Evaluation of a Chemical Dissolved Air Flotation System for the Treatment of Restaurant Dishwasher Effluents

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Wanpeng Wu, candidate for the degree of Master of Applied Science in Environmental Systems Engineering, has presented a thesis titled, *Evaluation of a chemical dissolved air flotation system for the treatment of restaurant dishwasher effluents*, in an oral examination held on February 7, 2017. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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ABSTRACT

Large quantities of fresh water are consumed by restaurant dishwashers every day, producing significant amounts of high strength oily wastewater in the process. An internationally patented chemical dissolved air flotation (DAF) system (Young and Munoz, 2012) was evaluated in this research to determine if it was capable of reclaiming restaurant dishwasher effluents (RDEs) in a cost-effective and reliable manner. Different chemicals and process conditions used in chemical DAF were evaluated. Dimethylamine P/W epichorohydrin (Polymer 572), a cationic polymer, was determined to be the optimal demulsifier among eight demulsifiers tested. Influent and effluent water quality was evaluated in terms of oil concentration, turbidity, chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD$_5$), and total solids. Removal efficiencies were evaluated at demulsifier doses ranging from 0 to 0.40 mg/L, at alum concentrations ranging from 0 to 250 mg/L, and at pH ranging from 4.5 to 10. A Polymer 572 dose = 0.10 mg/L at an alum concentration = 200 mg/L and pH = 9, yielded optimal results for the treatment of RDEs. Under these conditions, removal efficiencies as high as 95.6%, 94.6%, 73.0%, 94.4%, and 52.5% were achieved for oil, turbidity, COD, BOD$_5$, and total solids, respectively. Residual oil, COD, BOD$_5$, total solids, total dissolved solids, total suspended solids, and turbidity were 23.2, 188, 25.3, 9.03, 3.91, 5.12 mg/L, and 10.5 NTU, respectively. Total suspended solids were below the Canadian Guideline for Reclaimed Water Use in Toilet and Urinal Flushing (Environment Canada, 2006). However, BOD residual
prohibited direct reuse. The results also indicated that Polymer 572 could be used in the chemical DAF system without requiring any pH adjustment. The present findings suggest that the use of Polymer 572 was able to overcome many of the drawbacks of alum as a chemical demulsifier for the treatment of RDEs. The chemical DAF remains a viable pretreatment option for RDEs and an effective method for removing major contaminants, particularly oil, which is difficult to remove using other methods.
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<table>
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<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BOD&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Five-day Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>DAF</td>
<td>Dissolved Air Flotation</td>
</tr>
<tr>
<td>Epi-DMA</td>
<td>Epichlorohydrin-dimethylamine Copolymer</td>
</tr>
<tr>
<td>G</td>
<td>Mean velocity gradient</td>
</tr>
<tr>
<td>HLB</td>
<td>Hydrophilic- Lipophilic Balance</td>
</tr>
<tr>
<td>LCFA</td>
<td>Long Chain Fatty Acids</td>
</tr>
<tr>
<td>MBR</td>
<td>Membrane Bioreactor</td>
</tr>
<tr>
<td>MDBR</td>
<td>Membrane Distillation Bioreactor</td>
</tr>
<tr>
<td>FOG</td>
<td>Fat/Oil/Grease</td>
</tr>
<tr>
<td>OG</td>
<td>Oil/Grease</td>
</tr>
<tr>
<td>O/W</td>
<td>Oil/Water</td>
</tr>
<tr>
<td>PolyDADMAC</td>
<td>Polydiallyldimethylammonium Chloride</td>
</tr>
<tr>
<td>rbCOD</td>
<td>Readily Biodegradable COD</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>RDEs</td>
<td>Restaurant Dishwasher Effluents</td>
</tr>
<tr>
<td>RDE-BB</td>
<td>RDE from Beer Bros. Gastropub Restaurant</td>
</tr>
<tr>
<td>RDE-UR1</td>
<td>RDE from University of Regina Day 1</td>
</tr>
<tr>
<td>RDE-UR2</td>
<td>RDE from University of Regina Day 2</td>
</tr>
<tr>
<td>TDS</td>
<td>Total Dissolved Solid</td>
</tr>
<tr>
<td>TMP</td>
<td>Transmembrane Pressure</td>
</tr>
<tr>
<td>TN</td>
<td>Total Nitrogen</td>
</tr>
<tr>
<td>TOC</td>
<td>Total Organic Carbon</td>
</tr>
<tr>
<td>TP</td>
<td>Total Phosphorous</td>
</tr>
<tr>
<td>TS</td>
<td>Total Solid</td>
</tr>
<tr>
<td>TSC</td>
<td>Total Surface Charge</td>
</tr>
<tr>
<td>TSS</td>
<td>Total Suspended Solid</td>
</tr>
<tr>
<td>VFA</td>
<td>Volatile Fatty Acids</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

Water scarcity is a major challenge in many parts of the world. Increasing population, urbanization, industrialization, pollution, and climate change result in both regional and global water shortages. Despite the plentiful amount of water on the Earth, only 2.5 per cent is fresh water with less than one per cent directly available for human use (Wong, 2012). Water shortages threaten public health, food production, and industrial expansion. Water reclamation is one solution to the water crisis which simultaneously reduces wastewater loads and conserves freshwater resources.

Water reclamation has been studied on domestic, industrial, and commercial wastewaters to meet appropriate water quality criteria. However there is very little published research on the reclamation of restaurant dishwasher effluent (RDE) (Chung and Young, 2013). Restaurant dishwasher effluent represents a significant proportion of water used in restaurant-related industries, and may therefore be targetable for reusability. In order to determine the viability of reuse technologies for this application, more research is needed in this area.

1.1 Problem Statement

Large quantities of fresh water are consumed by restaurant dishwashers every day, and significant amounts of high-strength oily wastewater are produced simultaneously. This oily wastewater may cause serious problems to local plumbing and to the sewer distribution network upon discharge. Oil and grease become emulsified in restaurant
dishwasher water due to mechanical mixing and chemical stabilization under the influence of high temperatures and detergents. Pipe damage occurs when the oil and grease in the wastewater cool and solidify onto the inner surfaces of the pipes. This may constrict the flow of water and eventually clog the sewer liner due to the accumulation of grime and grease. Oil and grease can also float on the top of the water, block strainers and filters, and interfere with treatment upon entering the wastewater treatment plant (Chung and Young, 2013).

Previous research by Chung and Young (2013) demonstrated that a chemical DAF system could successfully reduce the oil concentration and turbidity of RDE. However some obstacles remain before the system can be practically implemented. These include following:

(1) Chemical dosing: The large amount of chemical coagulant required to produce the desired effluent quality may also produce excess sludge production and incur unnecessary costs due to suboptimal operation.

(2) pH balance: Adjusting pH to produce the desired effluent quality is a nuisance for owners and operators, as it requires an added layer of monitoring which complicates system operation.

(3) BOD removal: BOD is a critical parameter in the Canadian Guideline for Reclaimed Water Use in Toilet and Urinal Flushing (Environment Canada, 2006). In order for the DAF system to be useable and reliable, it should be able to consistently
meet the BOD guideline requirements.

1.2 Objectives

The objective of this research project is to overcome the aforementioned obstacles of the chemical DAF system and to improve its treatment performance by optimizing both chemical dosages and process conditions. The ultimate goal is to achieve a treated water quality suitable for toilet flushing.

The selection of an optimal demulsifier from among a variety of available options was determined on the basis of contaminant removal efficiency. The optimal demulsifier dose, pH, RDE dilution ratio, and coagulant dose were determined in a similar fashion. Finally, the performance of the optimized chemical DAF system was evaluated using different types of RDEs.

1.3 Significance of Research

This research significantly improved the design and operation of the chemical DAF system for RDE reclamation. Implementation of the chemical DAF system can significantly reduce freshwater consumption and wastewater production; this ultimately reduces the operating costs of restaurants and wastewater treatment plants.

This research may also indirectly benefit the food processing industry, particularly in areas which generate wastewaters similar to RDE. The use of demulsifiers and air flotation are commonly utilized in the treatment of oil refinery
wastewater. The selection of effective demulsifying agents, as determined in this research, may be a benefit in this regard.
2. LITERATURE REVIEW

2.1 Overview of RDE Treatment Technologies

2.1.1 Restaurant Wastewater Characteristics

Restaurant dishwasher effluents are highly variability in makeup, due to the diverse selection of cuisines, establishment sizes, and operational practices among eateries. Therefore it is both meaningless and impractical to have one characterization applied to all restaurant wastewaters (Chung and Young, 2013). Table 2.1 provides a comparison of wastewaters produced from various types of food preparation, including dishwashing in a Chinese fast food restaurant (Chu and Hsu, 1999). As shown, the major concern for restaurant wastewater is oil/grease (OG) and chemical oxygen demand (COD). This is largely due to the effect these materials impose on plumbing, namely the blockage of pipes. Dishwashing was listed as an individual food processing activity with OG varying from 365 to 6827 mg/L and COD varying from 4695 to 25304 mg/L over 2433 washes (Chu and Hsu, 1999). Note also that these significant variations of major contaminant concentrations were observed within the same restaurant performing the same food processing activity.
Table 2.1 Wastewater characteristics of different types of food preparation (Chu and Hsu, 1999)

