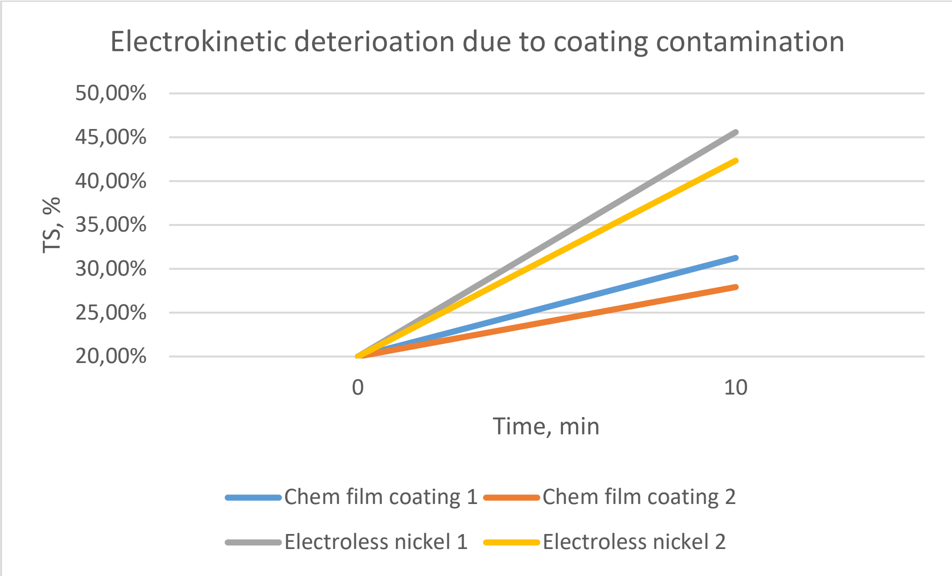


Figure 57. Unfortunately, both coatings showed bad results, as each one had formed a layer, which leads to results decrease. Moreover, chem film coating decreased the efficiency of the process.

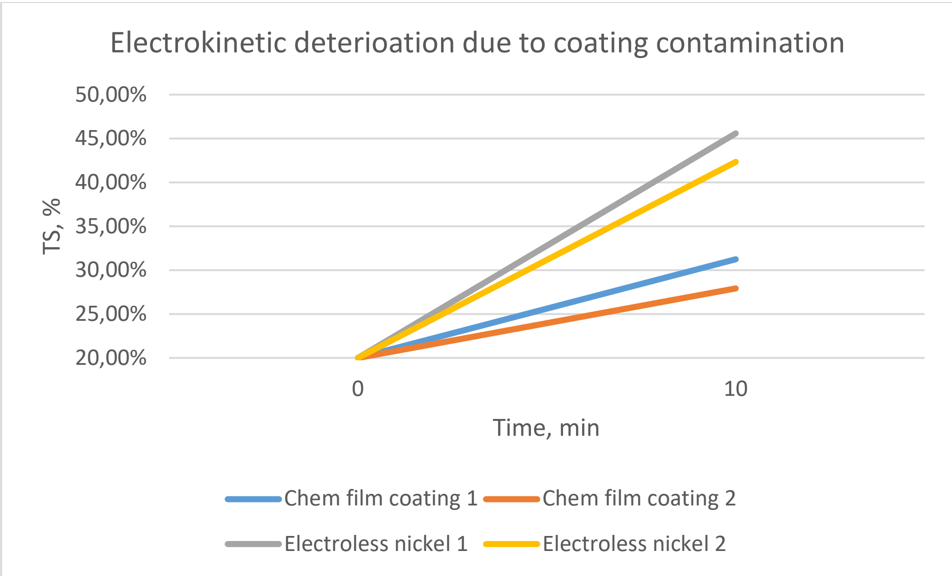


Figure 57. Results of the different coatings.

Another solution that was tried is reversing the direction of the current by making horn acts as cathode and filter mesh to acts as anode so that electrochemical reaction would happen at the filter mesh side. The mesh is easier to replace, and it is stainless steel, so has better resistance to corrosion and contamination. The results are presented in Figure 58.

