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VOxFlotation:
Future Solution for Water Treatment

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Flotation is one of the most widely used approaches in water and wastewater treatment technology. Flotation is utilized in separating suspended matters such as solids and oils from water. There are variety of flotation methods depending on treatment targets and purposes. Among those, *Dissolved-Air Flotation (DAF)* is believed to be the most commonly applied. Several advantages compared to sedimentation make DAF more preferably used. On the basis of DAF but with highly intelligent technology, SansOx Ltd has developed a new and unique flotation technology, known as the *VOxFlotation*, which is totally distinguished from any ever-known flotation system. All-in-one feature, small footprint, energy-efficiency, and cost-saving are the most important expectations from the VOxFlotation.

The objective of this thesis was to design a small-scale VOxFlotation system and to test the solids removal efficiency of the technology when treating the synthetic wastewater sample. The *Design of Experiment (DOE)* was conducted in the way that varies two quantitative variables in the VOxFlotation design: the diameter of nozzles (X) and the compressed-air pressure (P) to see how those factors would influence on the final Solid Removal Efficiency *(SRE)* of the system as well as their correlation. At last, the direction for optimizing the process would be predicted.

The experiment results show that, generally, the designed VOxFlotation acceptably performed the solid removal although the maximum achieved SRE was only about 54%. Also, summary from regression model illustrates that the variables have significant influences on the removal efficiency and there is clear interaction between two variables. Higher removal efficiency is expected to be achieved at both higher diameter and compressed-air pressure. In brief, those interpretations can provide SansOx basic information and good starting points for their further testing with VOxFlotation system.

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Abbreviation

DAF: Dissolved-Air Flotation

SansOx Ltd: SansOx Limited

DOE: Design of Experiments

SRE: Solid Removal Efficiency

X: Diameter of Nozzles

P: Compressed-air Pressure

$Al_2(SO_4)_3.7H_2O$: Aluminum Sulfate Hexahydrate

Acknowledgement

Generally, I would like to kindly say thank you to all people, without the enormous contribution of whom, this study could not be possibly completed. Especially, I would like express deep appreciation to the following organizations and persons.

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Sincerely
Hung Bui

Hung

1 Introduction

1.1 Overpopulation, Reasons, and General Consequences

At the moment of writing this sentence, the world population reaches approximately 7,500,000,000 people (Wolrdometers, 2017). Compared to the year 1959, only half-a-century ago, the world population has doubled, and it is estimated to become 9 billion in the next over 20 years (United Nations Population Division, 2008). High birth-rate and improvement in food production are believed to be the two most important factors constituting this rapid growth. Besides, together with the development of science and technology in medicine, the infant mortality has been reduced considerably. As a result, public health has been improved, and conventionally people can now enjoy even longer life expectancy than in the past. This condition would be so-called *overpopulation* a very popular term nowadays.

Eartheclipse.com (n.d.) defines *overpopulation* as: "Overpopulation is the state whereby the human population rises to an extent exceeding the carrying capacity of the ecological setting". Thus, it would be said overpopulation has been resulting in millions of different issues, in terms of both short-term and long-term effects, predominantly pressing the environment into more stress. Urbanization, production and exploitation activities from humans are contributing to diminishing in environment quality as well as other environment issues. For instance, deforestation, ecological destruction, mass extinction, environmental pollution, and global warming are some common terms which can be heard every day and everywhere through media channels nowadays, but probably even not enough to raise people awareness. We, human beings, have not stopped our destruction activities yet, and we do not have to wait long to see beforehand the consequences. Absolutely, it is no need to wait until next generation, we are already witnessing some results of our cruel actions against nature. Fossil fuels such as oils are running out, which means we will soon have nothing to even lit up bulbs in our room. Air pollution and water pollution are threatening our life every second with many new diseases and cancers which medicals have not found effective remediation. Also, we are now experiencing more and more society problems and conflicts due to the imbalance in development among countries. In brief, although it seems to contradict the outcomes from the devel-

opment, life expectancy will be surprisingly shorter in next generations, where an extinction may totally be possible. If we do not act as soon as possible, "Life expectancy will be the shortest in fastest growing countries." (David E. Bloom, 2011).

1.2 Water Availability on Earth

As a universally accepted truth, water is the most primary and essential element for life to exist. All living species, included human being who is always proud of their intelligence, cannot survive without water. We do not only need water for basic survival as other animals, we even strongly rely on water to take part in all aspects of our life, for example: cooking, taking bath, irrigation and production. Thus, human being is the species who is the most vulnerable to water problems. On this planet, there is just 2.5 % of fresh water beside 97.5 % salt water (Figure 1). In 2.5 % of usable water, groundwater accounts for the most amount we can use directly compared to just 1% of surface water (the largest source is 68.7 % but in ice or glaciers form) (Environmental Canada, 2005).
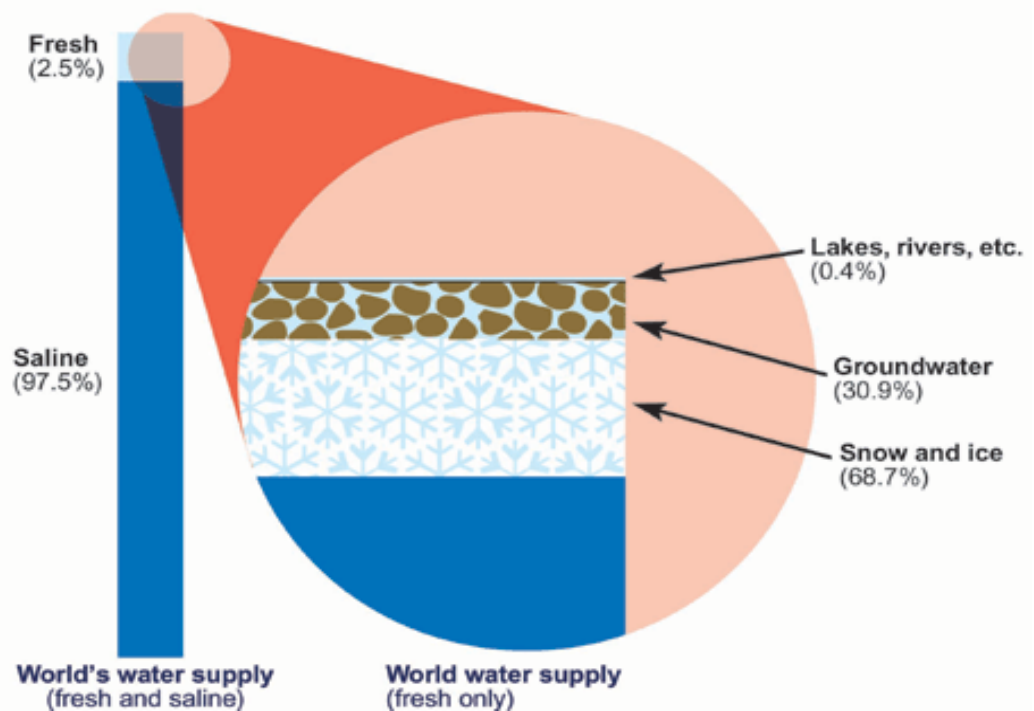
Figure 1.Water availability on earth (Environmental Canada, 2005)

1.3   Overpopulation Resulting in Different Water Issues

Among the previous mentioned consequences caused by overpopulation, those relating to water issues are the most clearly seen and do cause the most adverse effects. As the population increases and the expansion of urban area as well as production activities as described previously, water demand also rises drastically, for both domestic and industrial use. Thus, as a result, demand for wastewater treatment also increases since much more discharge is produced.

Among the environmental factors, the water resources seem to be the most vulnerable one to human activities simply because we are living very near the water sources. The water resources might be very diverse; they are not limitless nevertheless. These days, the water resources are most contaminated by human activities than ever before. Unfortunately, not everyone is aware of water contamination although we are now suffering tons of serious consequences from polluted water. "We never know the worth of water till the well is dry." (Fuller, n.d.). *Water-stress*, the term that refers to a lack of access to clean water sources, are now threatening many parts of the world, especially in Africa and Asia. A total of 37 countries are now facing "extremely high" level of water-stress (Water Resources Institute, 2013). Climate change and over-exploitation are believed to be the two main causes.

The next issue is water contamination. The natural water resources quality is diminishing seriously due to human activities, such as solid waste from municipality, fertilizers and pesticides from agriculture, as well as wastewater from industrial plants without proper treatment directly discharged to nearby lakes or rivers. Once being contaminated, especially the groundwater aquifers, are inevitably very difficult to clean and remediate (Harter, 2012).

Fortunately, we are now more aware of our mistakes. Governments from many countries are increasingly concerned about environment and water-related issues. More legislation and policies have been established to have stricter inspection and effective environmental management. More agreements have been archived to limit and control the waste discharged into environment and water resources. Especially, scientists are making much effort to improve the present water treatment methods as well as innovate new approaches which are more efficient, small footprint, and energy-efficient.

1.4   Overview on Modern Water Treatment Technology

Nowadays, along with the growing demand for water treatment as well as development in technology, we have a variety of choice to select accordant treatment methods, in terms of both potable water treatment and wastewater treatment. Basically, the water treatment methods can be classified into mechanical, physical, chemical, and biological methods. Mechanical methods are screening, sedimentation, and flotation. Physical methods can be filtration and membrane treatment. Popular chemical treatment approaches are coagulation, flocculation, and disinfection. As to biological methods, the conventionally used activated sludge growth, is believed to be the most commonly used method in many wastewater treatment plants. However, in practical application, water treatment is accomplished through the combination of the above-mentioned methods. A typical treatment process consists of many treatment units, each of which is responsible for different roles.

Among the above-mentioned methods, flotation is very widely used nowadays. It is utilized because of its many remarkable advantages. SansOx Ltd has recently developed a new flotation technology, a new way to perform flotation as they emphasized. *VOxFlotation*, as SansOx calls its innovation is expected to totally change the future for water treatment.

2   SansOx Ltd Introduction

Originally, SansOx Limited is a part of the Finnish Cleantech Cluster of companies, which is a very big group of companies in Finland who do business in fields of water treatment and environment technology. After being founded in 2012, SansOx Ltd is growing strongly and becoming one of the most successful start-up companies in Finland with wide vision and clear growth-orientation.