<table>
<thead>
<tr>
<th>Food Processing Activities</th>
<th>Quantity of Activities</th>
<th>Activity Definition</th>
<th>Sampling Frequency</th>
<th>Oil/Grease Range mg/L</th>
<th>COD Range mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot and pan washing</td>
<td>36</td>
<td>Number</td>
<td>A</td>
<td>117 to 19850</td>
<td>873 to 67853</td>
</tr>
<tr>
<td>Dish washing</td>
<td>2433</td>
<td>Number</td>
<td>A</td>
<td>365 to 6827</td>
<td>4695 to 25304</td>
</tr>
<tr>
<td>Meat soaking for defrosting</td>
<td>106.3</td>
<td>Meat weight, kg</td>
<td>B</td>
<td>11 to 161</td>
<td>71 to 2875</td>
</tr>
<tr>
<td>Wok washing</td>
<td>8</td>
<td>Number</td>
<td>A</td>
<td>530 to 15340</td>
<td>4118 to 25720</td>
</tr>
<tr>
<td>Floor washing in kitchen</td>
<td>41.31</td>
<td>Floor area, m²</td>
<td>C</td>
<td>2478 to 8641</td>
<td>13320 to 24142</td>
</tr>
<tr>
<td>Pre-boiled broth</td>
<td>22</td>
<td>Food weight, kg</td>
<td>1 grab</td>
<td>23 to 579</td>
<td>63 to 448</td>
</tr>
<tr>
<td>Leftover of soup and beverages</td>
<td>1913</td>
<td>Number of cups</td>
<td>C</td>
<td>136 to 940</td>
<td>13961 to 56553</td>
</tr>
<tr>
<td>Rice washing</td>
<td>25</td>
<td>Mass of rice, kg</td>
<td>1 grab</td>
<td>89</td>
<td>2716</td>
</tr>
<tr>
<td>Food cooling</td>
<td>22</td>
<td>Mass of food, kg</td>
<td>2 grabs</td>
<td>229</td>
<td>608</td>
</tr>
</tbody>
</table>

The meat includes pork, spring chicken, chicken wings, and beef.

Sampling frequency: A = breakfast*1, lunch*1, tea time*1, dinner*1; B = pork*1, spring chicken*1, chicken wings*1, beef*1; C = mixture of four operation sections: breakfast, lunch, tea time, and dinner.

The most recent characterization of RDE in this regard was published by Chung and Young (2013) and listed in Table 2.2. Similar to Chu and Hsu’s findings (1999), the characteristics of RDE showed a high degree of variability, with the notable
exception of pH. Chemical oxygen demand was the most variable, with a range from 456 to 1588 mg/L (Chung and Young, 2013). The relatively stable pH of RDE enables the possibility of a practical implantation of a chemical DAF system in restaurants (Daaou and Bendedouch, 2012).

Table 2.2 Dishwasher effluent characteristics from the Beer Bros. restaurant (Chung and Young, 2013)

<table>
<thead>
<tr>
<th>Parameter</th>
<th># of Samples</th>
<th>Unit</th>
<th>Average</th>
<th>STDEV</th>
<th>Min/Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>25</td>
<td></td>
<td>11.09</td>
<td>0.22</td>
<td>10.55/11.67</td>
</tr>
<tr>
<td>Turbidity</td>
<td>27</td>
<td>NTU</td>
<td>261</td>
<td>111</td>
<td>91/502</td>
</tr>
<tr>
<td>TSS</td>
<td>20</td>
<td>mg/L</td>
<td>216</td>
<td>122</td>
<td>43/506</td>
</tr>
<tr>
<td>Oil</td>
<td>22</td>
<td>mg/L</td>
<td>382</td>
<td>129</td>
<td>173/650</td>
</tr>
<tr>
<td>COD</td>
<td>6</td>
<td>mg/L</td>
<td>1106</td>
<td>472</td>
<td>456/1588</td>
</tr>
<tr>
<td>BOD₅</td>
<td>6</td>
<td>mg/L</td>
<td>308</td>
<td>105</td>
<td>168/458</td>
</tr>
</tbody>
</table>

To sum up, the major contaminants in RDE are oil and grease (Li et al., 2007; BCDHE, 1997), with both of these parameters demonstrating significant variability even when sampled from a single location (Chung and Young, 2013).

2.1.2 Existing RDE Treatment Systems

The high variability of RDE makes it challenging to provide consistent treatment performance using existing treatment strategies (Han, 2000; Auflem et al., 2001; Chen and He, 2003). Experimentally this also poses a challenge, as it is difficult to keep the experiment consistent and continuous while treating the RDE. As a result, existing studies on RDE treatment are limited. Most research related to RDE treatment focus
on how to separate and treat the oil and grease from the water using synthetic wastewater. However the continuity and consistency of these data do not accurately represent real raw RDE (American Petroleum Institute, 1969; Manning and Snider, 1983; Patterson, 1985).

Currently, the main treatment strategies for RDE can be categorized as physicochemical treatment, biological treatment, or a combination of the two (Metcalf and Eddy, 2003; Chan, 2010). A common way to reclaim RDE is to utilize flotation, thus taking advantage of the low density of oil and grease (Ying et al., 2002).

The chemical DAF system is an example of physicochemical treatment (Al-Shamrani et al., 2002a; de Nardi et al., 2008). It provides good removal of oil, turbidity, COD, and TSS, but cannot always satisfy the guideline requirements for BOD₅ (Environment Canada, 2006). Improving BOD₅ removal can often be done using biological treatment. Some research has been done using biological treatment systems to remove OG and COD, but these studies were not done specifically using RDE (Zouboulis and Avranas, 2000; Gregory and Zabel, 1990). Thus, the viability of biological treatment for RDE reclamation remains currently unclear. As recommended in Chung and Young’s research (2013), the chemical DAF unit may function as an effective pretreatment prior to a biological treatment process, which would be used to reduce residual BOD₅. Under this configuration, it is likely that the treated water would meet the guideline for toilet flushing (Chung and Young, 2013).

Several biological treatment technologies that may be suitable for the treatment
of RDEs, include: (1) submerged membrane bioreactor (Yang et al., 2012), (2) membrane distillation bioreactor (Goh et al., 2015), (3) bio-additive for the treatment of grease trap wastewater (Tang et al., 2012), and (4) bio-fuel oil extraction/anaerobic methane production from post-extracted residue (Kobayashi et al., 2014). Membrane bioreactors are the main form of biological treatment; however membrane fouling continues to be a major problem (Yang et al., 2012; Yang et al., 2006; Liu, et al., 2012). Therefore, pre-treatment using a chemical DAF system prior to biological treatment is necessary (Hanafy and Nabih 2007; Britz et al., 2006; Boyd et al., 1971). As discussed before, the highly variable chemistry of RDE presents a challenge for existing treatment systems, often requiring researchers to utilize synthetic wastewater. It should be noted that the objectives of these studies were more focused on oil removal in general, rather than RDE in particular. Nevertheless, the findings are still somewhat relevant to RDE treatment.

A comparison between membrane interception and biological treatment, and the control of membrane fouling caused by the addition of dishwashing detergent were investigated by Yang et al. (2012) in a submerged membrane bioreactor. A submerged membrane bioreactor was employed as a subsequent process to treat the simulated restaurant wastewater following electro-coagulation and electro-flotation (Yang et al., 2012). The first major finding in Yang et al.’s research was that detergents, one of the main sources of surfactants abundant in restaurant wastewater, has the function of reducing membrane fouling so long as the detergents interact sufficiently with the membrane surface. Two parallel submerged MBRs were simultaneously monitored to
investigate the effects of oil and detergent on the performance of an MBR at respectively high and low initial concentrations of oil and detergent (Yang et al., 2012). The better performance of the MBR with high concentration of oil and detergent was considered to be attributed to the membrane surface modification and loose sludge cake attached to the membrane for the high detergent content feeding. During the test, the biological treatment system was found to be the dominant contributor to BOD removal rather than membrane interception. As detergent is found in most RDE, the membrane fouling reducing function of detergent could provide knowledge for the treatment of RDE.

High temperature is another characteristic of RDE which can be exploited in an emerging biological treatment method called a membrane distillation bioreactor (MDBR). An MDBR is a modified MBR which was developed to utilize waste heat commonly present in industrial wastewater (Goh et al., 2015). This process works by using a thermophilic bio-process in conjunction with a membrane distillation process. Water vapor is transferred across a thermal gradient through a hydrophobic microporous membrane to produce water. Water in the hot feed vaporizes on the membrane surface and diffuses down the vapor pressure gradient before it is condensed and removed at the permeate/distillate side. The feed temperature should be greater than 50°C, since the flux driving force is the vapor pressure gradient. This makes the MDBR potentially viable for RDE treatment due to the high temperature of RDE.
However, before MDBR can be implemented in this way, several challenges need to be overcome. For instance, low COD removal was observed in an MDBR which could be attributed to reduced colloidal COD removal, reduced biodiversity, temperature induced changes in pH, organic acids production under micro-aerobic conditions, and nutrient deficiency (Goh et al., 2015). The MDBR is still an emerging technology with the potential to reduce the heat consumption of some industries and might eventually be applied to RDE treatment. However further research is needed to optimize COD removal (Goh et al., 2015).

