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## Electrochemical Disinfection of Municipal Wastewater using Alternating Current

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# Electrochemical Disinfection of Municipal Wastewater using Alternating Current

A Thesis

Submitted to the Graduate Faculty of the  
University of New Orleans  
in partial fulfillment of the  
requirements for the degree of

Master of Science  
In  
Engineering (Environmental Engineering)

By

Xavier A. Chávez Reyes

B.Sc., University of New Orleans, 2013

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## **List of Units**

mg/L	Milligrams per Liter
mL	Milliliters
cfu	Colony Forming Unit
L/min	Liters per Minute
BOD <sub>5</sub>	The Five-day Measure of the Biochemical Oxygen Demand
TSS	Total Suspended Solids
sec	Seconds
ms	Milliseconds
min	Minutes
L	Liters
cm	Centimeters
m	Meters
m <sup>3</sup>	Cubic meters
MGD	Mega Gallons per Day
LPM	Liters per Minute
PSI	Pounds per Square Inch
°C	Degrees Celsius
A	Amperes
V	Volts
Ω	Ohms
kW	Kilowatts
kWh	Kilowatts-hour

\$/L	Dollars per Liter of treated wastewater
\$/ m <sup>3</sup>	Dollars per Cubic meter of treated wastewater
\$/ MG	Dollars per Mega Gallon of treated wastewater



## **List of Acronyms**

CWA	Clean Water Act
NPDES	National Pollutant Discharge Elimination System
DEQ	Department of Environmental Quality
LDEQ	Louisiana Department of Environmental Quality
BOD <sub>5</sub>	The Five-day Measure of the Biochemical Oxygen Demand
TSS	Total Suspended Solids
E. coli	Escherichia coli
TCR	Total Coliform Rule
CDC	Center for Conventional Disease Control and Prevention
PVC	Polyvinyl Chlorine
CERM	Center for Energy Resource Management
USEPA	United States Environmental Protection Agency
NESC	National Environmental Services Center
CAD	Computer Aided Design
AC	Alternating Current
DC	Direct Current
V	Voltage
I	Current
R	Resistance
ROS	Reactive Oxygen Species
WVDEP	West Virginia Department of Environmental Protection

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## **Abstract**

This research focused on chlorine-free disinfection of wastewater by complying with today's regulations. The equipment used was a continuous flow electrochemical reactor connected to an alternating current (AC) power supply. The electrodes used were made out of titanium coated with iridium oxide. To determine the inactivation of *Escherichia Coli*, a bacterial count method based on the USEPA method 1603 was used.

After several experiments it was determined that electrochemical disinfection using AC was not efficient and economic enough to be classified as a viable alternative to chlorine disinfection. It was demonstrated that chlorine can be produced by electrolysis using AC and that no hydrogen could be noticed as a byproduct of the electrolysis of wastewater. When the results from this investigation were compared to the ones obtained using DC in Acosta (2014), it was determined that the belief that AC and DC are equally efficient at disinfecting wastewater is wrong.

**Keywords:** wastewater, electrochemical disinfection, alternating current, *Escherichia Coli*

# **Section 1**

## **Introduction**

### **1.1 Problem Statement**

With population growth in the last century, the demand for natural resources has increased and so has the pollution of the environment and bodies of water. This increment in water pollution has been raising concerns around the world. Even though both, developed and developing countries have created regulations to accomplish better usage of natural resources, in the majority of underdeveloped countries regulations might be not enforced by local governments or might be lacking more updated information. As a result, it is common to find hazardous waste being discharged to water bodies and causing environmental and health issues (Mosquera, 2013).

Disinfection through chlorination has been used for more than 100 years, due to its efficacy in bacterial and virus inactivation. According to the Center for Disease Control and Prevention, "one of the first known uses of chlorine for disinfection was not until 1850, when John Snow used it to attempt to disinfect London's water supply during that now-famous cholera epidemic" (CDC, 2014). Chlorine is the most widely used disinfectant for the treatment of municipal wastewaters due to its high oxidizing properties of cellular material. There are several forms in which chlorine can be supplied, depending on the suitability of the disinfectant in a treatment facility. One of the drawbacks of using chlorine is that residual chlorine, even at low temperatures, is very toxic to aquatic life and might require dechlorination, which will increase the costs of operation. Another disadvantage is that shipping and storing chlorine containing agents might pose a risk for humans, and strict safety regulations have to be used (USEPA, 1999).