Constantly, SansOx is always trying to create new innovations and solutions, even from old things, in order to develop products that are optimal for the various needs of their customers. Aiming at bringing cost-effective solutions, quality improvement, and genuine added value to customers.

SansOx's main business is to develop innovative applications for intelligent water treatment. SansOx's products are applied very widely in potable water treatment, process

water treatment, and fish farming. Customers of SansOx are global and vary in different industrial branches, mostly water technology and fish farming companies. Some well-known products from SansOx are the OxTube, SaoxFuge, and VOxFlotation. Recently, SansOx has been the double winner of EU Innovation Award: OxTube for 2014 and SaoxFuge for 2015, which are considered as the most highlighted successes SansOx has achieved (Figure 2).

SansOx's current official main office is at Lönnrotinkatu 32 E, 00180 Helsinki.

Figure 2. SansOx Logo (A) and their awards (B) (SansOx Brochure, 2016)

3   Goals and Scope

The objective of this thesis was to examine the influences of different design parameters on the performance of the entire VOxFlotation system, from which the optimum design criteria will be drawn. The reason was believed to be the unreasonable selection of those parameters when designing the system. Thus, in this study, some parameters are varied by some alternative values to see how they affect the system efficiency as well as each other, in a set of experiments so-called *Design of Experiment (DOE)*.

There are many process variables involved in the performance of the flotation system. These variables are temperature, pH, air pressure, water characteristics, and chemical dose. However, it is absolutely too huge for the scope of Bachelor's thesis when taking all those parameters into consideration. Thus, in the scope of this study, some parame-

ters are determined and fixed to be less complicated. In the preparation stage, the synthetic wastewater sample was prepared. The aluminium sulphate coagulant was added into the water to better the process performance. To determine the suitable dose, jartesting was performed.

In the DOE, two quantitative variables in the VOxFlotation design: the diameter of nozzles (X) and the compressed-air pressure (P) were varied to see how those factors have influences on the final Solid Removal Efficiency *(SRE)* as well as their correlation and direction for optimization. The 2^N design was used to design the experiments. All experiments were conducted and carefully inspected at Metropolia Environmental Laboratory, with the support from SansOx and instruction from the principal supervisor.

4 Theory Review

4.1 History of Flotation

The history of flotation comes from a technically stagnant problem in mining industry during 19th century. Klassen and Mokrousov (1963) described flotation as: "…one of the most outstanding achievements in 20th century technology". During the end of 19th century, as the demand for metals substantially increasing on account of the development of heavy industries, the world was running out high-grade ore. Basic technologies for extraction at that time were only gravity methods, which seemed to be impossible and unprofitable when dealing with low-grade ore and waste rocks. This was said to put the mineral industry into stagnant condition and then pose challenge for engineers and scientists to innovate a new approach. Flotation was then invented, as a result of which the history development can be divided into three main stages (Habort, 2010):

From 1860 to 1900
The first commercial flotation plant was built by the Bessel Brothers in Dresden, Germany in 1877 to clean graphite ore (Graichen, 1977). Another flotation plant to process sulfide ore was developed by Carrie Everson, but it was not commercially successful like that of the Bessel Brothers.

From 1900 to 1925

In 1905, the world's first froth flotation was built at Broken Hill, which also brought substantial commercial success. Continuing with those achievements, the United States and Britain also innovated successfully their technology. Without the invention of the froth flotation, nowadays cheap metals such as copper and zinc should have been extremely costly and rare (Bunyak, 2000).

From 1960 to now

Along with the development of science, such as X-ray and radioisotope, several research could be conducted in order to improve and provide a better control and optimization for the flotation process. Nowadays, flotation is not only used in mining industry, but also widely applied in water and wastewater treatment, which is also the main researching scope of this thesis.

4.2   Classification on Flotation Process

Nowadays, flotation application is not only limited to mining industry, but it is also utilized widely in water and wastewater treatment. Actually, there are no absolute benchmarking for classifying the flotation technology. In this thesis, I am going to recommend one plausible. This classified method is on the basis of which purposes/industries the flotation technology is utilized for. On the basis of those criteria, flotation can be divided into two main types: *Mining Flotation* used in mining industry, from which flotation primarily came from; and *Water Flotation*, in which flotation is utilized to treat the water and wastewater. Mining Flotation is commonly Froth Flotation (FF). Water Floatation includes Dissolved-Air-Flotation (DAF) and similarly Induced Gas Flotation (IGF). VOxFlotation from SansOx LTD is also designed basically on the basis of the principles of DAF. Besides, flotation technology is also applied in oil industry, but this is not going to be mentioned in the scope of this thesis.

4.3   Theory Behind Flotation Process

Conceptually, the term *flotation* is named for any concentration processes in which selective hydrophobic materials are separated from hydrophilic materials by 'floating' process (Jameson, 1992). Conventionally, flotation is used to separate the suspended matters (solid and liquid), which are insoluble and poorly settable, from the liquid. In typical flotation process, the particles are adhered onto the air bubbles, which are then floated

into the surface if its density is less then water density and removed. Chemicals such as coagulants can also be utilized to improve the process performance.

Prof. Pylkkänen, Chief Engineer at SansOx Ltd, the creator of VOxFlotation (2016), suggested that the flotation process is absolutely very complicated, but it can comprise three main steps: collision, attachment, and detachment. He also explained the theory behind flotation as follows:

Collision

The collision is achieved by particles being within the *collision tube* of a bubble. The *collision tube* refers to the region in which a particle will collide with the bubble, with the perimeter of the collision tube corresponding to the grazing trajectory. The collision process is influenced by two main factors: *the velocity* and *radius of the bubbles*.

Attachment

The *induction time* will be mainly responsible for the attachment process between particles and bubbles. The particles can adhere to the air bubbles when the time required for them to bind is larger than *induction time,* which is primarily affected by: the fluid viscosity, particles and bubbles size, and the forces between particles and bubbles.

The attachment process could be described by using Young-Duprè Equation (Pylkkänen, 2016):

$$\gamma_{lv} \cos\theta = (\gamma_{sv} - \gamma_{sl}) \qquad (4.1),$$

where:

- γ_{lv} is the surface energy of the liquid/gas vapor interface
- γ_{sv} is the surface energy of the solid/gas vapor interface
- γ_{sl} is the surface energy of the solid/liquid interface,
- θ is the contact angle, the angle formed at the junction between gas, solid, and liquid phases.

Detachment

The detachment process occurs when the force exerted by surface tension is exceeded by shear force and gravitation force. Those forces are actually very complicated and vary depending on the flotation cell. Prof. Pylkkänen (2016) also suggested that high shear will be experienced close to the impeller of a mechanical flotation cell and mostly gravitational force in the collection and cleaning zone of a flotation column.

Collection Efficiency

One parameter which can be used to evaluate the collection efficiency of flotation process is determined as Flotation Recovery (R). This value is presented by the probabilities of collision and attachment of particles to gas bubbles (Pylkkänen, 2016):

$$R = \frac{N_c}{\left(\dfrac{\pi}{4}\right)(d_p + d_b)^2 Hc} \qquad (4.2),$$

whereas:

- $N_C = PN_c^i$ is the product of the probability of the particle being collected, where P is probability and the number of possible particle collision
- d_p is particle diameter
- d_b is bubble diameter
- H is a specified height within the flotation which the recovery was calculated
- c is the particle concentration

4.4 Mining Flotation- Froth Flotation (FF)

4.4.1 Definition

Bunyak (2000) defined in his journal: "The term flotation has been loosely used for all concentration processes in which heavier mineral particles have been disengaged from lighter waste particles in water by "floating" the mineral away from waste".

4.4.2   Common Terms

The Figure 3 illustrates a typical FF unit:
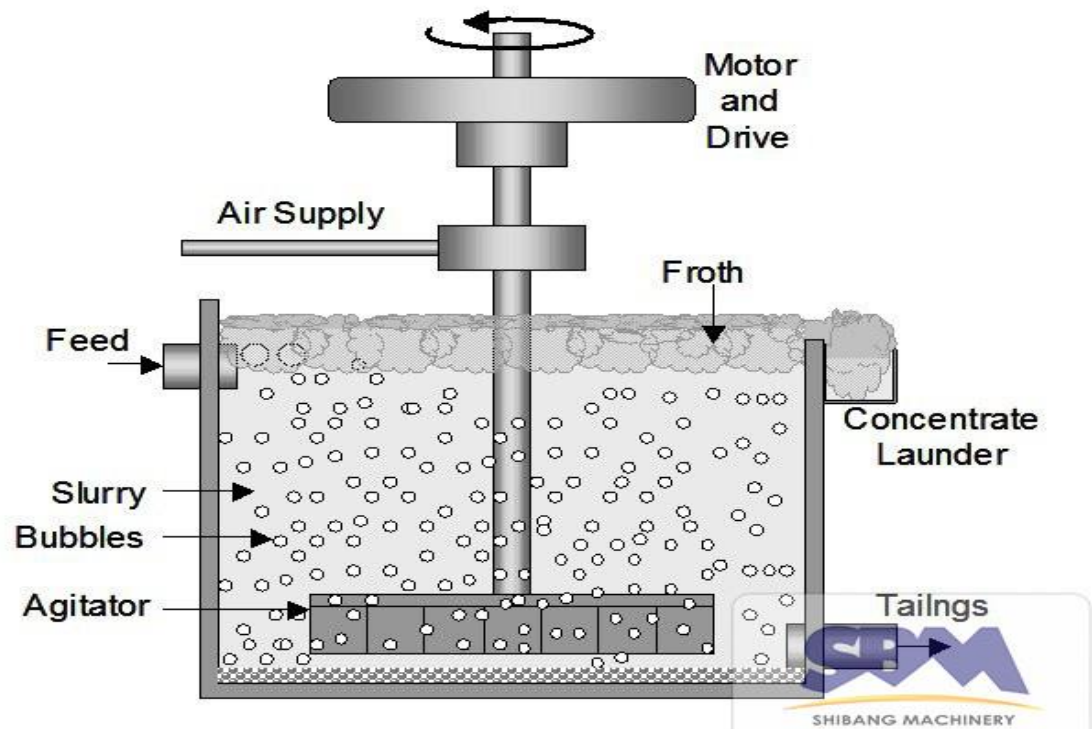
Figure 3. Overview diagram of a typical FF (Shibang Machinery, n.d.)

Concentrators or Mills

It is named for the place where the flotation process is operated in mining industry.