In the test, the 20 kHz transducer was used with the reverse current induced by 20 V, which left the horn surface only slightly contaminated from the contact with the seeds. However, no signs of the electrochemical reaction were found at the surface of the horn. The result was compared to the average result that was calculated from the four tests that were previously done using 20 kHz transducer and the same parameters with current flowing normal direction. Reversing the current showed much better results, and a maximum TS of 60% was achieved after 30 minutes and lower voltage, while in other tests 60% could be achieved only after 1 hour and higher voltage.

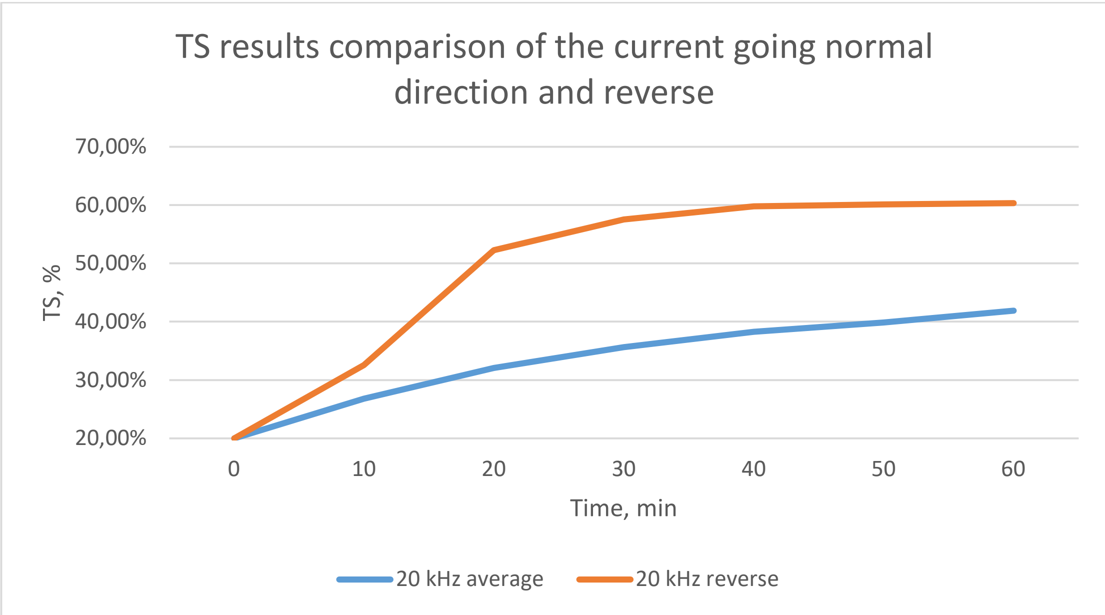


Figure 58. Effect of current direction change on the TS content result.

5 DISCUSSION

The purpose of this chapter is to analyze the results obtained from the practical experiments described in Chapter 4 and offer conclusions about the practicality of using the US and EK to enhance sludge dewatering. At first, the outcome of the experiments is discussed. Then, the problems that were faced during the experiments are presented with proposed improvements to the experiment setup. Lastly, recommendations for future research into dewatering are presented.

5.1 Dewatering was dramatically enhanced by adding a combination of US and EK

The dewatering experiments started with only pressure being applied to the sample that resulted in a slight increase in the chia seeds TS content going from 20% to 25%. The TS content did not increase with a prolonged test duration or an increase in pressure. This revealed that the sample had a small amount of free water that could be removed with simple filtration under pressure and the rest was bound water that required enhanced dewatering.

Using only US or EK resulted in final TS being 35% and 48% respectively, while the combination of US and EK enhanced dewatering yielded 56% TS content, which is considerably better than the conventional dewatering processes that can reach only up to 40% TS content. All tests were done with the same time duration.