Tang et al. (2012) found a group of bacteria, called Bio-Amp, which could biodegrade fat, oil, and grease (FOG) in wastewaters. Bio-Amp is a bio-additive from Eco Bionics (Irving, TX, USA). Eco Bionics introduced a system that could provide high concentrations of five bacterial species to degrade FOG. These species were *Pseudomonas fluoresces*, *Pseudomonas putida*, *Bacillus subtilis*, *Bacillus licheniformis*, and *Bacillus thuringiensis* (Table 2.3). These bacterial species can produce an array of metabolic enzymes, allowing the breakdown of FOG in wastewaters. *Bacillus* are gram-positive bacteria that produce enzymes to breakdown fat into glycerol and fatty acids while *P. putida* and *P. fluoresces* are gram-negative bacteria that can further break down fatty acids, and oxidize unsaturated fatty acids (Tang et al., 2012). It is postulated that these bacteria may also be used to remove FOG from RDEs.
Table 2.3 Bio-Amp bacteria composition (Tang et al., 2012)

<table>
<thead>
<tr>
<th>Genus/species</th>
<th>Class</th>
<th>Enzymes/food</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Pseudomonas fluoresces</em></td>
<td>Aerobic</td>
<td>Lipase multiple enzyme systems</td>
</tr>
<tr>
<td><em>Pseudomonas putida</em></td>
<td>Aerobic</td>
<td>Lipase multiple enzyme systems</td>
</tr>
<tr>
<td><em>Bacillus subtilis</em></td>
<td>Aerobic</td>
<td>Lipase multiple enzyme systems</td>
</tr>
<tr>
<td><em>Bacillus licheniformis</em></td>
<td>Facultative anaerobic</td>
<td>Protease amylase cellulose</td>
</tr>
<tr>
<td><em>Bacillus thuringiensis</em></td>
<td>Facultative anaerobic</td>
<td>Protease amylase lipase</td>
</tr>
</tbody>
</table>

Oil and grease separated from the previous treatments could be extracted and used as fuel, while the post-extracted residue could be anaerobically digested to methane (Kobayashi et al., 2014). This could potentially benefit the waste treatment strategy for RDE by generating useful by-products in addition to reusable water.

2.2 Overview of Dissolved Air Flotation Technology

2.2.1 Dissolved Air Flotation (DAF)

DAF has been used for decades in water treatment systems for the separation of colloidal particles which cannot be settled by gravity (Bratby, 2006; Younker and Walsh, 2014; Rozainy et al., 2014). These particles typically include fat, grease, and oil (Miranda et al., 2013). Their removals are achieved by dissolving air in water or wastewater under pressure and then releasing the pressure in a flotation tank (Naghd and Schenk, 2016). The dissolved air forms microbubbles upon entering the flotation tank due to the rapid change in pressure. The microbubbles adhere to suspended
colloids as they float upward, causing the colloids to coalesce as a scum on the surface (Bahadori et al., 2013; Palaniandy et al., 2010; Geraldes et al., 2008).

Wastewater containing emulsified oil and grease can be treated by DAF (Zhang et al., 2016). The use of chemical reagents to destabilize and increase the size of the emulsions, prior to physical separation, is a common way to treat such wastewater (SNL Floerger, 2003). Coagulation and flocculation followed by DAF is an example of such a physicochemical treatment (Zhang et al., 2016; Lakghomi et al., 2012; Tansel and Pascual 2011). This method has been widely applied for the removal of paper fibres from paper mill wastewater; to remove oil, fat, and similar material from food plant effluents, refineries, and dry washes; to concentrate metallic ores in mining operations; and to concentrate sludge (Shutova et al., 2016).

The effectiveness of a chemical DAF system for removing oils, hydrocarbons, suspended solids, and turbidity has been investigated by Chung and Young (2013). It was found that BOD₅ removal was low, which prohibited direct reuse of the treated water.

The chemical DAF system was implemented to treat RDE (Chung and Young, 2013). The chemicals used were alum in conjunction with an anionic polymer. These chemicals performed the role of coagulant and flocculant, respectively. The optimal dose of alum and polymer were 300 and 1.5 mg/L, respectively (Chung and Young, 2013). The optimal recycle ratio was determined to be 14% while the rapid and slow mixing speeds were $G = 193 \text{ s}^{-1}$ (800 mL/min) and $G = 62 \text{ s}^{-1}$ (80 mL/min), respectively. The optimal pH was tested to be 5.5 to 6.5 regardless of temperature.
(Chung and Young, 2013). Supplemental research on dishwasher effluent reclamation was conducted by Hassan-Zadegan (2013). The oil removal efficiency was improved by adding a solution of Poly(acrylamide-co-diallyldimethylammonium chloride) as a flocculant. The same optimal mixing speeds and recycle ratio as Chung and Young’s study were used. However this method required large amounts of alum. Excess alum consumption results in a high alum residual in the treated water and an increase in operating cost (Filho et al., 2016; Zhang and Guiraud, 2013). Therefore, reducing alum dosages is desirable.

The performance of a modified DAF system named PosiDAF was investigated by Karhu et al. (2014). The charge modification on the film of the air bubbles was achieved in the flotation column using a conventional coagulation-flocculation DAF. However a positively charged chemical was added directly into the saturator to neutralize the air bubbles before entering the flotation column in the PosiDAF system. Karhu et al. (2014) found that PosiDAF, with the addition of polydiallyldimethylammonium chloride (polyDADMAC), improved performance as COD reductions were higher than a conventional coagulation-flocculation DAF. However, the disadvantages of PosiDAF require further study (Karhu et al., 2014), as this system may experience corrosion to the saturator and foaming of chemicals during the circulation of the chemical-water solution. This could affect pump efficiency.

2.2.2 Mechanism of Dissolved Air Flotation for Oil Removal
DAF is used to enhance the buoyancy difference of emulsified oil droplets by the attachment of micro-air bubbles, which are produced by dissolving air in water under pressure and releasing it to a vessel at normal pressure (Lakghomi et al., 2015). Studies have concluded that the size of the air bubbles was a key factor affecting the removal efficiency of oil and grease. The microbubbles were required to be less than 100 µm for most cases to achieve the best flotation performance (Karhu et al., 2014).

The flotation process relies on the attachment of gas bubbles to the dispersed oil droplets, and this attachment significantly depends on the complex processes involving the surface characteristics of the oil droplets and their interaction with gas. (Moosai and Dawe, 2003; Zhang et al., 2014). The oil/bubble contact, the interactions of chemical additives in aiding this contact, and the spreading of the oil around the gas bubble are included in the attachment mechanism (Moosai and Dawe, 2003). Before the attachment, initial agglomeration of oil emulsion droplets is needed to increase the size of the droplet to approximately 60 µm for effective flotation (Karhu et al., 2014).

A successful air bubble attachment process in DAF has been developed by Moosai and Dawe in 2003. When two drops (oil/oil, oil/gas) approached each other, a thin layer of water was created. Further approach caused liquid to squeeze out and create a dimple. When the liquid film dropped to a critical thickness (approximately 0.10 µm) the disjoining pressure dominated and very strong intermolecular forces came into effect. The laminar layer became unstable and ruptured very quickly, which
caused the gas bubble and oil droplet to close together. Finally, the spreading of oil over the bubble occurred and the oil-gas agglomerate was strong enough to withstand the upward rise (Moosai and Dawe, 2003).

2.3 Demulsifier

2.3.1 Mechanisms and Functions of a Demulsifier in a Chemical DAF

Demulsification is needed for the removal of dissolved oil using DAF (Bondelind et al., 2013; Behin and Bahrami, 2013). A demulsifier works by partially replacing the emulsifiers (surfactants) in the water-oil interface, which decreases the interfacial viscosity and elasticity and breaks the emulsion (Tong et al., 2013; Kang et al., 2012).

The DAF process cannot function well without chemical intervention for demulsification, coalescence, and bubble attachment, when the median droplet diameter of the oil-in-water emulsion is less than 10 µm (Moosai and Dawe, 2003). Oil droplets less than 10 µm do not float well because a very thin unstable film forms around the bubble during the spreading process. This makes the agglomerate too weak to survive the upward rise. Therefore, demulsification is required to enlarge the droplets to over 40 µm. The demulsifier enables droplets and bubbles to approach each other and remain sufficiently close. This allows drainage and rupture to occur so that oil can spread over the gas. Demulsifiers achieve this by introducing an opposite charge between oil droplets and the oil-gas interface, which encourages the oil
droplets to flocculate and attach to the gas. If the demulsifier failed to perform this job, spreading would not occur and the gas bubble would rebound from the oil droplets (Moosai and Dawe, 2003).

### 2.3.2 Performance of Demulsifiers in the Chemical DAF System

The treatment performance of a chemical DAF is affected by many factors such as the type of demulsifier, its dose, pH, and pre-coagulation. It is critical to determine the optimal demulsifier in a chemical DAF treatment process (Ma et al., 2013). The research on demulsifiers for the treatment of oily wastewater has recently gained in popularity due to its potential to separate oil from wastewater (Carneiro et al., 2015).

Many types of demulsifiers have been widely used for oil-water separation including physical, chemical, and biological demulsifiers (Abullah et al., 2016; Huang et al., 2013; Al-Sabagh et al., 2011). Chemical demulsifiers are classified as either organic or inorganic. Inorganic demulsifiers include alum and ferric salts, while organic demulsifiers include cationic, anionic, and non-ionic polymers.

The most common coagulants are aluminum and ferric salts which are added to cause three effects: the precipitation of emulsifying agents, the reduction of interfacial tension, or the neutralization of electrical charges (Eckenfelder, 2000). Some cationic polymers are able to achieve coagulation and flocculation simultaneously (Karhu et al., 2014).

Cationic polymer demulsifiers can be used as a coagulant, flocculant, flotation aid, or all of the above (Karhu et al., 2014). Therefore, the use of a cationic polymer
alone or in conjunction with alum or ferric salts has the potential to reduce chemical dose and sludge production in comparison to the use of alum or ferric salts alone. The cationic polymers CTAB (cetyltrimethylammonium bromide) from Acros Organics, PolyDADMAC (polydiallyldimethylammonium chloride), and Epi-DMA (epichlorohydrin-dimethylamine copolymer) manufactured by Kemira Oyj were tested in a chemical DAF system (Karhu et al., 2014). The PolyDADMAC was analyzed to be the most efficient demulsifier among the three polymers (Karhu et al., 2014).