In the last years the need for newer disinfecting technologies has been increasing. Ozone and ultraviolet light are the other alternatives to disinfect water but are more expensive technologies. Municipalities are looking for chlorine-free ways of disinfecting water and wastewaters that are both economical and highly effective. There are many proposals for newer ways of treating water, one of them is electrochemical disinfection, which is based on the electrolysis of water inside a reactor which contain parallel plates that act as electrolytic cells. Electrochemical disinfection of wastewaters, as its name implies, uses wastewater as the electrolyte. While pure water is a bad conductor of electricity, drinking water on the other hand contains minerals, as calcium, magnesium and sodium, increasing its conductivity. Since wastewaters include kitchen wastewater, the table salt used also increases the conductivity and the chlorides content. When electrolysis occurs, oxidation and reduction takes place, decomposing water into oxygen and hydrogen and sodium chloride into sodium and hypochlorite ion. Commercial electrochemical disinfection reactors commonly use direct current, which favors the generation of free residual chlorine. Chlorine residual, in turn, is regulated as a pollutant when final effluents are discharged into receiving waters. As an alternative, several researchers such as Barashkov et al. (2010), Park et al. (2004) have suggested that using AC substantially decreases the generation of free chlorine.

The purpose of this research is to determine how feasible it is to use electrochemical disinfection using an alternating current (AC) power source as an alternative disinfecting method for secondary clarifier wastewater effluents. To determine the efficacy of the method, the inactivation of *Escherichia Coli*, a common wastewater indicator organism, is measured by comparing untreated secondary clarifier effluent and treated wastewater with an electrochemical reactor. The laboratory unit used in this research was manufactured by Ecolotron Inc. This

reactor provided the flexibility of being able to use different reactor volumes and a different number of titanium electrode plates coated with iridium oxide (Ti/IrO<sub>2</sub>). The main objective of this research is to find the most economical configuration of electrodes, to achieve a bacterial inactivation that complies with the National Pollutant Discharge Elimination System (NPDES) regulations.

## **1.2 Technology Description**

When the electrolysis of water occurs, the electrolysis of other electrolytes present in the water occurs as well. When there is sodium chloride on the water (table salt), or any other chlorine containing compound, the conductivity of water is increased. When the electrolysis of said compounds occur, chlorine is formed in the anode of the electrolytic cell. Depending on several factors, higher or lower quantities of chlorine can be formed during electrolytic processes.

According to the available literature, electrochlorination does not appear to be the main disinfecting part of the electrolytic process. The production of H<sub>2</sub>O<sub>2</sub>, [O], ·OH, and ·HO<sub>2</sub>, which are more powerful killing substances with a short life, is what provides a high degree of disinfection. According to Pulido (2005), the bactericidal efficiency of the process generally increases when the detention time and current density are increased. The parameters under which disinfection was achieved varies from millivolts to kilovolts depending on the electrodes used and on the limitations of each research. A literature review is presented in the following section.

## **Section 2**

### **Literature Review**

#### **2.1 Regulations and Permits**

In order to carry out activities that involve management, use and discharge of water and wastewater, certain permits must be obtained and regulations need to be complied. Some standards and regulation are enforced by federal agencies while others only apply locally. Depending on the water intended to be used, different standards may apply. Water Quality Standards describe the parameters for a designated water body depending on its uses by a setting a criteria to protect water's quality from specified pollutants. The Clean Water Act (CWA) contains water quality standards that depend of four basic elements:

- Designated uses of the water body (e.g., recreation, water supply, aquatic life, agriculture),
- Water quality criteria to protect designated uses (numeric pollutant concentrations and narrative requirements),
- An antidegradation policy to maintain and protect existing uses and high quality waters, and
- General policies addressing implementation issues (e.g., low flows, variances, mixing zones).

(WVDEP, 2014)

The Clean Water Act established the basic structure for regulating the discharge of pollutants into the body of waters of the United States. It also regulates quality standards for surface waters. The basis of the CWA was enacted in 1948 and was called the Federal Water



Pollution Control Act, but the Act was significantly reorganized and expanded in 1972. "Clean Water Act" became the Act's common name with amendments in 1972 (Mosquera, 2013).