To understand what parameter (frequency, pressure, voltage) had the biggest impact on the dewatering results, 2k and CCD experiment plans were drawn up and conducted. The figure demonstrates the results received from the experiments. Figure 59 shows that frequency has a negative impact on the overall result, that is, lower frequencies yield the best results. Both pressure and voltage had a positive effect, and their amplitude of impact was considerably bigger than that of frequency. Voltage is revealed to be the main influence on the results.

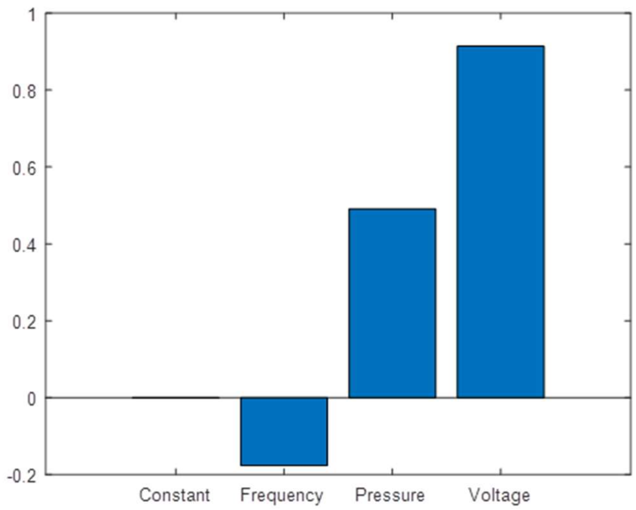


Figure 59. Impact of frequency, pressure and voltage on the results.

5.2 Proposed changes to improve the dewatering process

Corrosion

The main problem that occurred during the testing was corrosion of the horn surface due to electrochemical reactions. Electrode corrosion in electro-osmotic dewatering is a common occurrence that is being dealt with by using a more resistive coating or a more often maintenance of the electrodes.

For our tests, we used aluminum foil that was corroding instead of the horn and was changed between tests. This solved the problem and prevented horn contamination. However, a more permanent solution was still required.

Selection of coating that prevents corrosion in electro-osmotic dewatering presents a challenge because corrosion-resistant coating does not go on par with electrical conductivity, which is essential for the dewatering process to work. Moreover, depending on the sludge type (municipal, mining, bio) that is going to be dewatered, different coatings must be used.

Chem film applied to the horns and tested on chia seeds did not provide a suitable result. Coating the horns with Teflon-impregnated electroless nickel gave better results but did not eliminate coating buildup on horn surfaces. The first coating reduced electrical conductivity and would quickly get contaminated, while the second coating, having good corrosion resistance and electrical conductivity, would chemically react with the fatty acids, that were released from the chia seeds during dewatering process, and get a burnt surface.

Changing the direction of the electrical current removed corrosion of the horn surface and even improved the results. With changed electrical direction the filter mesh was acting as an anode and getting corroded, however, it was made of stainless steel and had better corrosion resistance than the aluminum horns and would only get noticeable corrosion during high voltage tests. The horns would still get contaminated but were easier to clean.

The ultrasonic horns were made of aluminum, which was chosen for its excellent acoustic properties. However, aluminum is a chemically active metal and corrodes easily. For industrial applications, the ultrasonic horns could be made of titanium, which would prevent such corrosion. Another option is to run the current in reverse and make the filter mesh corrode, since it is much cheaper to replace.

Water extraction

During the tests, that were run with current in the normal direction, the water was pulled to the filter mesh, which was acting as a cathode. In this case the water would easily pass through the filter. However, when the tests were run with current in reverse direction, the water started going up. The amount of water was small but with higher sample mass it would become noticeable and would negatively affect the outcome.

Reducing the gap between the horn and the filter cup would prevent water from rising above the cup and spilling out, however, in that case it would just gather on top of the sludge cake negatively affecting the dewatering results. Making holes in the side of the cup just above the sample would allow water to go to the side and down to the drain elimination any problems with the water extraction.

5.3 Future research

The results of the experiment showed that a combination of US and EK enhanced dewatering can dramatically improve the dewatering of the sludge and has a potential for further development.