The performance of PosiDAF with CTAB for the treatment of an oil/water (O/W) emulsion was poor, because CTAB did not remove the oil but instead remained in the sample solution, increasing COD and neutralizing the total surface charge (TSC) value. Epi-DMA and PolyDADMAC were significantly more efficient in breaking O/W emulsion in both PosiDAF and coagulation-flocculation DAF than CTAB, according to the COD reduction and TSC neutralization. The COD removal efficiency for PosiDAF with PolyDADMAC was better than conventional coagulation-flocculation followed by DAF. Also the dosage of PolyDADMAC in PosiDAF was less than coagulation-flocculation DAF. However the neutralization of TSC in coagulation-flocculation DAF was better than PosiDAF (Karhu et al., 2014).

Karhu et al. (2014) also explained the mechanism of such CTAB, PolyDADMAC, and Epi-DMA performances. A surfactant, such as CTAB, with a low molecule weight is likely to lie close to the bubble with a hydrophobic tail adsorbed
tightly at the air-liquid interface, leaving the hydrophilic head on the outer edge of the bubble. The higher MW polymers will more loosely attach to bubbles due to their more hydrophilic nature. The extent to which the polymer reaches into the solution depends on the hydrophobic/hydrophilic portions of the molecule. Both Epi-DMA and PolyDADMAC are more hydrophilic than CTAB with a significantly larger molecular weight. Thus they attach themselves to bubbles with the hydrophobic tail more loosely than CTAB and leave a higher sweeping range. The PolyDADMAC has a higher molecular weight than Epi-DMA, which can enable bridging between bubbles and oil droplets. This is probably why PolyDADMAC is more efficient than Epi-DMA (Karhu et al., 2014).

Karhu et al.’s study (2014) suggests that cationic polymers, such as Epi-DMA and PolyDADMAC, can achieve coagulation and flocculation simultaneously. Therefore they possess the potential to act as both coagulant and flocculant in the chemical DAF system.

2.3.3 Different Types of Demulsifiers

High oil-water separation efficiency has been achieved by using several different types of demulsifiers (He et al., 2016; Alsabagh et al., 2016). In particular, these demulsifiers have been studied for their use as emulsion breakers in the oil processing industry (Ojinnaka et al., 2016; Laplante et al., 2015). Chung and Young (2013) conducted research on the treatment of restaurant dishwasher effluent, where an anionic polyelectrolyte polymer was used in conjunction with alum. The demulsifier
categorized as natural seed gum extracted from Cassia obtusifolia seeds was determined to act as a coagulant aid to treat palm oil mill effluent (Hosny et al., 2015). The demulsifier classified as natural polymer (chitosan/carboxy methyl cellulose) from shrimp shell mixed with coagulant aluminum sulfate could achieve a 96.35% oil removal under optimal conditions (Shak and Wu, 2015). However the demulsifiers categorized as cationic polymers might achieve the coagulation and flocculation simultaneously according to Karhu et al.’s research (2014).

The demulsification role of an anionic polymer (such as Tween 20) as a chemical demulsifier has been determined in the separation of water from heavy crude oil emulsions (Roodbari et al. 2011). Tween 20 or polysorbate 20 is a polymeric surfactant derived from PEG-ylated sorbitan (a derivation of sorbitol) esterified with fatty acid. The hydrophilic-lipophilic balance (HLB) is a concept used to explain the amphiphilicity of non-ionic surfactants. Surfactants with low HLB give rise to water-in-oil emulsions, whereas high HLB surfactants give rise to oil-in-water emulsions (Griffin, 1949). In Nastaaran’s research, Tween 20, with its high amount of hydrophilic groups and short length lipophilic groups, was compared to other closely related compounds. The results showed that Tween 20, with its higher HLB, could demulsify more efficiently than the other demulsifiers due to its oxyethylene groups which could form hydrogen bonds and force droplets together via attraction (Roodbari et al., 2011).

Some biological demulsifiers can be considered as oil-degrading bacteria since they possess the potential to degrade hydrocarbons and use them as a food source.
which decreases the BOD₅ level of the treated effluent while simultaneously
demulsifying the water-oil emulsion (Li et al., 2012; Long et al., 2013; Liu et al.,
2009). Low toxicity, environmental compatibility, and high demulsifying efficiency
under extreme conditions are some of the advantages of biological demulsifiers over
chemical demulsifiers; however cost-effective mass production of bio-demulsifiers
has thus far hindered their application (Liu et al., 2010). Bacillus mojavensis XH1 and
its demulsification efficiency were investigated by Li et al. (2012). Bacillus
mojavensis XH1 was isolated from petroleum contaminated soil from the Daqing Oil
Field by the State Key Laboratory of Urban Water Resource and Environment (China)
and maintained at 4°C on an agar slant plate. Two main factors that affect the
demulsification ratio are temperature and the carbon source. The demulsification ratio
was detected to be 85.5% at temperatures lower than 75°C, but the ratio decreased as
temperatures rose beyond this level. The hydrocarbons (hexadecane, kerosene, and
liquid paraffin) from petroleum and soybean oil could promote the demulsifying
activity of the extracellular metabolites of XH1 when supplemented with glucose (Li
et al., 2012). Glucose and liquid paraffin were identified as the best complex carbon
sources to promote the biosynthesis of bacillus mojavensis XH1 (Li et al., 2012).

To overcome the limitation on cost-effective mass production of bio-demulsifiers,
a comparison between waste frying oil and paraffin as a carbon source in the
production of the bio-demulsifier Dietzia sp. S-JS-1 has been studied (Liu et al., 2009).
S-JS-1 was isolated from petroleum contaminated soil and exhibited high biomass dry
weight and excellent demulsification performance when cultured in waste frying oils.
obtained from the production of Chinese fast food. The results proved that waste frying oil culture showed a high biomass production after 7 days of cultivation by substituting the same amount of paraffin as a carbon source in the biosynthesis of S-JS-1. However, the chemical composition and the surface properties of the biological demulsifier changed when waste oils were used as a substitute carbon source. The factors causing these changes are still a mystery (Liu et al., 2009). In Coutinho’s research on the demulsifying properties of extracellular products and cells of Pseudomonas aeruginosa MSJ isolated from petroleum-contaminated soil, demulsification control was also complex (2013). Demulsification varied with growth media, culture age, and cell hydrophobicity (Coutinho et al., 2013).

Few published papers on the use of demulsifiers in a chemical DAF system can be found. Therefore, more research is required in this area.
3. METHODOLOGIES AND EXPERIMENTAL SETUP

This chapter explains the experimental setup in detail. Sections included will discuss the bench scale DAF system, chemicals, sample collection and preparation, DAF operation, and analytical tests and methods used.

3.1 Bench Scale DAF System

A bench scale DAF system was operated to evaluate its performance in the treatment of RDE. The pressure tank was pressurized with tap water rather than flotation effluent to simulate the recycling of RDE.

Schematic diagrams and a general overview of the bench scale DAF system are shown in Figure 3.1, Figure 3.2, and Figure 3.3. The main components of the system consist of an air compressor (DeWALT D55141 Heavy-Duty, 2 gal, 150 psi), a 3 L pressure tank, an air pump (Whisper® 30-60), an air diffuser (Elite A-984), and a 1.75 L flotation column. The pressure tank was filled approximately halfway with clean water. The air compressor was then used to increase the air pressure within the pressure tank to 60 psi. The compressed air within the tank dissolves into the water to form a supersaturated solution relative to atmospheric pressure. A small fraction of this water is passed from the pressure tank to the flotation column following coagulation and flocculation. The rapid change in pressure initiates microbubble formation in the release water. These microbubbles adhere to suspended floc and buoy them to the surface, leaving the remaining mixture relatively clear. The treated water
can then be easily extracted from the flotation column using an extraction port.

![Schematic diagram of the bench-scale chemical DAF system.](image)

**Figure 3.1 Schematic diagram of the bench-scale chemical DAF system.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Air Compressor</td>
<td>9</td>
<td>Air Diffuser</td>
</tr>
<tr>
<td>2</td>
<td>Pressure Control Valve</td>
<td>10</td>
<td>Wastewater Addition</td>
</tr>
<tr>
<td>3</td>
<td>Pressure Gauge</td>
<td>11</td>
<td>Sampling Port</td>
</tr>
<tr>
<td>4</td>
<td>Pressure Tank</td>
<td>12</td>
<td>Air Control Valve</td>
</tr>
<tr>
<td>5</td>
<td>Flow Control Valve</td>
<td>13</td>
<td>Air Flowmeter</td>
</tr>
<tr>
<td>6</td>
<td>Flow Control Valve</td>
<td>14</td>
<td>Air Pump</td>
</tr>
<tr>
<td>7</td>
<td>Chemical Addition</td>
<td>15</td>
<td>Storage Tank</td>
</tr>
<tr>
<td>8</td>
<td>Flotation Column</td>
<td>16</td>
<td>Treated Water</td>
</tr>
</tbody>
</table>
The flotation column was designed to achieve coagulation, flocculation, and flotation within the same volume, while the mixing was accomplished using an air pump and air diffuser. Air bubbles produced from the air diffuser performed the mixing in the liquid body. Rapid mixing and flocculation could be simulated by controlling the flow rate of the air pump. Both the air diffuser and the release of the air-water mixture occurred at the bottom of the flotation column.