In Louisiana, the Louisiana Department of Environmental Quality (LADEQ) has been running the NPDES program since 1996. It contains two sections of the LPDES; one is focused on industrial water permits and the other in municipal general water permit. The National Pollutant Discharge Elimination System Permit regulates wastewater treatment in Louisiana under the permit number LA0038091. This is what defines limits to which municipal wastewater has to be treated before discharging into the Mississippi River (Pulido, 2005).

The permit establishes the limits for conventional and unconventional pollutants that should be monitored such as Biological Oxygen Demand (BOD), Total Suspended Solids (TSS), Fecal Coliforms, pH, Residual Chlorine and Visible Foam. The definition of these terms are the following:

- BOD<sub>5</sub>: The five-day measure of the biochemical oxygen demand.
- Total Suspended Solids (TSS): The amount of solid material suspended in water, commonly expressed as a concentration in terms of mg/L.
- pH: Measure of acidity of an aqueous solution.
- Fecal Coliform: A gram negative, non-spore-forming, rod-shaped bacteria found in the intestinal tract of warm-blooded animals

<b>Table 2.1: NPDES permit summary (Cagle, 2012)</b>		
Parameter	Weekly	Monthly
BOD <sub>5</sub>	45 mg/l	30 mg/l
TSS	45 mg/l	30 mg/l
Fecal Coliform	400 MPN/100 ml	200 MPN/100 ml
Escherichia Coli	235 cfu/100 ml (one dose)	200 MPN/100 ml (30 day rolling)
pH	Between 6 and 9	Between 6 and 9
Total Residual Chlorine	0.05 mg/l	0.05 mg/l
Other requirements	No floating solids or visible foam	No floating solids or visible foam

## 2.2 Typical Wastewater Bacteria

Wastewater treatment is a process that must be taken care of and regulated properly. The presence of pathogenic microorganisms in wastewater is a potential threat to human health.

Waterborne diseases such as diarrhea can be caused by common pathogens like bacteria (*Shigella dysenteriae*, *Escherichia Coli*, *Salmonella typhi* and *Campylobacter*), viruses and parasites (*Entamoeba histolytica*) including protozoa (*Giardia lamblia* and *Cryptosporidium*), worms and rotifers that are usually spread by the fecal-oral route.

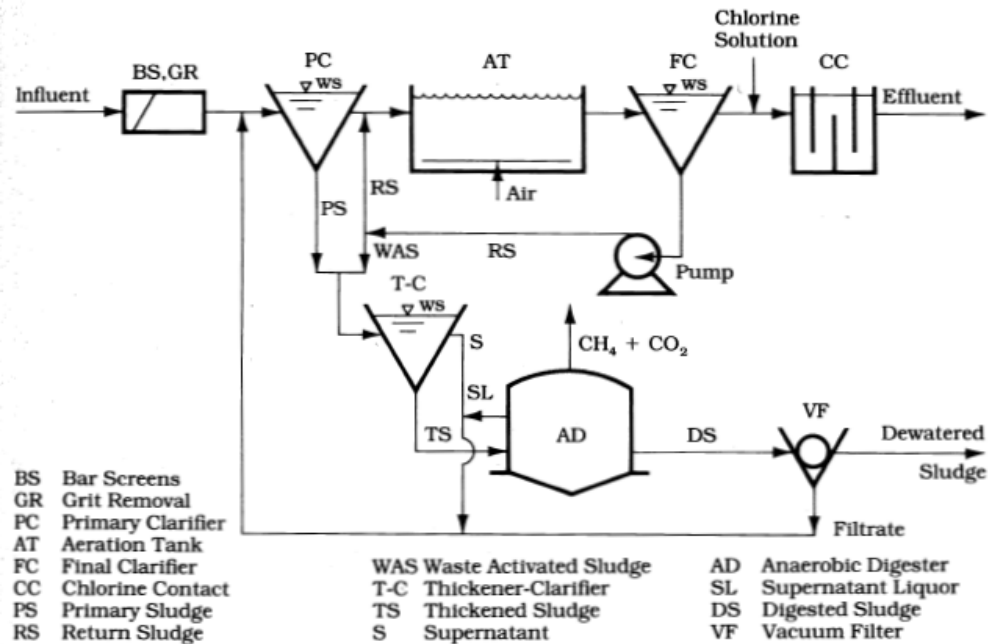
The bacteria chosen for this investigation is the *Escherichia Coli* (*E. Coli*). This bacteria is one of the several types of bacteria that normally inhabit the intestine of humans and animals. Some strains of *E. coli* are capable of causing disease under certain conditions when the immune system is compromised or disease may result from an environmental exposure. This bacterium has been used as a biological indicator since 1890. (Shanson, 1999)