All experiments were conducted using the same sample thickness, however, to have a better perspective on the scalability of the process, higher sample thicknesses need to be tested. Also, continuous processes are more predominant in industry than batch processes, which was used in the lab scale testing. Continuous processes should be tested as well.

Reverse current showed better results than the current going normal direction. There are several explanations for this. First, chia seeds have positive zeta potential and therefore current in the normal direction is not as efficient as it would be for samples with negative zeta potential. Second, when voltage is reversed (cathode on top), hydrolysis occurs that helps with the speed of the dewatering. Both of these explanations suggest that chia seeds behave differently depending on the direction of the electric flow. This phenomenon needs more detailed testing.

6 CONCLUSION

The main goal of this thesis was to design an apparatus to enhance sludge dewatering by combining US and EK. Apparatus effectiveness was evaluated in a series of tests. These tests showed that by combining US and EK, it is possible to reach 60% TS content, which is significantly dryer than what is attainable using conventional methods.

This work is a continuation of another project where several mechanical problems emerged. All of them were solved. Using a vortex cooler for spot cooling hot parts of the transducer eliminated heating problems. The experiment was conducted in an isolated room that would dampen the noise for other people in the vicinity. In addition, an enclosure out of acrylic was made to surround the test apparatus. Each experiment procedure was conducted with proper ear protection. The noise level outside of the experiment room did not exceed 75dB, which meets the human exposure level requirements set by the American Conference of Governmental Industrial Hygienists (ACGIH 89). The pneumatic cylinder was used as an actuator for the experiment setup, which made it possible to regulate the amount of force extruded on the sample.

Approximately 10,000 euro was spent on both the mechanical and the electrical parts. The total cost of the experiment setup and the data acquisition hardware was 20,000 euro. Including power consumption for both US and EK, the cost of running this enhanced dewatering was calculated to be 0.0007 euro per kg per %TS.

The final experiment setup had both mechanical and electrical processes applied to the sludge to extract the maximum possible water amount from it. The mechanical process included pressure that was used to compress the cake. Electrical processes consisted of an ultrasonic transducer used to break down the bonds in the sludge and the electrokinetics, which induced water flow and improved water extraction.

Experiments were conducted on chia seeds samples due to their exceptional ability to absorb large volumes of water. The prepared chia seed samples had 20% TS content. Applying only mechanical force did not significantly affect TS content. This shows that the prepared samples contained mostly bound water, which is not affected by mechanical dewatering methods. When US and EK were applied, it was possible to reach up to 60% TS content.

The practicality and scalability to the industrial level were not tested. Also, it is yet to be decided at which stage of dewatering it would be more efficient to apply US plus EK enhanced dewatering: before, during, or after the dewatering process.

In conclusion, the overall results of the experiments are positive and, with a few exceptions (electrical corrosion, current direction effect), were as expected. It was possible to dramatically enhance sludge dewatering and combine several dewatering methods together to achieve a better effect. The achieved results show that the proposed dewatering method is effective in the extraction of bound water and the next step would be to test US plus EK enhanced dewatering on industrial sludge samples.

REFERENCES

Aesarabia. (2019). Sludge Thickening. [online] Available at: http://www.aesarabia.com/sludge-thickening/ [Accessed 18 Oct. 2019].

Andreoli, C., Sperling, M. and Fernandes, F. (2007). Sludge treatment and disposal. London: IWA Publishing.

Beijing Ultrasonic. (2012). 25KHz 100W Piezoelectric Ultrasonic Cleaning Transducer (PZT-4). [online] Available at: https://www.bjultrasonic.com/shop/25khz-100w-ultrasonic-cleaning-transducer/ [Accessed 9 Sep. 2019].

Berg, R. (2013). Ultrasonics. [online] Encyclopedia Britannica. Available at: https://www.britannica.com/science/ultrasonics [Accessed 9 Sep. 2019].