Figure 3.2 Dimensions of the flotation column.
3.2 Chemicals

In this research, alum \((\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O})\), was used as the primary coagulant, and the high molecular weight anionic polymers, Superfloc C-572, 573, 577, 581, 587, 591, 592, and 595 (listed in Table 3.1) were used as the flocculant. These compounds were provided by the Sigma-Aldrich company. Sulfuric acid and sodium hydroxide were used to adjust the pH.

The coagulants and flocculants were prepared daily before testing. Alum was prepared at a concentration of 10% (or 100 mg/mL), and Superfloc C-572, 573, 577, 581, 587, 591, 592, and 595 were prepared at a concentration of 0.05% (or 0.5 mg/mL) as suggested by the manufacture.
Table 3.1 Polymer information (Kemira, 2016)

<table>
<thead>
<tr>
<th>Product Name</th>
<th>Polymer Name</th>
<th>Chemical Structure</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superfloc C-572</td>
<td>Dimethyl amine P/W epichlorohydrin</td>
<td><img src="image1" alt="Chemical Structure" /></td>
<td>(C₅H₁₂NCl)x(C₂H₆N₂)y</td>
</tr>
<tr>
<td>(Polymer 572)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superfloc C-573</td>
<td>Dimethylamine epichlorohydrin-ethylenediamine</td>
<td><img src="image2" alt="Chemical Structure" /></td>
<td>(C₅H₁₂NCl)x(C₂H₆N₂)y</td>
</tr>
<tr>
<td>Superfloc C-577</td>
<td>Dimethylamine epichlorohydrin-ethylenediamine</td>
<td><img src="image3" alt="Chemical Structure" /></td>
<td>(C₅H₁₂NCl)x(C₂H₆N₂)y</td>
</tr>
<tr>
<td>Superfloc C-581</td>
<td>Dimethylamine epichlorohydrin-ethylenediamine</td>
<td><img src="image4" alt="Chemical Structure" /></td>
<td>(C₅H₁₂NCl)x(C₂H₆N₂)y</td>
</tr>
<tr>
<td>Superfloc C-587</td>
<td>Polydiallyldimethyl ammonium</td>
<td><img src="image5" alt="Chemical Structure" /></td>
<td>(C₈H₁₆N)n</td>
</tr>
<tr>
<td>Superfloc C-591</td>
<td>Polydiallyldimethyl ammonium</td>
<td><img src="image6" alt="Chemical Structure" /></td>
<td>(C₈H₁₆N)n</td>
</tr>
<tr>
<td>Superfloc C-592</td>
<td>Polydiallyldimethyl ammonium chloride</td>
<td><img src="image7" alt="Chemical Structure" /></td>
<td>(C₈H₁₆NCl)n</td>
</tr>
<tr>
<td>(polyDADMAC)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superfloc C-595</td>
<td>Polydiallyldimethyl ammonium</td>
<td><img src="image8" alt="Chemical Structure" /></td>
<td>(C₈H₁₆N)n</td>
</tr>
</tbody>
</table>
3.3 Sample Collection and Preparation

3.3.1 Sample Collection

The collection of RDE samples was conducted at the Club & Catering, University of Regina, and the BeerBros. Gastropub. Both restaurants serve typical North American cuisine. RDEs were collected on different days of the week at different times of the day to ensure the variability of the wastewater was represented. Composite samples were used for analysis. The RDE was collected into three 20 L buckets filled to about 75% and delivered back to the laboratory as quickly as possible. This was done to minimize the changes in wastewater quality that occurs over time. All experimental work was carried out in the Research and Innovation Centre at the University of Regina.

3.3.2 Sample Preparation

The hot RDE samples were cooled down to 21±1°C before analysis. The turbidity, pH, BOD₅, COD, Total Solids (TS), Total Dissolved Solids (TDS) and oil concentration were immediately analyzed. The treatment of the RDE was conducted as soon as possible to avoid the bio-degradation of organic compounds over time.

3.3.2.1 Flow Pressurization in the Pressure Tank

A 3 L pressure tank was filled with tap water to 90% capacity and then connected to an air compressor (DeWALT D55141 Heavy-Duty, 2 gal, 150 psi) with an open
pressure control valve. The pressure in the tank was pressurized and kept at 60 psi by the compressor. The tank was swirled for about 1 minute to help dissolve the air into the water. Then the tank was connected to the dissolved air flotation column. When the pressurized water enters the DAF column, the change in pressure forces the pressurized air to come out of the solution in the form of microbubbles. These bubbles are used to float coagulated material to the top of the column.

3.3.2.2 pH Adjustment

To evaluate the effects of pH, the pH of the raw RDE was adjusted using sulfuric acid and sodium hydroxide before each trial. Due to the use of detergents in the dishwashing process, the initial RDE samples were usually alkaline.

3.4 DAF Operation

The 1.75 L flotation column was filled with raw RDE samples. A predetermined dose of alum or polymer was then added to the column. The samples were rapidly mixed for 3 minutes at mean velocity gradient - add to the list of symbol $G = 62 \text{ s}^{-1}$ followed by a slow mixing for 15 minutes at $G = 193 \text{ s}^{-1}$. The calculation of $G$ and the recycle ratio are shown in the Appendix A - Calculations (Camp, 1955). The mixing rates were simulated using an air pump (Whisper® 30-60) and air diffuser (Elite A-984). Rapid and slow mixing was performed at air discharge rates of 80 and 800 mL/min, respectively, which were the optimal mixing conditions determined by Chung and Young (2013). After the slow mixing, the air flotation process was initiated.
by opening a valve on the pressure tank to allow 378 mL of tap water to flow into the flotation column. Optimal flotation was achieved at a saturation pressure of 60 psi and a recycle ratio of 14% as suggested by Chung and Young (2013). The cloud of micro-bubbles caused the oil/grease conglomerates up to the top. The flotation process took 30 minutes. The treated water samples were collected from the sampling port near the base of the flotation column.

3.5 Analytical Tests and Methods

The pH, turbidity, and oil concentration of both raw and treated RDE were measured throughout the entire experiment. Oil concentration was selected to measure the performance of the chemical DAF system. Parameters such as TS, TDS, BOD$_5$, and COD were measured only in the treated water quality tests when the DAF was operated at its optimum conditions. This was done in order to save time and reduce cost.

Oil concentration and turbidity were measured for both raw and treated wastewater samples. Each reading was measured in triplicate. Oil content concentrations were analyzed using the Horiba OCMA-310 oil content analyzer (Horiba Instruments Inc., CA). Tetrachloroethylene was used in this experiment as an extraction solvent because of its cost effectiveness. Turbidity was measured using a HACH 2100N turbidimeter.

The 5-day biochemical oxygen demand was measured using the WTW OxiTop Control 12 BOD respirometric based system. Total solids were determined according to
the *Standard Methods* (APHA, 2005). Chemical oxygen demand was measured using a HACH chemical test kit (TNT 821).

The pH was measured using a WTW pH 730 meter in accordance to the procedures detailed in the *Standard Methods* (APHA, 2005). The pH meter was calibrated using pH = 4, pH = 7, and pH = 10 standard buffer solutions provided by Fisher Scientific. Calibrations were performed on a daily basis.
4. RESULTS AND DISCUSSION

This chapter will discuss the composition of the different RDEs. It will then discuss the basis for the selection of an optimal polymer type among the eight chemicals tested. The effects of polymer dose, pH, alum concentration, and dilution ratio of the RDEs on treatment performance will be discussed. Finally, the analyzed results on chemical DAF treated water will be discussed.

4.1 Analysis of RDEs

The objective of testing the composition of RDEs was to characterize the RDEs from different locations. Therefore the feasibility of the chemical DAF system could be estimated based on the RDEs composition which the chemical DAF system would be tested against. The results are summarized in Table 4.1.

Table 4.1 Composition of RDE on different days

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>RDE-UR1</th>
<th>S.D.</th>
<th>RDE-UR2</th>
<th>S.D.</th>
<th>RDE-BB</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>240</td>
<td>30.32</td>
<td>522</td>
<td>85.34</td>
<td>1772</td>
<td>139</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>224</td>
<td>2.02</td>
<td>196</td>
<td>1.87</td>
<td>1138</td>
<td>10.11</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>560</td>
<td>103</td>
<td>696</td>
<td>123</td>
<td>2840</td>
<td>583</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/L</td>
<td>340</td>
<td>54</td>
<td>450</td>
<td>67</td>
<td>2300</td>
<td>487</td>
</tr>
<tr>
<td>TS</td>
<td>mg/L</td>
<td>18.45</td>
<td>2.01</td>
<td>19.03</td>
<td>2.21</td>
<td>23.05</td>
<td>3.58</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>3.50</td>
<td>0.54</td>
<td>2.8</td>
<td>0.45</td>
<td>3.58</td>
<td>0.49</td>
</tr>
<tr>
<td>pH</td>
<td>N/A</td>
<td>8.5</td>
<td>0.12</td>
<td>8.5</td>
<td>0.13</td>
<td>9.0</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 4.1 shows the composition of samples from the same dishwasher from the
University of Regina and the Beer Bros. restaurant. The data are organized from lowest value to highest value. Oil, COD, and BOD$_5$ demonstrated the largest ranges from 240 to 1772, from 560 to 2840, and from 340 to 2300 mg/L, respectively. Turbidity ranged from 224 to 1138 NTU. The high variability of RDEs could be affected by many factors such as: the items that were washed, who was operating the dishwasher, and how busy the restaurant was at the time the wastewater was generated. TDS were tested to be as low as 3.5, 2.8, and 3.58, respectively. Therefore the dissolved solids were not determined to be a significant parameter for RDE. The pH of RDEs was tested to be from 8.5 to 9.0 and more stable than the other parameters. The alkalinity of RDE is likely related to the inclusion of detergent, which often contains sodium hydroxide. The comparatively narrow pH range means that it is possible to operate the system with no pH adjustment, provided that a suitable polymer can be found to operate well within this range. The compositions of the RDEs tested in this study were highly variable, which supports the findings of previous research (Chung and Young, 2013; Chu and Hsu, 1999).
4.2 Determination of the Optimal Polymer Type