Slurry and Collector

Slurry (Pulp) is the mixture of ground ore and water. By adding the suitable chemicals, which is known as *collector*, the desired minerals can be rendered hydrophobic. For example, sodium ethyl xanthate is used as *collector* in lead and zinc mining.

Flotation cells

Flotation cells are the tanks where the flotation takes place (it is aerated to produce air bubbles for flotation process). This term will be used many times again in this thesis.

Froth and frothers

The particles after attaching the air bubbles are floated into the surface. This is known as *froth*, where the name froth flotation comes from. Frothing agents, known as *frothers*, can be added to make the froth formation on the surface stable.

Concentrate

The froth is then removed from the cells, forming concentrate of the desired minerals, which is also known as *con* in short.

Flotation tailings or flotation tails

They are referred to the materials which do not float onto the surface.

4.4.3 Process Description

Typically, the principles of operation for froth flotation consists of the following main stages:

Crushing (Liberation)

The ore will be crushed into the sufficient size so that the targeted minerals can exist as separate grains. Particularly, the size is around 100 µm, but sometimes it can be smaller than 7-10 µm (Bowen, 1998).

Addition of Chemicals

Particular *collectors* and *frothers* are added to optimize the adherence and concentration process performance.

Air Bubbles Formation

The air bubbles are created by compressed-air and made rise upwards into the surface of the flotation cell together with attached mineral particles to form the froth, which is then collected by skimmer arm.

Collection of Concentrates

The final concentrates are then collected and shipped to smelters. Before this step, the concentrates can be subjected into more flotation stages, known as *cleaning* in order to remove more undesired minerals to make the final concentrates "cleaner" (Bowen, 2013). Meanwhile, a stage called *scavenging* is used for flotation tailings to recover any minerals that does not float.

Flotation is conventionally conducted in several stages to optimize the recovery efficiency of the minerals in the concentrate and minimize the energy input (Pease, 2013).

4.5   Water Flotation- Dissolved-Air Flotation (DAF)

4.5.1   Basic Concept

Beychok (1967) defined:

"Dissolved air flotation (DAF) is a water treatment process that clarifies wastewaters (or other waters) by the removal of suspended matter such as oil or solids. The removal is achieved by dissolving air in the water or wastewater under high pressure and then releasing the air at atmospheric pressure in a flotation tank basin. The released air forms micro bubbles which adhere to the suspended matter causing the suspended matter to float to the surface of the water where it may then be removed by a skimming device."

Basically, DAF looks very identical to the FF principles discussed above, since all kinds of flotation share the same principles. The difference is only the area that flotation is applied, which means which type of materials we would like to concentrate or remove.

In mining industry (FF), the target is to make desired minerals from the ore floated onto the surface to be collected and utilized. Meanwhile, in water treatment (DAF), the objective is to separate the suspended solids (SS) from the water to make it clean. Thus, the floated matters are the waste in this case. Nowadays, DAF is very widely applied in treating the discharge from oil refiners, petrochemical, pulp and paper, and other industries. Historically, and surprisingly, it was Finland where the first DA was used in potable water treatment during the 20s of last century (ADKA and Sveen-Pedersen). Nowadays, DAF is believed to be one of the most widely used water treatment method all over the world, especially in Nordic countries, UK and US. (Nguyen, 2013)

4.5.2 Process Description

Nowadays, a typical DAF seems to be more recirculating than only conventional to optimize the process efficiency. The compressed-air is dissolved in a pressure vessel (air drum) together with a small amount of clean water recycled from the DAF unit by a recycle pump (Figure 4). Those actions result in a saturated air-water solution. This solution is then fed through a pressure-reduction valve into the float tank. Due to the pressure reduction, micro reaction bubbles are formed increasingly and involve in the SS removal process. In the flotation cells design, lamellas structure can be utilized to optimize the process efficiency by increasing separation surface. Also, as *collectors* in FF, coagulation and flocculation can also be used as pre-treatment by adding particular chemicals before the DAF to improve the attachment process.
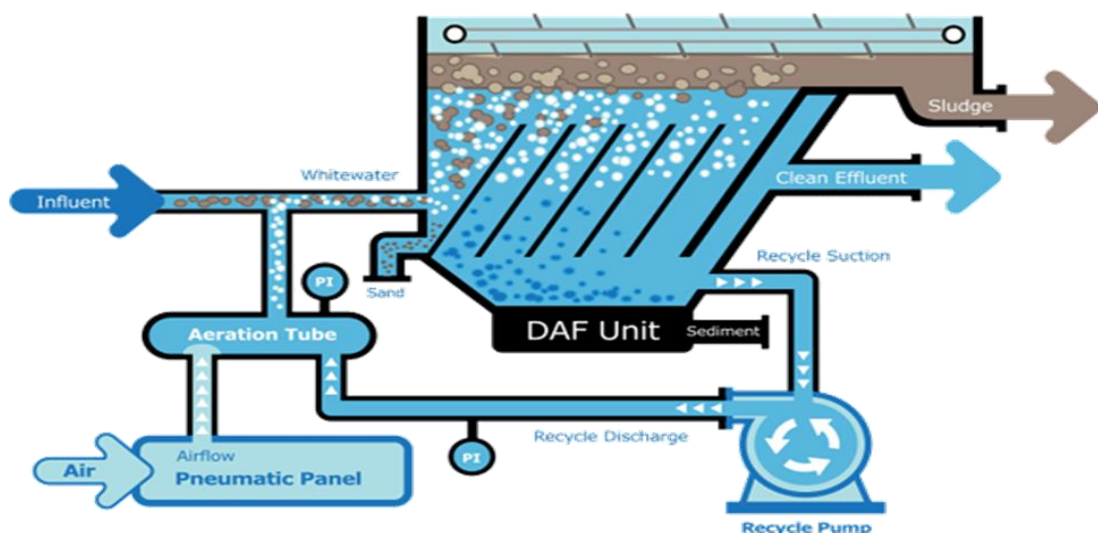
Figure 4. Diagram of a Typical DAF unit (Frcsystem.com, n.d.)

4.5.3   Application

The main function of DAF is to remove SS from the water. It is utilized in clarification after flocculation process, after the aero-tank in activated sludge process, thickening of sludge, or combined with other treatment processes. Compared to sedimentation, DAF is conventionally more alternative.

4.5.4   Design Criteria

Practically, from practical experience, operation parameters and design criteria for DAF can be presented as follow:

Table 1. Operation Parameters for DAF Units (Nguyen, 2014)

No	Parameter	Values
1	Compressed air	3.7- 7 atm
2	Recirculating water rate	30-70%
3	Hydraulic retention time in float tank	20-60 min
4	Surface loading rate	20-325 m3/m2.d
5	Air demand	15-50 L/m3
6	Retention time at pressure vessel	0.5-3 min

The factor Recirculating Water Rate can also be known as Recycle Ratio (RR), which determines the ratio between the recirculating water flow and treated water flow. Study conducted by Han (2007) showed that the higher RR is, the higher DAF efficiency will be. Practically, the RR is conventionally kept at 20% (Nguyen, 2013).

Also, there are other practically important factors which should be carefully considered when designing DAF system. They are supposed to be TSS contents, bubble size and bubble concentration volume, chemical dose, and A/S ratio.

Bubbles and TSS

It is very perspicuous that the fundamental characteristics of bubbles and particles has been studied very carefully as they are certainly two most importance factors contributing to the DAF efficiency. TSS refers to total suspended solids contents and particle size, which is also relevant to the water quality. Bubbles factor consists of bubble size and bubble volume concentration (amount of bubbles).

The control of bubble size and amount is of great important in a DAF system since they directly influence the DAF efficiency. Those values are usually regulated by the compressed-air pressure. Actually, it is very complicated to calculate the optimum bubble size by pure theory. As a rule of thumb, engineers have found out that the bubble size should be in range between 10 μm and 120 μm (mini bubbles), and 40 μm is believed to be the most optimum one (Nguyen, 2013). Besides, apart from the size, the bubbles should be formed stably with large amount (large volume concentration) in order the optimize the attachment and flotation process.

The TSS also plays an important role. Jinho (2007) has found in his study that the larger and larger compared to bubble size the particles size is, the higher the DAF efficiency will be. Apparently, it is not very difficult to understand in this case, as the particles size is larger, the collision and attachment probability between particles themselves and with mini bubbles would increase, which then contributes to improving the DAF efficiency. That is the main reason why chemical pre-treatment is very essential in both sedimentation and flotation, which can make the particles concentrate to form larger flocs, which are then more easily to settle in sedimentation, or float in flotation.

Chemical Dose

As stated above, chemical dose, which involves in coagulation and flocculation process, is strongly recommended before the flotation to improve the performance. The theory behind coagulation and flocculation is very complicated, so it is not necessary to be discussed in detail here. Only one point should be noted that; as has been proven, most of suspended particles in water have negative charge; hence coagulants which can produce positive ions are chosen. Nowadays, three coagulation agents are most preferred: aluminum salt, ferric salt, and PAC. The amount of coagulant added depends on the TSS concentration in water. Besides, each type of coagulants has their specific conditions where they perform best: pH, dosing amount, and mixing speed. That is the reason why those factors are also very important in a DAF process; thus a number of pre-tests should be conducted to determine suitable values. Those tests are usually known as *jar-testing*.

Aluminum coagulation agents are aluminum salt, conventionally $Al_2(SO4)_3.18H_2O$. When using aluminum coagulant, pH should be in range 5.5-7.5 and temperature is between 20-40°C. Highlighted feasibilities from aluminum coagulant are low-cost and easy to use.

Ferric coagulant is usually $FeCl_3$ or $FeSO_4.nH_2O$ (n=1-6). Best pH range for ferric agent is 5-9. One positive point of ferric compared to aluminum agent is that ferric agent is less influenced by the pH as its pH range is very wide. However, one disadvantage for both ferric and aluminum coagulant is they change the pH of the water a bit due to hydrolysis.

The final coagulant is Poly Aluminum Chloride, an inorganic polymer, known as PAC. It is also the most widely used coagulant nowadays due to its more outstanding character-istics compared to traditional one such as aluminum or ferric salt. PAC has been proven to achieve 4-5 times better efficiency compared to any other coagulants. Also, PAC does not change the pH of water considerably as ferric and aluminum agents do. In reality, PAC is usually used together with Poly Acrylic Acid (PAA) as coagulant aid. As a rule of thumb, 1.2-4.5 g PAC should be dosed per 1 kg TSS in water.