Canada.ca. (1991). Guidelines for the Safe Use of Ultrasound: Part II - Industrial & Commercial Applications - Safety Code 24 - Canada.ca. [online] Available at: https://www.canada.ca/en/health-canada/services/environmental-workplace-health/reports-publications/radiation/guidelines-safe-use-ultrasound-part-industrial-commercial-applications-safety-code-24.html [Accessed 18 Nov. 2019].

Cracknell, A. (1980). Ultrasonics. London: Wykeham Publications.

ctgclean. (2012). Ultrasonics - Ultrasonic Generators - Introduction. [online] Available at: https://techblog.ctgclean.com/2012/01/ultrasonics-ultrasonic-generators-introduction/ [Accessed 18 Oct. 2019].

ctgclean. (2018). What is an Ultrasonic Generator?. [online] Available at: https://www.ctgclean.com/blog/what-is-an-ultrasonic-generator [Accessed 18 Oct. 2019].

Dukane. (2010). How does your Ultrasonic Probe/Stack work?. [online] Available at: https://www.dukane.com/how-does-your-ultrasonic-probestack-work/ [Accessed 17 Sep. 2019].

Branson. (2012). Ultrasonic horn catalog. [online] Available at: https://www.emerson.com/documents/automation/catalog-ultrasonic-horn-branson-en-us-160126.pdf [Accessed 22 Oct. 2019].

Ends report. (1993). Thames Water gets go-ahead for two sludge incinerators. [online] Available at: https://www.endsreport.com/article/1576148/thames-water-gets-go-ahead-two-sludge-incinerators [Accessed 6 Sep. 2019].

European Environment Agency. (2017). Urban waste water treatment. [online] Available at: https://www.eea.europa.eu/data-and-maps/indicators/urban-waste-water-treatment/urban-waste-water-treatment-assessment-4 [Accessed 3 Sep. 2019].

Eurostat. (2019). 487 kg of municipal waste generated per person. [online] Available at: https://ec.europa.eu/eurostat/en/web/products-eurostat-news/-/DDN-20190123-1 [Accessed 9 Sep. 2019].

Fahrni, H. (2011). Sewage Sludge Disposal in Switzerland. [ebook] Available at: https://pdfs.semanticscholar.org/3b11/3ec50b9cb12db8c33b3c650862cd14ce3adf.pdf [Accessed 12 Oct. 2019].

Forno, A. Da and Gronchi, P. (2015) ‘D2.1 - State of the art of existing technology – review’, Journal of China and International Relations, 2(2), pp. 1–50.

Gallego-Juárez, J., Elvira-Segura, L. and Rodríguez-Corral, G. (2003). A power ultrasonic technology for deliquoring. Ultrasonics, 41(4), pp.255-259.

Gallego-Juárez, J., Riera, E., de la Fuente Blanco, S., Rodríguez-Corral, G., Acosta-Aparicio, V. and Blanco, A. (2007). Application of High-Power Ultrasound for Dehydration of Vegetables: Processes and Devices. Drying Technology, 25(11), pp.1893-1901.

Gemert, G. (2009). Theoretical and Technological Development of an Energy efficient Dryer for sludge.

Kelessidis, A. and Stasinakis, A. (2012). Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Management, 32(6), pp.1186-1195.

Kyu Lee, J., Shang, J. and Xu, Y. (2016). Electrokinetic Dewatering of Mine Tailings Using DSA Electrodes. International Journal of Electrochemical Science, 11(5), pp.4149-4160.

Lévêque, J., Cravotto, G., Delattre, F. and Cintas, P. (2018). Organic Sonochemistry. SpringerBriefs in Molecular Science, pp.4149–4160.

Li, S., Brennen, C. and Yoichiro, M. (2015). Cavitation in medicine. Interface Focus, 5(5), pp.1-12.

Mahmoud, A., Olivier, J., Vaxelaire, J. and Hoadley, A. (2011). Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects. Water Research, 45(9), pp.2795-2810.