As discussed before, some cationic polymers have the potential to simultaneously coagulate and flocculate. Therefore, the polymers in this study were tested without any additional coagulating or flocculating agents. Eight different polymers, listed in Table 2.6, were tested at dosages of 0.10 mg/L, 0.50 mg/L, and 2.00 mg/L, respectively. The effects of the polymers were determined by the removal efficiencies of the chemical DAF systems for oil and turbidity. The doses were recommended by the producer (Kemira, 2016). The operational parameters were fixed as follows: rapid mixing \( (G = 193 \text{ s}^{-1}) \) of polymer for 3 minutes, flocculation for 15 minutes at \( G = 62 \text{ s}^{-1} \), flotation using a saturation pressure of 60 psi and a recycle ratio of 14% and a flotation time of 30 minutes. These operational parameters were suggested as optimal by Chung and Young (2013) for this particular DAF system. All of the experimental trials in this research were conducted under the same operational conditions.

![Figure 4.1 The effect of different polymers on oil and turbidity removal efficiencies (RDE-UR1).](image-url)
After conducting the three parallel tests, Polymer 572 was determined to be the optimal polymer. This can be clearly observed from Figure 4.1. The performance of Polymer 572 was much better than all of the other seven candidates at dosages = 0.10 and 0.50 mg/L. More than 81% removals on both the oil concentration and turbidity could be achieved when Polymer 572 was tested at 0.10 and 0.50 mg/L. Lower percentages of removals for both oil and turbidity were observed for Polymer 572 when the dose increased to 2.00 mg/L. However, the polymer still achieved better removals than its competitors. The oil concentration and turbidity removals decreased 17.1% and 17.9%, respectively, when the dosage was increased from 0.10 to 2.00 mg/L. This indicated that the polymer dose had a significant impact on treatment performance in regards to oil and turbidity removal.

Pictures of the treated water samples were taken to compare the performance of the various polymers at 2.00 mg/L. These images are shown in Figure 4.2. The third beaker from the right was the treated water sample from Polymer 572, which was slightly clearer than all of the other samples. A closer look is given in Figure 4.3 and Figure 4.4. The water sample treated with Polymer 572 was semi-transparent, while the others were not transparent due to the relatively high percentage of residual turbidity.
Figure 4.2 Treated water samples of the polymers.

Figures 4.3 and 4.4 Treated samples of the polymers (closer).
Regarding the results of the three tests above, polymer 572 was determined to be the optimal polymer among the eight polymers analyzed in the following sections.

4.3 Effects of Polymer Dose and pH on Treatment Performance

The effects of polymer dose and pH were evaluated in terms of the removal efficiencies of oil and turbidity. As discussed before, polymer dose affects the treatment performance of the chemical DAF system. The extent of this effect is evaluated in this section. The objective of performing the pH tests was to determine whether or not any pH adjustment was necessary. The pH adjustment can be omitted if the pH of the raw RDEs falls within the optimal pH range for the selected polymer.

The removal efficiencies of oil and turbidity were evaluated at Polymer 572 doses ranging from 0 to 0.40 mg/L, and at a pH ranging from 4.5 to 9. The operating parameters were fixed as follows: coagulation (G = 193 s⁻¹) for 3 minutes, followed by flocculation (G = 62 s⁻¹) for 15 minutes, followed by flotation using a saturation pressure of 60 psi, a recycle ratio of 14%, and a flotation time of 30 minutes.

As shown in Figure 4.5, the oil concentration and turbidity removals were both significantly affected by polymer dose. The highest oil removal was achieved at 0.10 mg/L. Therefore the optimal dose of Polymer 572 was determined to be 0.10 mg/L. A significant increase in both oil and turbidity removals was observed from dosages ranging from 0 to 0.10 mg/L. The transition from 0 to 0.05 to 0.10 mg/L was accompanied by an average of 33.9% and 14.8% for oil removal, and 45.6% and
22.2% for turbidity removal, respectively. Both oil and turbidity removals dropped when the polymer dosage was increased beyond 0.10 mg/L. From 0.10 to 0.25 to 0.50 to 0.75 mg/L, the accompanying oil removal decreased 2%, 1%, and 26%, while the turbidity removal decreased 1%, 0.2%, and 29%, respectively. The oil and turbidity removals fluctuated when the polymer dosage was adjusted to 0.75, 1.00, and 2.00 mg/L, with a peak turbidity removal of 84.9% at 1.00 mg/L. However, the optimal dose of Polymer 572 was determined to be 0.10 mg/L with a peak oil removal of 83.3%. For DAF applications, the removal of oil is more significant than the removal of turbidity. Therefore, it is desirable to optimize the system on the basis of oil removal efficiency and polymer dosage. Changing the polymer dosage from 0.10 to 1.00 mg/L, a 10-fold increase, only improved turbidity removal by 1.5%, while reducing oil removal by 6.9%.

Figure 4.5 Effect of Polymer 572 dose on oil and turbidity removals; RDE-UR1.
The sudden drop in removal efficiency at 0.75 mg/L stands out as an outlier in an otherwise decreasing trend at polymer dosages > 0.10 mg/L. The decreasing trend could indicate that further increases in dosage would have little improvement on the treatment efficiencies. This further supports the conclusion that the optimal dose of Polymer 572 is 0.10 mg/L.

The outlier at 0.75 mg/L may have resulted from the manual mixing performed on the air-in-water solution in the saturator. If insufficient mixing is achieved, then the solution may not be fully saturated when released into the flotation column. Saturation was designed to be conducted by manually swirling the saturator. Thus, achieving full saturation consistently cannot be guaranteed. When unsaturated water enters the flotation column, fewer air bubbles are released, resulting in lower oil and turbidity removals.

The effects of pH on oil and turbidity removal were evaluated at the optimal polymer dose of 0.10 mg/L. As shown in Figure 4.6, the effect of pH on the performance of the chemical DAF system was significant. The optimum pH range was determined to be from 8.0 to 9.0, where over 80% removals of both oil and turbidity could be achieved. The pH of the three raw RDE samples fitted within the optimal pH range in section 4.1. If a similar pH range could be determined for the other two RDE samples, then the nuisance of adjusting the pH could be eliminated.
The oil and turbidity removal efficiencies increased significantly as the pH increased from 6.0 to 6.5 to 7.0 to 8.0. Each of these pH values were accompanied by an average per cent oil removal increase of 17%, 18%, and 3%, and a turbidity removal increase of 25%, 3%, and 5%, respectively. Both the oil and turbidity removals peaked at a pH = 8.5, and were 87.3% and 90.0%, respectively. A recommended operational pH range (rather than one pH value) is suggested to be from 7.0 to 9.0, with the optimal range around 8.0 and 8.5. Adjustments to pH were determined to be unnecessary because raw RDE is naturally alkaline and falls within the recommended operational range.

The treatment performance of the chemical DAF system is summarized in Table 4.2 (Polymer 572 dose = 0.10 mg/L, and pH= 8.5). Oil and turbidity reached maximum values of 87% and 90%, respectively, while the removals of total and dissolved solids were much lower. This is principally because there are low concentrations of total and dissolved solids in the raw RDE initially.
Table 4.2 DAF treatment performance (RDE-UR1)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Raw RDE-UR1</th>
<th>Treated Water</th>
<th>Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>240</td>
<td>30.5</td>
<td>87%</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>224</td>
<td>22.5</td>
<td>90%</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>560</td>
<td>246</td>
<td>56%</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>mg/L</td>
<td>340</td>
<td>90.0</td>
<td>74%</td>
</tr>
<tr>
<td>TS</td>
<td>mg/L</td>
<td>18.45</td>
<td>8.54</td>
<td>53.7%</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>3.50</td>
<td>3.48</td>
<td>0.6%</td>
</tr>
<tr>
<td>pH</td>
<td>N/A</td>
<td>8.5</td>
<td>8.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

4.4 Effect of Alum Concentration and pH on Treatment Performance

The effects of different alum concentrations and pH values were evaluated in terms of oil and turbidity removal efficiencies. Alum was added to the flotation cylinder in conjunction with the predetermined polymer dose of 0.10 mg/L. The removal efficiencies were evaluated at alum concentrations ranging from 0 to 250 mg/L, and at a pH ranging from 6.5 to 10. As shown in Figure 4.7, the oil and turbidity removals were both affected by the alum dose. A significant increase in turbidity removal was achieved from 0 to 200 mg/L; however the oil removal was only increased by about 10%. Oil removal continuously increased from 50 to 250 mg/L, but the transition from 200 to 250 mg/L was accompanied by an increase of only 0.6%. Therefore the optimal dose of alum was determined to be 200 mg/L. The highest turbidity removal was also achieved at an alum dosage = 200 mg/L.
It was found that the addition of alum could not be effectively optimized in this manor, because both the alum (coagulant) dose and polymer (flocculant) dose were dependent on each other. This observation has been confirmed by other researchers (Moosai and Dawe, 2003). However, multi-variable testing is multiplicative based on the number of variables tested. Proper evaluation in this manner would require a more sophisticated setup, with some degree of automation, then available in this project. To narrow down the likely range of possible conditions, the optimal dose of Polymer 572 was reevaluated at the fixed optimal concentration of alum (prior to pH optimization). The oil and turbidity removals were evaluated at polymer doses ranging from 0 to 0.20 mg/L.