Due to the numerous quantities of bacteria present in wastewater, testing for every threat is not practical. To measure the suitability for drinking, bathing and returning water to the environment, different tests have been design. These tests work under the principle of identifying certain type of microorganisms that serve as indicators. The indicator tests help identify fecal pollution in water and make an estimation of the quantity of microbial pathogens. There are limits to the amount bacteria that can be present in the water. Regulations as the EPA Total Coliform Rule (TCR) total and fecal Coliform as well as the enterocci-fecal streptocci must be complied (Mosquera, 2013).

## **2.3 Wastewater Treatment Plants**

Wastewater is the drinking water after it has been used by a community for several different applications and that now contains a variety of compounds that are dangerous to humans and animals making it unsuitable to be used or returned to the environment before being treated (Tchobanoglous et al, 2014). Wastewater treatment plants treat the raw municipal sewage to protect the communities and the environment. There are several processes through which wastewater undergoes, the first step in the treatment of water is the removal of big particles using bar screens and grit and sand removers. With this pretreatment the damage of pumps and other accessories can be prevented. After pretreatment, sometimes the wastewater can be mixed with coagulants to accelerate the settling process.

Next, the water is placed in a primary clarifier or sedimentation basin to allow the water to settle at the bottom of the tank. The effluent from this sedimentation basin is then transferred to an aeration tank where air is injected to promote aerobic bacterial growth and substrate consumption. This water is then transferred to a secondary clarifier where the bio-solid waste due to bacterial flocculation will settle. The bio-solids are referred as sludge, part of this sludge is recycled and the other part is wasted. The wasted sludge is combined with the sludge from the primary clarifier to be treated in a thickener and undergoes other processes in order to be disposed. The wastewater from the effluent of the secondary clarifier is usually treated with chlorine and moved to a contact basin. The treated wastewater must have 200 or less coliforms per 100mL. Depending on the chlorine concentrations of the plant's effluent, dechlorination might be needed. Once effluent's quality complies with the environmental regulations, the water can be discharged into streams or any other free flow surface to be part of the environment again.



**Figure 2.1: Wastewater Treatment Plant Layout (Reynolds & Richards, 1996)**

## 2.4 Wastewater Disinfection

The terms wastewater disinfection, refer to the destruction or inactivation of the pathogenic organisms in order to avoid possible spread of waterborne diseases. Since the disinfection processes are not perfect, the inactivation of all the organisms in the water is not completely guaranteed. For this reason a disinfectant must have the following characteristics:

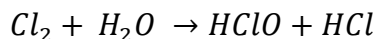
- ability to penetrate and destroy infectious agents under normal operating conditions
- lack of characteristics that could be hazardous to people and the environment before or during disinfection
- safe and easy handling, storage, and shipping
- absence of toxic residuals and mutagenic or carcinogenic compounds after disinfection
- affordable capital and operation and maintenance (O&M) costs

(Solomon et al., 1998)

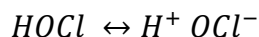
#### 2.4.1.1 Chlorination

For more than 100 years, chlorine has been the most widely used disinfectant due to its high efficacy at low concentrations. It is relatively cheap, and depending on the dose that was applied to a volume of water, a residual is formed. It has more than one form in which it can be applied, for example there is chlorine gas, sodium hypochlorite solution, chlorine dioxide among others.

When chlorine gas is added to water, the hydrolysis of chlorine occurs, generating hypochlorous acid (HClO); it follows this reaction:



The hypochlorous acid produced from the hydrolysis dissociates into a hypochlorite ion, as follows:



Although both the hypochlorous acid and the hypochlorite ion are effective disinfecting agents, the acid form is more effective which makes the relative distribution of both agents a very important factor (Reynolds & Richards, 1996).