A/S Ratio

A/S Ratio, meaning for Air to Solid Ratio, is calculation of how much air is being applied to a given amount of suspended solid within the DAF process (Ward, 2011). Thus, A/S Ratio can be expressed as mL air/mL solid, or mg air/mg solid.

Unfortunately, there are no fixed theoretical values for A/S Ratio, which considerably depends of type of solids as well as the DAF system itself. This parameter can be deter-mined by practical experiments. The following formula is suggested for calculating A/S in case of non-recirculating DAF system (Ward, 2011):

$$\frac{A}{S} = \frac{C_S \left(\frac{f.P}{1atm} - 1 \right)}{X_o} \qquad (4.3),$$

whereas:

- C_s = saturation value for dissolved air at 1 atm pressure (mg/L)
- P = operating pressure of pressure chamber (atm)
- f = fraction of saturation achieved in pressure chamber (0.5-0.8)
- X_o = suspended solids content of feed (mg/L)

In case of recirculating DAF system, the formula as follows:

$$\frac{A}{S} = \frac{C_S . R \left(\dfrac{f.P}{1atm} - 1 \right)}{Q_o X_o}$$

(4.4),

- Q_o = feed flow rate (L/min)
- R = recycle flow rate (L/min)

In recirculating system, as a rule of thumb, typical value for A/S is 0.01-0.1.

4.5.5   Advantages and Disadvantages

Compared to sedimentation, as also a popular solid removal process in water treatment, advantages and disadvantages of DAF are highlighted in the table below:

Table 2. Pros and cons of DAF system compared to sedimentation (Nguyen, 2014)

Advantages	Disadvantages
- Continuous process, widely used - Higher SS-removal rate than sedimentation, waste sludge produced with lower moisture - SS-removal up to 90-95% - Small footprint and time-saving - Low investment/ operational cost	- Efficiency strongly influenced by temperature, pressure…and technical requirements when operating - Not efficiently when temperature is larger than 40ºC

4.6   Induced Gas Flotation (IGF)

Actually, the principles of IGF is mostly similar to DAF. The difference is only, in case of potentially hydrocarbon-rich environment that could increase the risk of explosion due to presence of oxygen, natural gas is induced instead of normal air.

4.7 VOxFlotation

4.7.1 Overview

VOxFlotation, standing for, is new flotation technology invented by Prof. Pylkkänen, Chief Engineer at SansOx Ltd. Basically, VOxFlotation shares the basic principles with traditional DAF, but it is expected to be much more innovative, cost-effective, and energy-saving. SansOx Ltd has proudly stated that VOxFlotation can expectedly change the way to perform flotation in future water treatment.

Particularly, VOxFlotation is a part of a larger SansOx system, which is known as VOxSton system, which is capable of treating and recycling process wastewater effectively. This system is the combination of all SansOx products and considered as the most important brainchild of SansOx Ltd. However, on account of issue of business secret, detailed technical information regarding to VOxFlotation is very limited in this thesis. Only few general descriptions and illustrations are presented. Figure 5 shows an overview of the system.
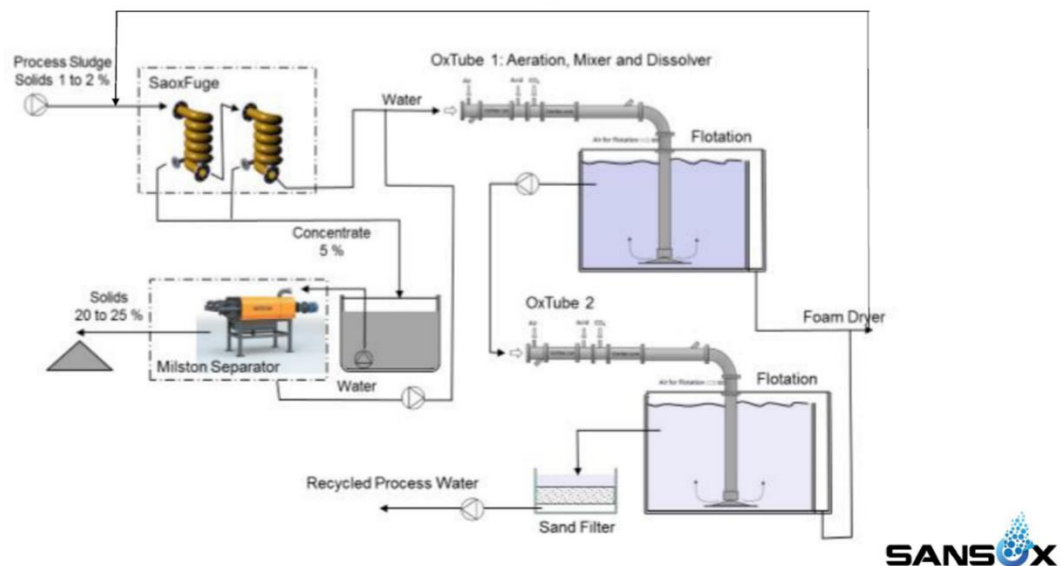
Figure 5. Overall VOxSton system and VOxFlotation system (right-hand-side part) (SansOx Brochure, 2016)

4.7.2 Process Description

Figure 6 below shows diagram of a typical VOxFlotation unit:
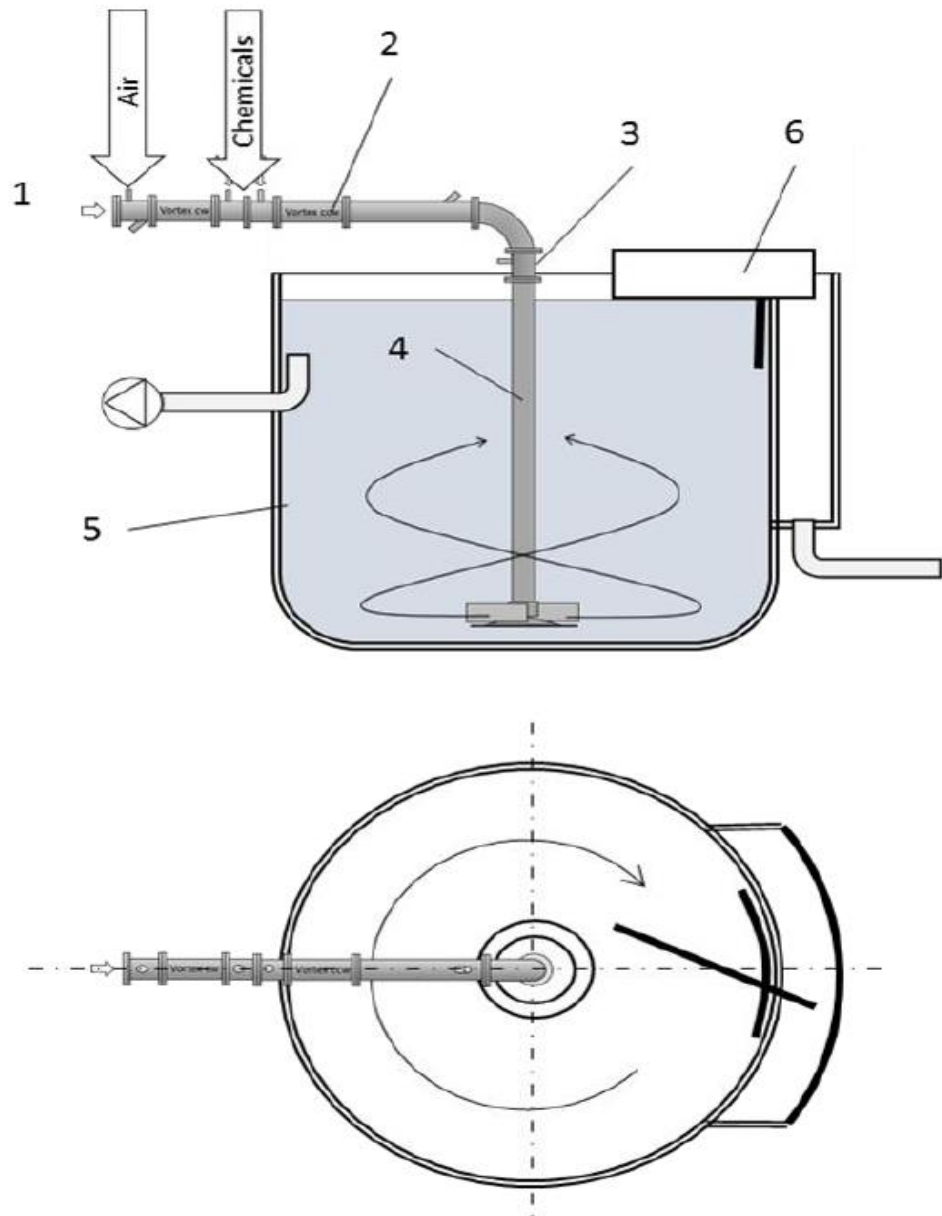
Figure 6. Diagram of a single VOxFlotation Unit (section view and plan view) (SansOx Brochure, 2016)

1. Liquid intake, 2. Feed, mixing and dissolving of additives by OxTube, 3. Additional flotation gas feed, 4. Vortex flow pipe of the treated liquid, 5. Flotation with round corners, 6. Foam scraping wing with height control

A brief process description is taken from SansOx technical paper as follows:

"Separation developed by SansOx is a unique separation method in which the liquid flows with the particles continuously in a vortex path, the gas bubbles are formed in inlet of the liquid flow and in the vortex flotation flow, the bubbles spin and cross the vortex liquid flow in optimal angle, the particles in the vortex flow stick gently on the spinning gas bubbles and are transferred to the cell surface.

The liquid is treated before the vortex flotation phase by the OxTube of SansOx. The treatment consists of gas and chemicals feed and mixing, gas dissolving and additional compressed-air feed if needed for additional air bubbles. The treatment is done continuously and fast in terms of seconds by the OxTube process that mixes chemicals, e.g. coagulants, dissolves gases, e.g. oxygen in to the liquid, and generates plenty of flocs and micro bubbles of air and reaction gases directly in to the flowing liquid."