The decrease in oil and turbidity removals at 50 mg/L alum may have resulted from incomplete coagulation at low alum concentrations. Adding polymer that fails to coagulate properly actually increases the turbidity, since there is more diffuse material
within the wastewater. For this reason, the baseline turbidity removal (when alum = 0 mg/L) is greater than the turbidity removal at 50 mg/L. At alum concentrations > 50 mg/L, more successful coagulation was achieved. Overall, there was an increasing trend in removal efficiency from 50 to 200 mg/L.

A significant decrease in turbidity removal was observed when more than 200 mg/L alum was added. However, the oil removal was not significantly affected by the extra alum. The reason for this is likely due to excess alum beyond 200 mg/L. Excess alum does not coagulate well with itself and will therefore contribute to the turbidity of the treated water. Excess alum did not hinder the removal of oil.

The re-determination of the optimal dose of Polymer 572 was performed at 200 mg/L alum. The results are illustrated in Figure 4.8. The oil and turbidity removals were still both significantly affected by the polymer dose, and peak removal was observed at 0.10 mg/L. Both the turbidity and oil removals significantly increased from 0 to 0.05 mg/L, with a minor increase from 0.05 to 0.10 mg/L. However a decrease in both turbidity and oil removals were observed from 0.10 to 0.20 mg/L. Therefore the optimal dose of Polymer 572 was determined to still be 0.10 mg/L, despite the addition of 200 mg/L alum and different RDE sample.
A significant increase in both oil and turbidity removals were observed by adding only 0.05 mg/L Polymer 572. At this dosage the average per cent oil and turbidity removal increased by 18% and 46%, respectively. Therefore Polymer 572 was determined to be more efficient than alum at improving the treatment performance of the chemical DAF system.

The effect of pH on the performance of the chemical DAF is shown in Figure 4.9. Similar to the previous set of pH tests, an increase in both oil and turbidity removals were observed when pH increased beyond 7. However a significant decrease for both oil and turbidity removals were observed when the pH exceeded 9.0. Both the oil and turbidity removals peaked at pH 9.0, at 98.0% and 88.2%, respectively. The optimal pH was therefore 9.0.
Figure 4.9 Effect of pH on oil and turbidity removals; RDE-UR2; alum = 200 mg/L, Polymer 572 = 0.10 mg/L.

Upon analyzing the results presented above, it is concluded that the optimal polymer dose, alum concentration, and pH are 0.10 mg/L, 200 mg/L, and 9.0, respectively. It was also concluded that no pH adjustment is necessary, because the optimal pH of 9.0 is fairly close to the pH of raw RDEs.

The treatment performance of the chemical DAF system on RDE-UR2 under optimal conditions is summarized in Table 4.3. All parameters, except for turbidity, were around or even below the maximum acceptable concentration (MAC) for toilet flushing (Environment Canada, 2006). Therefore the treated water could be reused for toilet flushing following a 1:2 effluent dilution. As such the consumption of fresh water could be reduced by half. The addition of alum increased BOD removal when compared to the RDE-UR1 treatment performance without alum. The BOD of the treated water was only approximate one third of the RDE-UR1. The importance of alum will be further discussed in the next section.
Table 4.3 DAF treatment performance (RDE-UR2)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Raw RDE-UR2</th>
<th>Treated Water</th>
<th>MAC</th>
<th>Percent Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>522</td>
<td>23.2</td>
<td>N/A</td>
<td>95.6%</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>196</td>
<td>10.5</td>
<td>5</td>
<td>94.6%</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>696</td>
<td>188</td>
<td>N/A</td>
<td>73%</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>mg/L</td>
<td>450</td>
<td>25.3</td>
<td>20</td>
<td>94.4%</td>
</tr>
<tr>
<td>TS</td>
<td>mg/L</td>
<td>19.03</td>
<td>9.03</td>
<td>N/A</td>
<td>52.5%</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>2.80</td>
<td>3.91</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>pH</td>
<td>N/A</td>
<td>8.5</td>
<td>9.0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TSS=TS-TDS</td>
<td>mg/L</td>
<td>16.23</td>
<td>5.12</td>
<td>20</td>
<td>68.5%</td>
</tr>
</tbody>
</table>

The treatment performance of the chemical DAF system is shown in Figure 4.10 (Polymer 572 = 0.10 mg/L, alum = 200 mg/L, pH = 9). The treated water was noticeably clearer than the raw RDE-UR2. By optimizing the operating conditions of the chemical DAF system, the treated water was also much clearer than the water treated with a Polymer 572 dose of 2.00 mg/L.
4.5 Effect of Dilution Ratio on Treatment Performance

The effects of dilution ratio on RDEs were evaluated in terms of oil and turbidity removal efficiencies. Removal efficiencies were evaluated at dilution ratios ranging from 1:4 to 1:1 with a fixed polymer dose of $= 0.10$ mg/L. Dilution ratio tests were done to evaluate whether the predetermined optimal conditions could be applied to highly variable RDEs. Dilution was used to simulate this variability. Two parallel tests were also conducted with and without 200 mg/L alum to determine the necessity of alum as a coagulant.

The results are depicted in Figure 4.11 and summarized in Table 4.4. The oil and turbidity removal efficiencies decreased significantly with the more diluted RDEs. The results also indicate that the addition of alum was not necessary.
Oil and turbidity removals, without alum, increased significantly from 1:4 to 1:2 to 1:1, with an 8.8% to 28.6% increase in oil removal, and a 23.7% to 16.4% increase in turbidity removal, respectively. Similar to the parallel tests, the oil and turbidity removals, with alum, both increased from 1:4 to 1:2 to 1:1, with a 79.2% to 12.3% increase in oil removal, and a 120% to 1.8% increase in turbidity removal, respectively. Both oil and turbidity removals peaked at a 1:1 dilution, indicating that the treatment efficiency of the chemical DAF system was highest when no dilution was performed.

Figure 4.11 Effect of dilution ratio on oil and turbidity removals; RDE-UR2.
Table 4.4 Effect of dilution ratio on the removal efficiency of RDE-UR2

<table>
<thead>
<tr>
<th>Dilution = 1:1</th>
<th>Raw Water</th>
<th>Treated Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>RDE-UR2</td>
</tr>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>522</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>196</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dilution = 1:2</th>
<th>Raw Water</th>
<th>Treated Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>RDE-UR2</td>
</tr>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>109</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>118</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dilution = 1:4</th>
<th>Raw Water</th>
<th>Treated Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Unit</td>
<td>RDE-UR2</td>
</tr>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>52.3</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>57.1</td>
</tr>
</tbody>
</table>

From Table 4.4, it was concluded that the addition of alum was unnecessary for the treatment of RDE. The residual oil in the water treated with alum at a dilution ratio = 1:1 was 23.2 mg/L. However, the residual oil in the water treated without alum was 22.5 mg/L. The results indicate that the addition of alum did not have any effect on improving the removal of oil. The measured effect was instead slightly negative. Because oil removal was the main objective of this study, the addition of alum was concluded to be unnecessary, despite its positive effect on turbidity removal.

Furthermore, at a dilution ratio = 1:4, the water treated without alum was observed to be clearer than the water treated with alum, both in terms of oil and turbidity removal. At a dilution ratio of 1:4, the alum dose was in excess relative to the strength of the wastewater. Hence, there was an observed increase in turbidity. From a practical standpoint, this makes the use of alum challenging, as its viability depends on the
relative strength of the wastewater. On the other hand, treatment using just polymer was relatively consistent.

Images shown in Figure 4.12 compare the treated water, with and without alum, at a dilution ratio = 1:1. The air bubbles were smaller and cleaner without alum. With alum, the sludge can be seen within the air bubbles. To investigate this further, a picture (Figure 4.13) was taken after 100 mL of sample was collected from the column. As the water surface dropped, the air bubbles collapsed and the sludge adhered to the wall of the cylinder. This residue was difficult to clean. As such, the addition of alum increased the required maintenance of the DAF system. Once more, this suggests that the use of alum in conjunction with polymer is undesirable.

![Flotation column without alum (left) and with alum (right).](image)
4.6 Effect of Polymer Dose on the Treatment Performance of RDE-BB

The effects of Polymer 572 dose on the treatment performance of RDE-BB were evaluated in terms of the oil and turbidity removal efficiencies. The removal efficiencies were evaluated at polymer dosages ranging from 0 to 0.40 mg/L with no alum or pH adjustment. The objective was to evaluate whether the predetermined optimal conditions could be applied to the high strength RDE-BB.