#### 2.4.1.2 Advantages of Chlorination

Chlorination is the most used method because:

- It is a well-established technology.
  - It is more cost effective than the disinfection using ozone or UV.
  - Because of its flexible dosing control, the chlorine residual that remains in the treated water can generate a prolonged disinfection.
  - Chlorine is very effective disinfecting a wide range of pathogenic organisms and in oxidizing certain organic and inorganic compounds, removing certain undesirable odors.
- (USEPA, 1999)

### **2.4.1.3 Disadvantages of Chlorination**

Amongst the drawbacks of using chlorine one can find:

- Due to chlorine's toxicity, dechlorination may be required.
- The storage, shipping and handling of chlorine signifies a risk because all forms of chlorine are highly corrosive and toxic.
- Some hazardous compounds might be formed due to the oxidation of organic matter, increasing the total dissolved solids in the treated effluent.
- The long term effects of discharging dechlorinated compounds into the environment are still unknown.

(USEPA,1999)

### **2.4.1.4. Dechlorination**

Because of chlorine's toxicity, discharging effluents that contain residual chlorine might be very harmful for marine ecosystems and wildlife. For this reasons the dechlorination is often necessary. Dechlorination, removes the free and combined chlorine residuals, reducing the effluent's toxicity. The NPDES permits require that the amount of residual chlorine in the water that is going to be discharged should be “non-detectable”. This means that dechlorination must be applied to the effluent. There are only a few chemicals that are commonly used to address this problem such as: Sodium bisulfate, sulfur dioxide, activated carbon among others. Sulfur dioxide is the preferred method for dechlorination because using activated carbon signifies very high operation costs. (Mosquera, 2013). Since older wastewater treatment plants have older and outdated equipments, the cost of dechlorination tends to be higher than in newer plants with more effective equipment that follow the NPDES. Because of this, new alternatives that meet or exceed the environmental standards as well as the operation standards are sorely needed (Cagle, 2012).

### 2.4.2.1 Alternatives to Chlorine

There are several alternatives to wastewater chlorination. Some of the most known alternatives to chlorine are the use of ozone and the use of UV light, which usually imply high costs of operation. Another method that is gaining reputation in wastewater treatment is pasteurization. The following table shows a comparison of the technologies used for disinfection of wastewater.

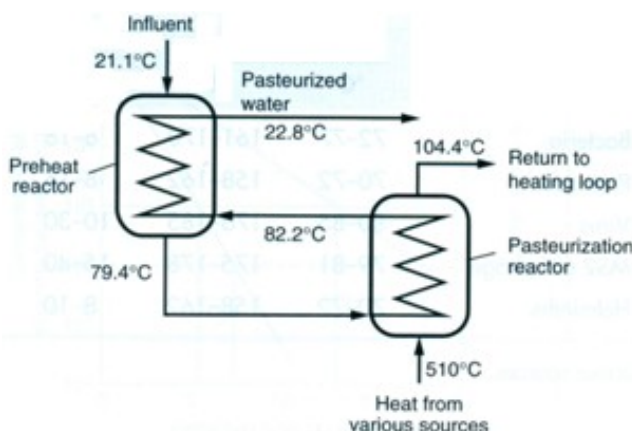
**Table 2.2: Comparison of technologies used for the disinfection of wastewater (Tchobanoglous et al, 2014)**

Characteristic <sup>b</sup>	Chlorine gas <sup>c</sup>	Sodium hypochlorite <sup>c</sup>	Combined chlorine	Chlorine dioxide	Ozone	UV radiation	Pasteurization
Availability/cost	Low	Moderately low	Moderately low	Moderately low	Moderately high	Moderately high	Moderate
Deodorizing ability	High	Moderate	Moderate	High	High	na <sup>d</sup>	na
Interaction with organic matter	Oxidizes organic matter	Oxidizes organic matter	Oxidizes organic matter	Oxidizes organic matter	Oxidizes organic matter	Absorbance of UV radiation	na
Corrosiveness	Highly corrosive	Corrosive	Corrosive	Highly corrosive	Highly corrosive	na	na
Toxic to higher forms of life	Highly toxic	Highly toxic	Toxic	Toxic	Toxic	Toxic	Toxic
Penetration into particles	High	High	Moderate	High	High	Moderate	High
Safety concern	High	Moderate to low	High to moderate <sup>a</sup>	High	Moderate	Low	Low
Solubility	Moderate	High	High	High	Moderate	na	na
Stability	Stable	Slightly unstable	Slightly unstable	Unstable <sup>f</sup>	Unstable <sup>f</sup>	na	na
Effectiveness for							
Bacteria	Excellent	Excellent	Good	Excellent	Excellent	Good	Excellent
Protozoa	Fair to poor	Fair to poor	Poor	Good	Good	Excellent	Excellent
Viruses	Excellent	Excellent	Fair	Excellent	Excellent	Good	Good
Byproduct formation	THMs and HAAs <sup>g</sup>	THMs and HAAs <sup>g</sup>	Traces of THMs and HAAs, cyanogens, NDMA	Chlorite and chlorate	Bromate	None known in measurable concentrations	None known in measurable concentrations
Increases TDS	Yes	Yes	Yes	Yes	No	No	No
Use as a disinfectant	Common	Common	Common	Increasing slowly	Increasing slowly	Increasing rapidly	Increasing slowly