Also, two or more VOxFlotation units can be combined to make a parallel system when needed as follows (Figure 7):

VOX – Flotation, new idea for Separation
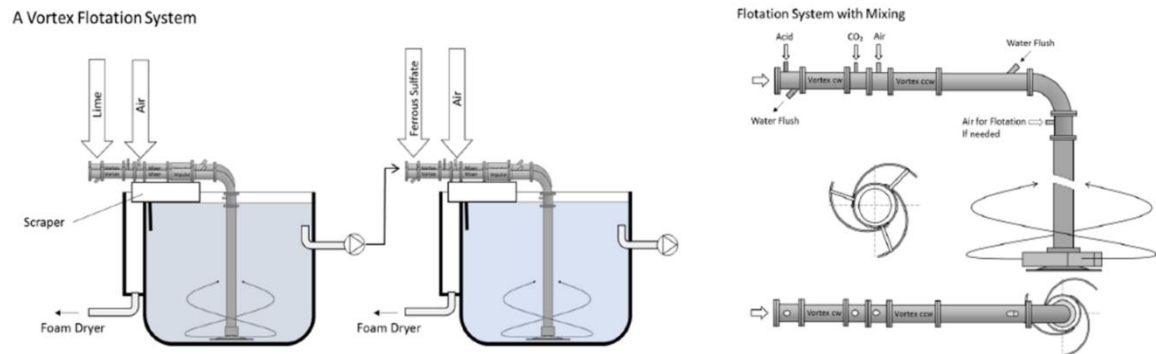
Figure 7. Parallel-DAF system with two combined single units (SansOx Brochure, 2016)

4.7.3   OxTube

As we can see from the process description, OxTube is the most important component in the system. Firstly, its function is to aerate the water and dissolve the oxygen into it, which is the most important step in a flotation process. Well-aerated water not only makes flotation more efficient but also helps prevent bacteria-growth and reduction of DO (Dissolved Oxygen). Also, chemicals such as coagulants are also fed into the injectors on OxTube, where they would be continuously dissolved and mixed. Continuous aerating, dissolving, and mixing are three most important performance conducted by the OxTube, which are also the key to success of entire VOxFlotation system. As mentioned above, OxTube is one in two most famous products supplied by SansOx Ltd (the other is the SaoxFuge) which won the EU awards in 2014 and 2015. Therefore, OxTube is mainly applied in fish and shrimp farming to supply the oxygen into the water due to its superior performance in air dissolving. Nevertheless, the innovation of VOxFlotation, suggests that we can see that OxTube can even do much more when being applied in water treatment. Figure 8 presents the design of the OxTube and Figure 9 depicts the aerated water flow from the OxTube.

Gas Ejector/feed Module
Gas Ejector/feed
Dispersion
Gas Ejector/feed Module
Impulse Module
Micro Bubbling Module
Gas Ejector/feed Module
Shelter Flange
Vortex
Water Flush Cleaning
Flush Water Out

- Fast aeration for higher dissolved oxygen concentration
- Efficient mixing of gas and liquid
- Feed via Ejector/feed Module
- Sufficient flow rate creates air suction through ejectors
- It can be cleaned with water flush
- The cartridges can be washed and changed quickly
- Modular Structure
- It can be tailored to fulfill customer needs

Figure 8. OxTube Design (SansOx Brochure, 2016)

Normal Water Flow

OxTube Aerated Water Flow

Figure 9. Performance of OxTube in air dissolving (SansOx Brochure, 2016)

4.7.4   General Evaluation

Some highlighted points in evaluation on VOxFlotation is also given in SansOx technical paper:

"

- The liquid is flowing without stopping through mixing, dissolving and flotation separation that increases performance and decreases energy consumption
- The bubbles are evenly distributed and small in size, average bubble diameter of 0.1 mm (100 μm, as typical bubble size for effective DAF)
- There are mixture of air and reaction gas bubbles in the liquid flow that increases separation performance
- The vortex flow turns bubbles and solids towards the main stream that reduces impact of shear and gravitational forces on the detachment
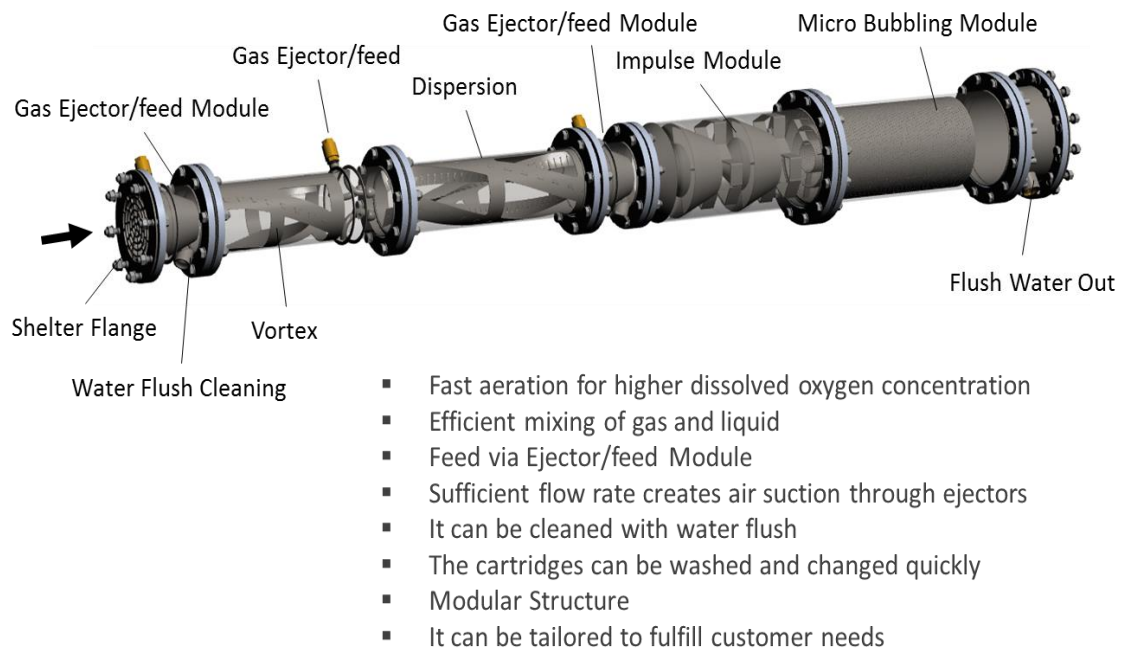- The vortex flow in the flotation cell provides the induction time enough for attachment of the particle to the bubble while the cell size is reduced
- The vortex flow in the flotation cell generates the spinning effect of the bubbles and solids that increases the attachment performance".

In brief, there are three main features contributing the superior performance of VOxFlotation. Firstly, it is the performance of the OxTube, which can be considered as the "all-in-one feature". As we see, in traditional DAF system, there are many stages such as chemical addition, air supply, and mixing, all of which are now done in one stage of OxTube. Apparently, it helps save more spaces, cost, time, water and energy. Thus, we can say that VOxFlotation is small footprint, energy-efficient and cost-saving. Secondly, it is the role of vortex flow in distributing the bubbles, attaching the particles, and optimizing the flotation efficiency. Finally, due to module design, all parts in VOxFlotation are easily to be installed, uninstalled, and replaced when needed. Hence, it would also save cost and time for fixing and maintenance. The highlights presented above indicate that there is clear evidence to expect that VOxFlotation is absolutely going to become a model for sustainable water treatment and recycling in future.

4.8   Water analysis parameters

Water characteristics is of great important since they have considerable influences on human health. Moreover, the water quality also affects the treatment efficiency, as different treatment technologies for different contaminants demand for different conditions.

The water characteristics can be determined by three categories: physical, chemical, and biological properties. Physical properties are temperature, pH, colour, turbidity, viscosity, taste and odor. Chemical properties are chemicals content in water, such as: phosphorus, nitrogen, metals, BOD, COD, TDS and TSS. Meanwhile, biological properties relate to microorganisms present in water. Absolutely, the swamp water sample used in this thesis, which is originally the natural surface water, usually contains less contaminants than concentrated domestic or industrial wastewater, which conventionally requires for simpler treatment process.

Temperature and pH

Temperature and pH are two most primarily important in any water treatment processes. For example, in activated sludge utilizing aerotank, the most popular wastewater treatment method, those parameters are alternatively 20-35ºC and 6.5-8 (Tran, 1999). In the flotation process, temperature and pH are also important as they require for chemical pre-treatment when adding coagulants before flotation.

Viscosity

The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress or tensile stress (Merriam-Webster Dictionary). For a flotation process to be effective, the viscosity of water at specific temperature should be known (Prof. Pylkkänen, 2016).

Turbidity and TSS

Turbidity and total suspended solids (TSS) are the most conventionally parameters to evaluate clarity of water. However, they are also usually mistaken and misunderstood because of not understanding the concept. TSS are particles that are larger than 2 microns found in the water column. In contrast, anything smaller than 2 microns (average filter size) is considered a dissolved solid (TDS) (Perlman, 2014). Thus, TSS is measurement of a matter in water, like BOD, COD, or total phosphorus, and is expressed as mg/L. Meanwhile, the turbidity of water is on the basis of the amount of light scattered by particles in the water column. Thus, turbidity measurements are often used as an indicator of water quality on the basis of clarity and estimated total suspended solids in water (Anderson, 2005). However, although turbidity can be used to estimate the TSS and water clarity, it is not very precise compared to the exact TSS measurement. Also, in case the matters in water has color, the estimated on the basis of turbidity might be falsified. Notwithstanding, the procedures for measuring turbidity are much simpler,

which requires only a turbidity meter, whereas the analysis of TSS requires much more complicated procedure. Hence, in this thesis, the turbidity is used as the response variable to calculate the removal efficiency.

5 Experimentation

5.1 Synthetic Wastewater Sample Preparation

At first, the swamp water sample had been planned to be used. However, due to the heavy winter condition in Finland, it was nearly impossible to collect a huge amount of swamp water required for experiments since most of lakes and rivers were still freeze at that time. Hence, a decision was made to use synthetic wastewater. With the synthetic wastewater, which was nearly unlimited in the amount, the condition was then more flexible and controllable.

Procedure for making the synthetic wastewater sample was very simple. An amount of garden soil was added into the clean tap water and mixed simultaneously. Those solids would act as the suspended solids presented in swamp water, which created the turbidity. The corresponding turbidity would be in range 15-50 NTU.