The results are depicted in Figure 4.14 and summarized in Table 4.5. The oil and turbidity removal efficiencies were significantly affected by polymer dose. More than 97% removal of both the oil and turbidity were achieved at the optimal polymer dose of 0.10 mg/L. No significant improvement was observed at dosages > 0.10 mg/L.
Both oil and turbidity removals increased from 0 to 0.05 to 0.10 mg/L, with an average per cent oil removal increase from 51.6% to 2.0%, and turbidity removal increase from 32.7% to 3.3%, respectively. Both oil and turbidity removals peaked at 0.10 mg/L; however both decreased slightly as the dosage transitioned from 0.10 to 0.20 to 0.40 mg/L. Significant increases in both were observed as the dosage transition from 0 to 0.05 mg/L. For both, about 95% removals could be achieved at a dose of 0.05 mg/L. As mentioned in Section 4.3 (Figure 4.5), the oil and turbidity removals were only 68.5% and 61.2% respectively at 0.05 mg/L for RDE-UR1. This is because there were less oil and turbidity in the RDE-UR1 than the RDE-BB. This phenomenon might indicate that the lower concentration of polymer might coagulate and flocculate more successfully in more concentrated RDEs.

The best treatment performance of the chemical DAF system was achieved at 0.10 mg/L using Polymer 572 as shown in Table 4.5. More than 95% removals were achieved for oil, turbidity, and BODs. However, due to the high residual BOD, at least a 1:6 dilution of the treated water is required before the water can be reused for toilet flushing. Total dissolved solids removal was found to be negative, indicating that the chemical DAF system could not remove solids at such low concentrations (3.58 mg/L). The addition of Polymer 572 might also contribute to the increase in total dissolved solids. However both the raw RDE-BB and the treated water had very low total dissolved solids; therefore it was not determined to be an obstacle to the implementation of the chemical DAF system. The optimal dose of Polymer 572 was determined to be 0.10 mg/L with no alum or pH adjustment, which indicated that the
predetermined optimal conditions could be applied to the more concentrated RDE-BB.

![Figure 4.14 Effect of Polymer 572 dose on oil and turbidity removals; RDE-BB, alum = 0 mg/L, pH = 9.](image)

**Table 4.5 Treatment performance of RDE-BB**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Raw RDE-BB</th>
<th>Treated Water</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>mg/L</td>
<td>1772</td>
<td>35.3</td>
<td>98.0%</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>1138</td>
<td>23.7</td>
<td>97.9%</td>
</tr>
<tr>
<td>COD</td>
<td>mg/L</td>
<td>2840</td>
<td>367</td>
<td>87.1%</td>
</tr>
<tr>
<td>BOD₅</td>
<td>mg/L</td>
<td>2300</td>
<td>110</td>
<td>95.2%</td>
</tr>
<tr>
<td>TS</td>
<td>mg/L</td>
<td>23.05</td>
<td>9.51</td>
<td>58.7%</td>
</tr>
<tr>
<td>TDS</td>
<td>mg/L</td>
<td>3.58</td>
<td>3.65</td>
<td>-2.0%</td>
</tr>
<tr>
<td>pH</td>
<td>N/A</td>
<td>9.0</td>
<td>9</td>
<td>N/A</td>
</tr>
</tbody>
</table>
4.7 Effect of Different RDEs on Treatment Performance

The effects of different RDEs (RDE-UR1, RDE-UR2, and RDE-BB) on the chemical DAF treatment performance were evaluated in terms of the removal efficiencies of oil, turbidity, COD, BOD₅, TS, and. The removal efficiencies were evaluated at a Polymer 572 dose = 0.10 mg/L with no alum or pH adjustment. The results are shown in Figure 4.15.

The oil and turbidity removals were all very high, ranging from 87% to 98% regardless of the RDEs, and slightly increased with dirtier RDEs. Both the BOD₅ and COD removals increased significantly as the contaminants in the RDEs were more concentrated. The BOD₅ removals increased from 73% to 95%, and the COD removals increased from 56% to 87%. The biodegradable oil content was a major contaminant and effectively removed, which contributed to the BOD₅ removals. Therefore the BOD₅ removals were higher than the COD removals. The removal of
total solids were from 52% to 59%, but were not strongly related to the increased strength of the RDEs. The removal of total dissolved solids ranged from -40% to 2%, which indicated that the chemical DAF system could not efficiently remove the total dissolved solids in the RDE. Only about 50% removal of total solids was observed, because the total solids of all the RDEs were lower than 20 mg/L, which is even lower than the maximum acceptable concentration for total suspended solids for toilet flushing.

To sum up, oil and turbidity removals were significant regardless of the RDE. The BOD$_5$ and COD removals were also significant, and gained efficiency with dirtier RDEs. The chemical DAF system could not efficiently remove total dissolved solids.
5. CONCLUSION

Restaurant dishwashers consume large quantities of potable water, and produce equal volumes of oily wastewater which clog and damage pipes over time. Therefore RDE was considered a possible candidate for onsite wastewater treatment. The intent of this research was to investigate the effects of various demulsifiers on the performance of the chemical DAF. The major findings of this research are as follows:

1) Among the demulsifiers tested, dimethylamine P/W epichorohydrin (Polymer 572) exhibited the best performance for the treatment of RDE.

2) The optimal dose of Polymer 572 was determined to be 0.10 mg/L and the optimal pH range was determined to be from 8.5 to 9.0; however pH adjustment was not recommended due to the naturally high alkalinity of the raw RDE. The optimal coagulant (aluminum sulfate) dose was determined to be 200 mg/L; however coagulation was not recommended when the RDE contained more than about 500 mg/L oil and 200 mg/L turbidity.

3) Analysis of raw RDE identified high levels of pH, turbidity, oil and low levels of TDS. High variability was experienced but did not seem to affect the treatment performance of the major contaminants – oil and turbidity, specifically.

4) Polymer 572 could achieve good treatment performance in the chemical DAF system without pH adjustment or coagulation for most RDEs using a dosage of only 0.10 mg/L. Therefore, Polymer 572 was able to overcome the challenges identified in
previous research, namely: (1) the generation of a large sludge volume, and (2) the nuisance associated with adjusting pH so that it falls within an acceptable operating range.

5) The treated water using the chemical DAF could not meet the reuse guideline values for non-potable applications. However, the present findings suggest that the chemical DAF is a viable pretreatment option for RDE and an effective method for removing its major contaminants, particularly oil, which is difficult to remove using other methods.
6. RECOMMENDATIONS

Based on this research, a number of recommendations are made for further study:

1) To investigate the addition of a treatment unit following chemical DAF to improve water quality such that it can meet the Guidelines for Domestic Reclaimed Water for Use in Toilet and Urinal Flushing.

2) To investigate the effects of different types of demulsifiers on treatment performance.

3) To evaluate the chemical DAF based on the treatment of other sources of wastewater produced within a restaurant kitchen.

4) To design a pilot scale continuous chemical DAF system for implementation at a restaurant.
7. REFERENCES


Chung, W. and Young, S. (2013). Evaluation of a Chemical Dissolved Flotation


Hanotu, J.; Bandulasena, H. C.; Chiu, T. Y.; Zimmerman, W. B. (2013). Oil Emulsion


Characterization of the Extracellular Biodemulsifier of Bacillus Mojavensis XH1


**Appendix A-Calculations**

Sample calculation of mean velocity gradient $G$ (Camp, 1955),

$$Q_a = G^2 \mu V \frac{(H/2 + 10.33)}{H \times 10^5} \text{ m}^3/\text{s}$$

Where,

$\mu = \text{absolute viscosity} = 10^{-3} \text{ N s/m}^2$ for water at 20°C

$V = \text{volume of liquid in basin (m}^3) = 0.001 \text{ m}^3$

$H = \text{depth of diffusers (m)} = 0.3\text{m}$

Therefore, if calculating for $G$ at $Q_a = 80 \text{ mL/min}$

$$Q_a = G^2 \mu V \frac{(H/2 + 10.33)}{H \times 10^5} \text{ m}^3/\text{s} \quad \Rightarrow \quad G = \sqrt{\frac{Q_a (H \times 10^5)}{\mu V (H/2 + 10.33)}}$$

$$G = \sqrt{\frac{(1.34 \times 10^{-6} \text{ m}^3/\text{s})(0.3m \times 10^5)}{(10^{-3} \text{ Ns/m}^2)(0.001 \text{m}^3)(0.3m/2 + 10.33)}} = 62 \text{ s}^{-1}$$
The ratio of pressurized recycle flow to the influent flow is described as the recycle ratio: $378mL/(3000mL \times 90\%) = 14\%$
### Appendix B-Standards

Table A Canadian Guideline for Reclaimed Water Use in Toilet and Urinal Flushing\(^a\)

(Environment Canada, 2006)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Water Quality Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Median</td>
</tr>
<tr>
<td><strong>BOD(_5)</strong></td>
<td>mg/L</td>
<td>≤10</td>
</tr>
<tr>
<td><strong>TSS(^b)</strong></td>
<td>mg/L</td>
<td>≤10</td>
</tr>
<tr>
<td><strong>Turbidity(^b)</strong></td>
<td>NTU</td>
<td>≤2</td>
</tr>
<tr>
<td><strong>Escherichia coli(^c)</strong></td>
<td>cfu/100 mL</td>
<td>Not detected</td>
</tr>
<tr>
<td><strong>Thermotolerant Coliforms(^c)</strong></td>
<td>cfu/100 mL</td>
<td>Not detected</td>
</tr>
<tr>
<td><strong>Total Chlorine Residual</strong></td>
<td>mg/L</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\(^a\) Unless otherwise noted, recommended quality limits apply to the reclaimed water at the point of discharge from the treatment facility or treatment unit. BOD\(_5\) = five-day biochemical oxygen demand; TSS = total suspended solids; NTU = nephelometric turbidity unit; CFU = colony-forming unit.

\(^b\) Measured prior to disinfection point. Only one of TSS and turbidity needs to be monitored in a given system.

\(^c\) Only one of *Escherichia coli* and thermotolerant coliforms needs to be monitored in a given system.