Mahmoud, A., Olivier, J., Vaxelaire, J. and Hoadley, A. (2013). Advances in Mechanical Dewatering of Wastewater Sludge Treatment. Wastewater Reuse and Management, pp.253-303.

Mason, T. (2014). Introduction to sonochemistry. [online] Sonochemistry. Available at: http://www.sonochemistry.info/introdution.htm [Accessed 20 Oct. 2019].

Maxodeals. (2019). SMC C95SDB80-60 Pneumatic Cylinder 80mm Bore 60mm Stroke NMP. [online] Available at: https://www.maxodeals.com/mdenglish/smc-c95sdb80-60-pneumatic-cylinder-80mm-bore-60mm-stroke-nmp [Accessed 18 Nov. 2019].

Mmech.com. (2019). Ultrasonic power transducer catalogue. [online] Available at: http://www.mmech.com/transducers/transducer-welding [Accessed 23 Sep. 2019].

Mobaraki, M. (2016). Investigating high-power ultrasonic vibration and vacuum as methods to enhance the extraction of water from municipal wastewater sludge. [online] Available at: http://urn.fi/URN:NBN:fi-fe2016091923830 [Accessed 26 Sep. 2019].

Nättorp, A. (2015). Phosphorus flows, policy and perspectives. [online] Phosphorusplatform.eu. Available at: https://phosphorusplatform.eu/images/Conference/ESPC2-materials/Nattorp - Sustainable Phosphorus management in Switzerland.pdf [Accessed 26 Nov. 2019].

Nikku & Ritvanen. Combustion of Dried Sewage Sludge and Municipal Solid Waste. In PAKU plus-Herge, 2015. Lappeenranta.

Peng, C., Momen, A. and Moghaddam, S. (2017). An energy-efficient method for direct-contact ultrasonic cloth drying. Energy, 138, pp.133-138.

Ruijters, J. (2018). Dutch experimence of sludge management and P-recovery. [online] nweurope. Available at: https://www.nweurope.eu/media/3386/1_p4y_environ2018_hvc-snb_ruijter.pdf [Accessed 29 Oct. 2019].

SKF. (2013). Profile rail guides catalogue. [online] Available at: https://www.skf.com/binary/68-69216/12942_1_EN_LLT_2013.pdf [Accessed 18 Nov. 2019].

Sonicitalia. (2017). Ultrasonic Booster. [online] Available at: https://www.sonicitalia.com/en/ultrasonic-components/ultrasonic-sonotrodes-and-boosters/ultrasonic-booster [Accessed 21 Nov. 2019].

Tuan, P., Mika, S. and Pirjo, I. (2011). Sewage Sludge Electro-Dewatering Treatment—A Review. Drying Technology, 30(7), pp.691-706.

Venkatesan, A., Done, H. and Halden, R. (2015). United States National Sewage Sludge Repository at Arizona State University—a new resource and research tool for environmental scientists, engineers, and epidemiologists. Environmental Science and Pollution Research, 22(3), pp.1577-1586.

APPENDIX 1. Methods summary: max TS, usage, advantages and limitation

Dewatering method	Advantages	Disadvantages	TS, %
Plate filter press	• High total solid content • Good results for sludge that is hard to process with other methods • Capacity can be easily increase later by adding more plates	• Batch process • High set up cost • Requirement for skilled personnel • Requirement for chemical conditioning for good results	30-50
Belt filter press	• Low set up and operational costs • Easy to stop the process • Easy to maintain	• Belt needs constant cleaning • Process is easily affected by sludge type and feed rate	20-30
Centrifuge	• Does not take much space • Easy to start and stop the process • Does not require constant monitoring • Good odor control	• High set up costs • High power consumption • High downtime during maintenance	25-35
Thermal drying	• Significant decrease in sludge volume • After treatment sludge can be used in variety of applications	• Significant energy consumption • Foul odor	65-95
Electrokinetics	• Good results for sludge that is hard to process with other methods • Long life service • Cost efficient	• Electrochemical corrosion • High electricity consumption	45-50

APPENDIX 2. Pneumatic diagram of the system