5.2 Wastewater Sample Analysis and Jar-testing Procedure

5.2.1 pH

To measure the pH, the Mettler Toledo device with pH-sensor was used (Figure 10). pH is of great important as it directly affects the performance of coagulation and flocculation process, which then influence the flotation efficiency (section 4.5.4).

5.2.2 Turbidity

Turbidity is the most important key parameter, as it is response variable of the DOE. HI 88713 - ISO Turbidimeter was used to measure the turbidity (Figure 10). For every experiment, the turbidity of wastewater sample was measured before and after experiment.

For each analysis, 5 samples were collected, analyzed, and the results were analyzed to have the precise measurements.

Figure 10. pH-sensor (A) and turbidity meter (B)

5.2.3 Jar-Testing Procedure

Before the flotation, chemical pre-treatment with the sample was utilized to make the flocs bigger and better for floating (section 4.5.4). The purpose of jar-testing experiment was to determine the best chemical dose for the sample. The coagulant used in this thesis was aluminum sulfate $Al_2(SO_4)_3.7H_2O$. The ferric sulfate salt was avoided since it made the solution yellowish. The device to perform jar-testing is Lovibond floc-tester (Figure 11). The procedure for jar-testing is described as follows:

Firstly, the wastewater sample was mixed well to make it homogeneous. Then, four 800-mL beakers were prepared with 500 mL of wastewater sample in every beaker and number them from 1 to 4. Aluminum sulfate mother-solution 1000 mg/L was prepared by dissolving 0.5 g of aluminum sulfate salt in 500 mL water in 500 mL-volumetric flask. Next, a suitable volume of this solution was added to every beaker with suitable pipettes so that the concentrations would be correspondingly 15 mg/L, 20 mg/L, 30 mg/L, and 40 mg/L. By simply using the formula C1*V1=C2*V2, the adding volume could be calculated as given in the table 3.

Table 3. Adding volume of ferric sulfate for each beaker

Beaker No	1	2	3	4
C (mg/L)	15	20	30	40
V added (mL)	7.5	10	15	20

The samples temperature was 25°C. Importantly, the pH must be adjusted between 5.5 and 7.5 by adding few drops of 0.1 M sulfuric acid or sodium hydroxide, which could be checked by the pH meter (section 5.2.1). In the next stage, we adjusted the jar-testing device with speed 20 rpm and time 10 min. After all, we let the stirring begin and observe the process. After 10 min of stirring, samples were let be there for another 10 min for the sedimentation and stabilization. Finally, we could observe the four beakers and make the conclusion.

Figure 11. Lovibond jar-testing device

5.3 VOxFlotation System Components

5.3.1 Assembling the OxTube

Because of module-design, the OxTube contains many smaller modules, which must be assembled carefully in correct order according to instruction from SansOx. Otherwise, it will not work. The exact assembling for the OxTube is shown in the Figure 12. The Ox-Tube used in experiment was OxTube DN25. The OxTube is the key component in VOxFlotation, which is decisive in main operation of the whole system.

Figure 12. Assembling the OxTube

5.3.2 Flotation Cell

Previously, there had been a plan to manufacture the standard flotation cell and other parts. However, the time was limited and the manufacturing time was too long. Finally, a large plastic bucket was utilized to stimulate the flotation cell. Although it was not designed as standard, it was still good enough to stimulate the required shape of flotation cell, the cylinder-shape (Figure 13). The idea of cylinder-shape is necessary for the flotation process based on vortex flow is referred to the design of flotation cell from Outotec Company and Metso Company. Dimensioning for the flotation cell was 52 cm in height (H = 52 cm) and 45 cm in diameter (D=45 cm) of cross section area.

5.3.3 Pump

The pump used was an electricity small submerged garden pump, which could deliver a minimum flow rate more than 0.75 L/s (Figure 13). Below this value, the VOxFlotation would not work precisely due to SansOx material.

Figure 13. Flotation Cell (A) and Pump with maximum 7500 L/h- 400W-500 m (B)

This pump was controlled by a float (usually turning the pump on/off by changing the float direction due to water level), which was actually done manually in this case. Also, diaphragm pump is not preferred, as it creates many pulses during operation, which can disturb the process performance.

5.3.4 Nozzles

Nozzles are the final parts installed to the end of OxTube, from which the water comes out and enters the flotation cell from the bottom (Figure 14). Like the OxTube, nozzles are also the most important part in the system which determine how the vortex flow performs in the flotation cell. At first, the nozzles had been planned to be manufactured according to a standard design. However, with limited time, a combination of tee, elbow90s, couplings and pipe nipples were utilized to make the nozzles. The nipples and reducers were then used to vary the output diameter of the nozzles (Figure 14). The nozzles were installed in the way that their directions were downward into the cell bottom and created a 30°-angle with the horizontal surface. The purpose of this action was to ensure all the solids settled down at the bottom would be blown away with the vortex flow.

5.3.5 Compressed-Air

As planned, the DOE was performed in case of free-suction and with compressed-air. In the second case, the compressed-air was supplied into to the injection module on the OxTube at 0.2 MPa from the laboratory air-line system. An air-flow meter was also installed to measure the pressure inside the OxTube and regulate the air flow rate Q_{air} at about 3-4 NL/min in both cases (Figure 14).

It should be noted that, in any cases without or with compressed-air, the pressure inside the OxTube must be less than 0.5 bar. Otherwise, the pump would not work since the maximum head it could pump was 5 meters (about 0.5 bar) as technical data shown in Figure 13.

Figure 14. Nozzles (A), nipples and reducers (B), and air-flow meter (C)

5.3.6   Chemical Feed

Due to lack of mechanical mixing device, chemical should not be added in the wastewater sample tank. Moreover, the flocs could be broken by the pump during operation as experience from SansOx last experiments. Fortunately, the OxTube is also outstandingly designed for adding and mixing the chemicals continuously, which can save time and cost from traditional feeding and mixing approaches. The coagulant was fed into other injectors on the injection module continuously during the experiment process, after the dose and the dosing rate had been determined (Figure 15). Actually, a chemical pump should be used to have precise dosing rate. However, due to limited conditions, it was controlled manually and relatively by general measurement and human sense.
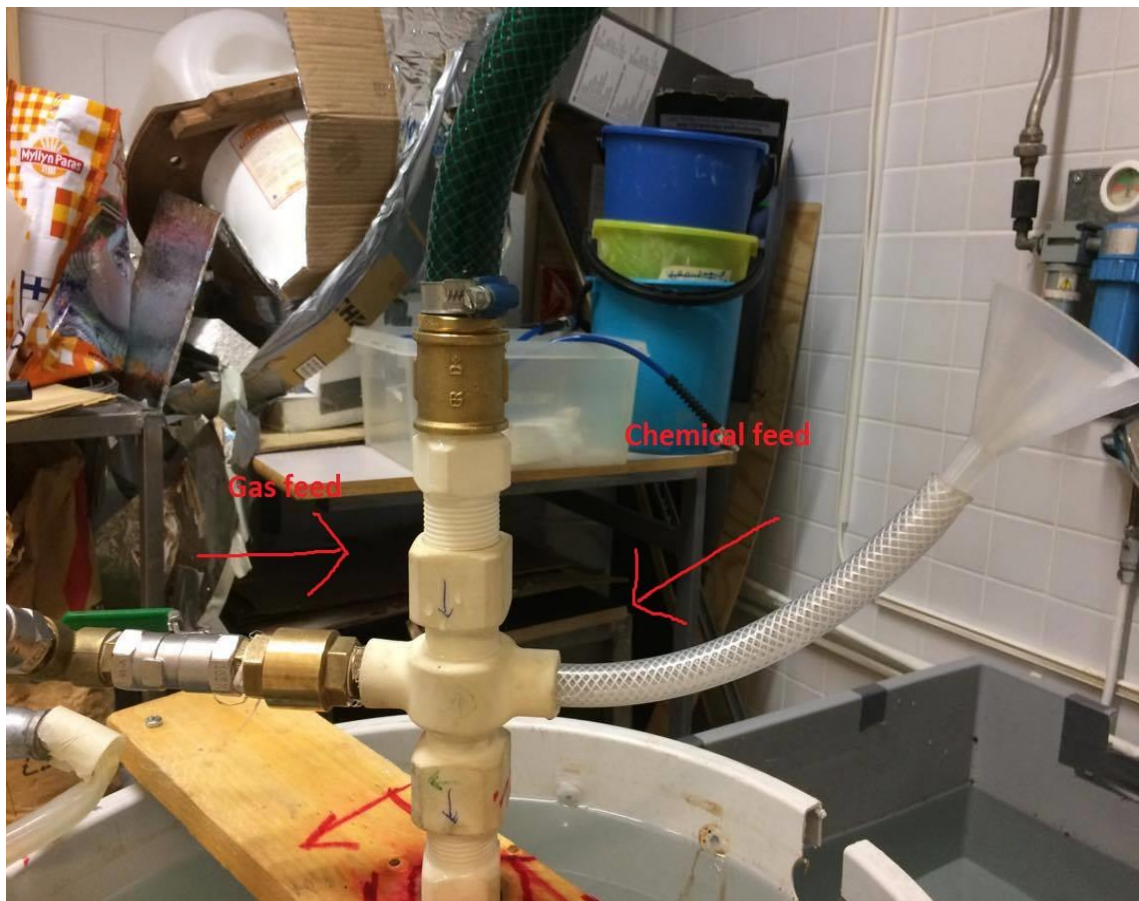
Figure 15. Chemical feed and gas feed

5.3.7   Pipes and Other Tools

Apart from the previously mentioned components, water pipe DN25 and other tools were also needed to connect the components and fix the system.

5.4   VOxFlotation System Design

After all the components were ready, they were installed, fixed, and connected to create a completed system. The OxTube was fixed as the central part of the flotation cell, along the cell height to the bottom so that a part of it was submerged under water during operation while the injection module was still above. The nozzles were installed at the end of OxTube near the bottom cell so that the water flow with air bubbles could enter the flotation cell from the bottom and moved vortex upwards. The pump was installed in the way that it could deliver water from wastewater sample tank to the flotation cell through the OxTube. Those components were connected by water pipe DN25 and with suitable fittings where needed. In brief, the completed flotation part with components can be shown clearly in Figure 16.

Figure 16. Flotation part with section view (A) and plan view (B)

5.5   Weir and Effluent Design

Weir and effluent design is a special structure designed to take the final effluent based on the design utilized in practical sedimentation or flotation tanks. Apparently, taking samples from the upper-flow was not an optimum option since the floating solids on the surface were not concentrated at a specific point and probably escape with the outflow due to a lack of skimming device. Thus, one alternative possibility is to collect the effluent at another point below the surface. A weir and effluent design to collect the effluent is shown as follows in Figure 17.

Particularly, when the water level increased within the flotation cell and was about to reach the surface, a part of water flow also passed the weir wall and ran into the collecting point. Due to the larger velocity of rising bubbles compared the effluent velocity, the solids could not escape with the effluent and they continued to float onto the surface. One should be noted that the effluent flow should not adjusted too fast, which could take the solids escaping with it.

Figure 17. Weir and effluent design with section view (A) and plan view (B)

5.6 Experiment Description

Figure 18 illustrates how the completed VOxFlotation system looks like:

Figure 18. VOxFlotation system overiew

The wastewater sample was first prepared in the wastewater sample tank, the initial turbidity was measured and the pH was adjusted. Before the experiment, all components should be checked carefully, and it should be ensured that there were no water leaking points. During the experiment, the pump submerged in the wastewater tank delivered the water through the OxTube, on which the chemical was added and air flow rate was adjusted. The main flotation process took place in the flotation cell. The vortex flow moved within the cell, with thousands of micro-bubbles escaping from the nozzles at the 37°-angle, attaching the solids and floating them onto the surface. The water level increased in the tank, and the upper-flow escaped from the top of the flotation. Finally, the effluent collection point was opened, at which the final effluent was collected and the final turbidity was analyzed. Every experiment took approximately 2 min.

5.7 System Variables Formulas

Flotation Cell Volume (V)

The Flotation Cell has a cylinder shape. The formula for calculating volume of the cell is shown as follows:

$$V = \pi \frac{D^2}{4} H \text{ ,}$$

(5.1)

- Whereas *D* is the cell diameter and *H* is the cell height.

Hydraulic Detention Time or Flotation Time (t)

Hydraulic Detention Time determines how long the water remains in the flotation cell. It is also the Flotation Time of the system. This parameter can be calculated as follows:

$$t = \frac{V}{Q} \text{ ,}$$

(5.2)

Nozzle Water Velocity (v)

Please note that there are two output nozzles, for which the water flow rate from each nozzle will be halved from the original flow rate Q. Thus, each nozzle velocity is calculated as follows:

$$v = \frac{2Q}{\pi d^2} \text{ ,}$$

(5.3)

- Whereas *Q* is water flow rate *d* is the diameter of the nozzles. Two types of nozzles were used, DN25 and DN32.

Hydraulic Loading Rate (HLR)

Hydraulic Loading Rate determines the volume of upper-flow water applied to the surface in a unit of time.

HLR can be calculated as follows:

$$HLR = \frac{4Q}{\pi D^2} ,$$ (5.4)

Chemical Dosing Rate (DR)

Chemical Dosing Rate could be calculated as follows:

$$DR = \frac{QC}{C_o} ,$$ (5.5)

- Whereas C is desired dose concentration from jar-testing (40 mg/L) and C_o is the concentration of feeding solution (5000 mg/L).

Solid Removal Efficiency (SRE)

Solid Removal Efficiency determines how clear the water will be after the flotation. SRE can be calculated as follows:

$$SRE = \frac{NTU_i - NTU_f}{NTU_i} \times 100\% ,$$ (5.6)

- Whereas NTU_i is the turbidity of the influent and NTU_f is the turbidity of the final effluent.

5.8   Design of Experiment (DOE)

5.8.1   General Introduction to Mathematical Modelling

Regression is a powerful tool to analyse the experimental results in case our desired model contain only *continuous variable*s, such as: pH, temperature, and pressure (Veli, 2015). Among different types of designs, the two-level design (2^N-design) is believed to be one of the most favoured design as it is very fast and cost-effective. The 2^N-design is very useful to build the model and analyse influences among different variables as well as their interactions and direction for optimizing the process. Based on this, another type of design can be utilized later on to optimize the process performance.

5.8.2   Design of Experiment (DOE)

In the DOE of this thesis, two quantitative variables in the VOxFlotation design: the diameter of nozzles (X) and the compressed-air pressure (P) are varied to see how those factors have influences on the response variable Solid Removal Efficiency (SRE) as well as their correlation. In this case, the used design was 2^N design (N=2). There are two levels of each variable, which makes up to 2*2= 4 experiments. However, two replicates should be made per experiment. This created 8 experiments in total. All the experiments should be conducted in random order to guarantee the statistical independence of the experimental errors.

The two qualitative variables can be written in the following form: X (25,32) and P (0,0.2). The table 4 illustrates how the DOE should look like:

Table 4. Design of Experiment in physical unit

No	X (mm)	P (MPa)
1	25	0
2	25	0.2
3	25	0
4	32	0.2
5	32	0
6	25	0.2
7	32	0.2
8	32	0

Based on the experimental results, a liner plus pair-wise interaction model was created to achieve the desire outcomes. The equation for this model could be expressed as fol-lows:

$$SRE = \beta + \beta_X * X + \beta_P * P + \beta_{XP} * X * P \text{, (5.7)}$$

Whereas:

- X,P: two quantitative variables
- SRE: response variable
- β, β_X, β_P, β_{XP}: model coefficients

It should be noted that the term X*P in the Equation 5.7 illustrates the interaction between two variables. However, very importantly, in order to create the model, all variables should be coded unit. Hence, the design table in coded unit should like Table 5 below:

Table 5. Design of Experiment in coded unit

No	X	P
1	-1	-1
2	-1	1
3	-1	-1
4	1	1
5	1	-1
6	-1	1
7	1	1
8	1	-1

6   Results and Analysis

6.1   Process Variables

Flow rate, pressure, and other process variables which were approximately measured or calculated based on the formula in section 5.6 are shown in Table 6 as follows:

Table 6. System variables (all units were conversed accordantly during calculation)

Variable	Value	Unit
Q	1.4	L/s
$P_{compressed-air}$	0.2	MPa
Q_{air}	3-4	NL/min air
H	52	cm
D	45	cm
V (formula 5.1)	80	L
t (formula 5.2)	1	min
v_{DN25}(formula 5.3)	1.4	m/s
v_{DN32}(formula 5.3)	0.9	m/s
HLR (formula 5.4)	8.8 x 10^-3	$m^3/m^2.s$
DR (formula 5.5)	0.7	L/min

6.2   Jar-Testing Results

The results from observing jar-testing showed that Beaker 4 (with the largest coagulant dose) performed the best flocculation, while the result of Beaker 1 was the poorest. Hence, the dose 40 mg/L was selected.

6.3   DOE Results

6.3.1   Interpretation

The experimental results are given in Table 7:

Table 7. Experimental results

No	X	P	SRE (%) (equation 5.5)
1	-1	-1	40.6
2	-1	1	47.3
3	-1	-1	41.2
4	1	1	**54.2**
5	1	-1	43.2
6	-1	1	46.8
7	1	1	53.0
8	1	-1	44

Obviously, we can see that the designed VOxFlotation system has performed an average removal efficiency from the influent with varying turbidity. The best removal efficiency was achieved at DN32 and 0.2 MPa (54.2%).

The R-Studio software was utilized to analyse the given results. In order to create and summarize the model conveniently, a powerful tool called *DOE_function* was applied. This function is developed and applied with the permission by Mr.Veli-Matti, Applied Mathematics Lecturer at Metropolia. The model summary printed from R-command is given below:

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept)  46.2875     0.2050 225.776 2.31e-09 ***
X             2.3125     0.2050  11.280 0.000352 ***
P             4.0375     0.2050  19.694 3.92e-05 ***
I(X * P)      0.9625     0.2050   4.695 0.009345 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

s: 0.5799 on 4 degrees of freedom
Multiple R-squared: 0.9926,
Adjusted R-squared: 0.9871
F-statistic:   179 on 3 and 4 DF, p-value: 0.0001022
```

From this summary, several conclusions can be drawn based on some specific data with level of significance 0.05:

- P-value

There are two types of p-value which should be noted. The first one is p-value=0.0001020, which is much less than 0.05. Hence, there are clearly significant relations among variables. The second one is the Pr value. From the summary, it is obviously seen that all the terms are strongly significant, including the interaction term.

- Adjusted R-squared:

The adjusted R-squared 0.9871 (98.71%) shows that our model is very good.

- Residuals Standard Error:

Residual Standard Error is s=0.5799. In a good regression, this value should be close to the repeatability error of experiments (Veli, 2014). However, in this case, it is also the repeatability error of experiments because lack-of-fit test could not be conducted (discussed later in chapter 6).

In brief, our model can be expressed as following equation:

$$SRE = 46.2875 + 2.3125 * X + 4.0375 * P + 0.9625 * X * P$$

, (5.7)

Again, please note that X and P must be in coded unit.

6.3.2 Data Plotting and Pair-wise Interaction Analysis

From the above section, we have learnt that all the variables have significant influences on the removal efficiency. Moreover, there is a clear interaction between variables. We are also interested in this interaction term. In order to illustrate how the reaction direction and interaction perform, some useful plots should be made for our model.

The first one is called *contour plots*. Contour plots illustrate the plot for three variables in 2-D viewing (David, n.d.). Fortunately, the *DOE_function* also allows to make the contour plot easily.

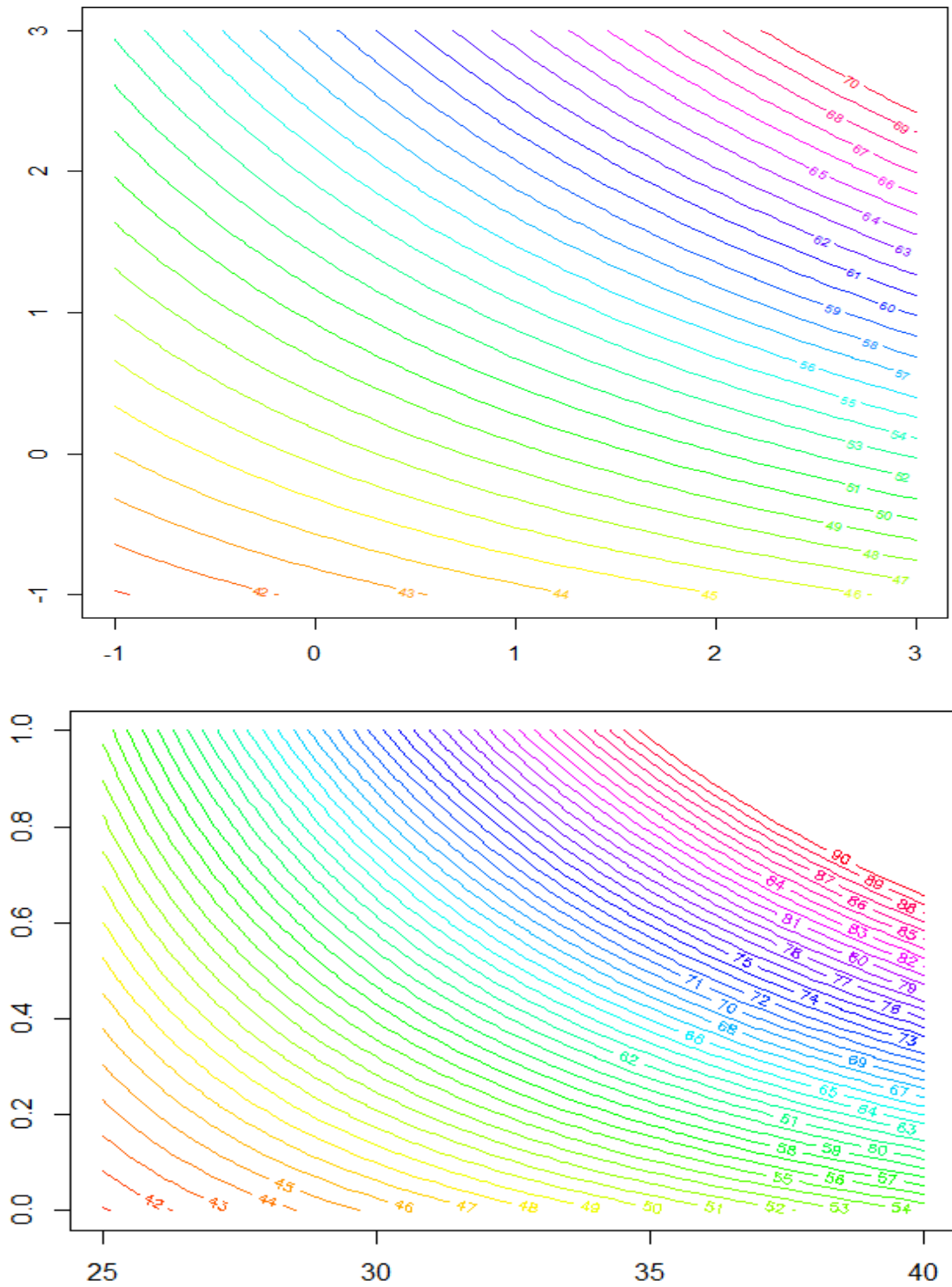The plots in both coded unit and physical unit can be shown as follows:

Figure 19. Contour plot for model in coded unit (A) and physical unit (B)

From this contour plot for our model, we can deduce that higher removal efficiencies at about 70-80% can probably be predicted to achieve in the area of both higher diameter and compressed-air pressure.

In order to have an easier viewing for interaction term, we can make a plot for SRE against X at two P values as follows:
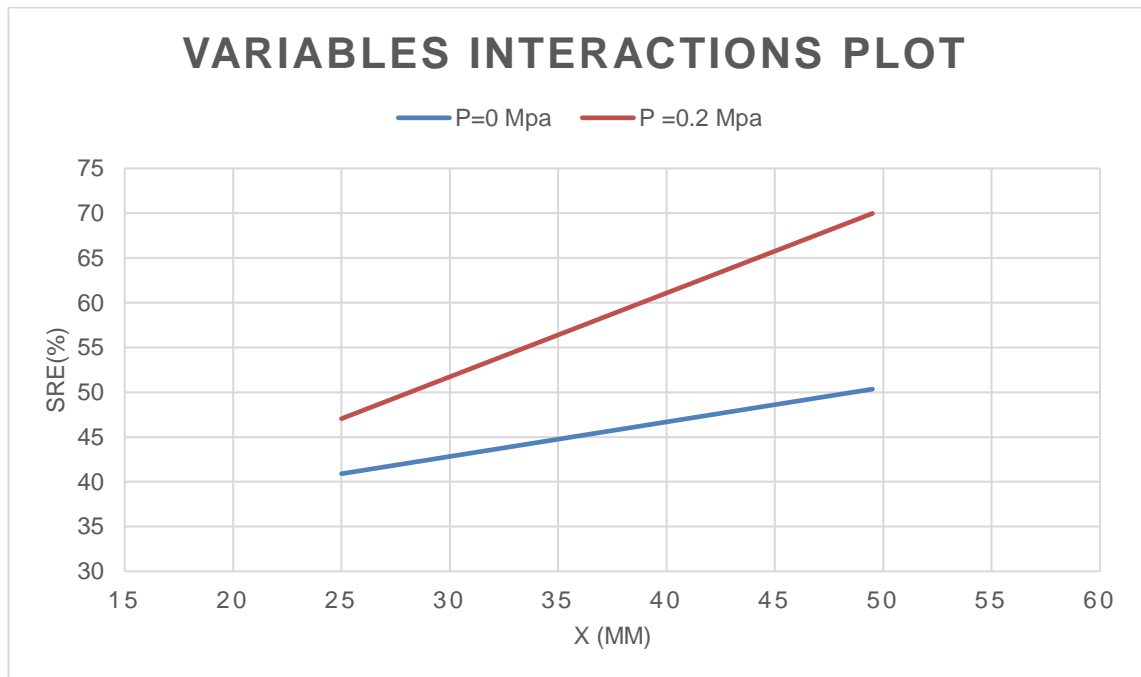
Figure 20. Removal Efficiency plotted against diameter and pressure

The chart is drawn based on the created model equation, Equation 5.7. From this line plot, we can see that the efficiency absolutely increases with diameter for both compressed-air pressures. Also, the interaction is shown apparently as the slope is clearly larger with larger pressure. Besides, the efficiency seems to increase faster with higher pressure at larger nozzles' diameter.

7 Discussion and Limitations

7.1 Discussion

Overall, the following interpretations can be concluded from the results presented in section 6.3. Firstly, the experimental results highlighted the highest removal efficiency achieved at nozzles DN25 with 0.2 MPa compressed-air supply. Secondly, on the basis of DOE and regression understanding, a model to stimulate the influences and interactions among variables was created, and it was also proven to be a good model. Both nozzles' diameter and compressed-air pressure show strong influence on the solids removal efficiency of the VOxFlotation system as well as there is also clear interaction between them. Finally, it can be predicted that the efficiency will significantly improve when we increase both nozzles' diameter and compressed-air pressure. Once again, it should be noted that we cannot be sure anything since it is only the prediction and we are still lacking of much important data. However, this interpretation is expected to somehow provide SansOx much useful information, good starting points and experience for their further testing.

7.2 Limitations and Recommendations for Improvement

There are still many limitations in the study, which can be divided into experiment limitation and model limitation. In the experiment limitations, they are summed to be several issues. The first limitation is the wastewater sample used for conducting experiments. As previously mentioned, the synthetic wastewater sample was made by dissolving soils into clean water instead of real swamp water. It seemed to be impossible to stimulate exactly the properties of natural surface water, which are believed to significantly affect some measurements and the objectives of the system. Hence, in the future when the weather is becoming more suitable, testing with real swamp water sample is strongly recommended to have precise results. Secondly, all the components in our VOxFlotation system were not manufactured from standard materials (stainless steel) with accurate dimensioning, which may have affected the process performance considerably. Especially, the flotation cell used in experiments was too small, which was only 80L instead of 400-500L as recommended in SansOx material. Thus, the vortex flow and rising bubbles paths within the cell were not optimized, which could certainly affect the vortex flotation process. Also, together with small cell volume, the hydraulic retention time was too short, which was only 1 min compared to 5 min recommended in SansOx theory. It might

not be sufficient for effective flotation as well as mixing water with coagulants inside the OxTube. Besides, because due to the lack of chemical pump, dosing rate might be not controlled precisely. Thirdly, by observing the bubbles paths during experiments, two nozzles seemed to be not sufficient to distribute bubbles evenly within the cell, making some area limited for floating the solids. The lack of a skimming device to collect the floating solids on surface could also be mentioned as one disadvantage. In a nutshell, in SansOx later testing, it is recommended that a standard manufactured system with suitable components and tools should be used in order to have best experiment conditions and achieve the precise outcomes.

Finally, the model had some limitations. Apparently, our 2^N design was missing experiments at central points. However, it is also nearly impossible to conduct testing at central points since there are no diameter sizes between 25 mm and 32 mm. By missing those points, linearity-test and lack-of-fit test were not available although those functions are also included in DOE_function. Hence, only predictions could be made without any confirmations as the linearity of the model was not totally certain. Moreover, the 2^N design is only useful to evaluate the influences and direction for optimizing. In the future, in order to find the optimum point, on the basis of already known conclusions, another type of design can be utilized by making more experiments at desired points.

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Appendix 1. R-Command for creating the model and making Plots

```
1   #Sourcing the DOE_function
2   source('http://users.metropolia.fi/~velimt/R/DOE_functions_v5.r')
3   #Input the data
4   Data <- read.table('Data.txt',header=TRUE)
5   M <- Data[,1:2]
6   y <- Data[,3]
7   #COnverse data to coded unit
8   N <- code(M)
9   #Creating the model
10  model1  <- quad.model.fit(N,y,1.5)
11  print(summary(model1))
12  #Making contour plot in physical unit
13  minx <- c(0,25)
14  maxx <- c(.2,32)
15  quad.plot(model1,xlim=c(25,40),ylim=c(0,1),ixy=c(2,1),zlevels = 40:90,minx,maxx)
16  #Making contour plot in coded unit
17  windows()
18  quad.plot(model1,xlim=c(-1,3),ylim=c(-1,3),zlevels = 40:90)
19
20
21
```

15:71   (Top Level) ⬍   R Script ⬍

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Appendix 2. Meeting between SansOx and Metropolia for cooperation in testing VOxFlotation as thesis-work at Metropolia Laboratory