### 2.4.3.1 Disinfection by Pasteurization

Pasteurization is known as the process in which food or water is heated to a specified temperature for a determined amount of time with the purpose of killing microorganisms. This process was first demonstrated to work by Pasteur and Bernard. Due to some problems related with wine which were called "diseases of wine", solutions had to be found. Pasteur defined the exact time and temperature that was required to kill specific microorganisms, without altering the taste of wine (Tchobanoglous et al, 2014). Pasteurization is extensively used in the food industry to ensure the consumer health protection. It has also used in environmental engineering for

sludge stabilization/disinfection, and recently it has demonstrated its applicability for wastewater disinfection (Salveson et al., 2011). A diagram of the operating process is shown in the figure below.



**Figure 2.2: Wastewater Pasteurization Process (Tchobanoglous et al, 2014)**

As can be seen in Figure 2.2, the wastewater that is going to be disinfected is introduced in a preheat reactor where the heat from the treated effluent is used increase the temperature of the incoming flow. This preheated influent is then moved into the pasteurization reactor where the heat from an external source is used to increase the temperature of the influent to a desired temperature and the fluid is held for a determined period of time. The external heat source can be from a turbine exhaust, engine exhaust, waste gas burner exhaust or from any other heat source that can be utilized instead of just liberating the heat into the air. There are three different types of pasteurization: batch, high-temperature short time (HTST) and ultra-high temperature (UHT). Batch pasteurization is only recommended for small treatment plants because of the large volumes required. HTST is used for most industrial operations and is the form used for the treatment of wastewater. The UHT pasteurization process is also known as flash pasteurization and is only used in more specialized applications (Tchobanoglous et al, 2014).



<b>Table 2.3: General operation ranges for pasteurization technologies (Tchobanoglous et al, 2014)</b>			
Pasteurization Technology	Temperature [°C]	Time	Comments
Batch	62 - 64	30 - 35 min	Inactivates most vegetative bacterial cells including streptococci, staphylococci, and mycobacterium tuberculosis
High-temperature short time (HTST)	72 - 75	8 - 30 s	Same effect as batch, but at much shorter times
Ultra-high temperature (UHT)	135 - 140	< 1 - 5 s	Lethal for most bacterial cells at even shorter times than HTST

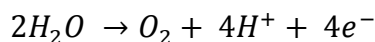
The following figure shows the detention times and temperatures necessary to achieve approximately 4-log removal inactivation of selected microorganisms using the high-temperature short time pasteurization process.

<b>Table 2.4: General operation ranges for HTST (Tchobanoglous et al, 2014)</b>			
Microorganism	Temperature [°C]	Time [s]	Comments
Bacteria	72 - 77	6 - 16	Essentially complete inactivation
Protozoa	70 - 72	8 - 16	
Virus	80 - 85	10 - 30	
MS2 Coliphage	79 - 81	15 - 40	Essentially complete destruction
Helminths	70 - 72	8 - 10	

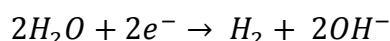
#### 2.4.4 Electrochemical Disinfection

Electrochemical disinfection can be define as the inactivation of microorganism due to the application of a current in the water that needs to be treated. It is a relatively new disinfecting method and consists of applying a current and a voltage to a set of electrodes to produce the electrolysis of water and of the electrolytes present in water. The electrode that possesses a positive charge is called anode and the one with a negative charge is called cathode. When an electric current is applied to an electrochemical disinfectant, by its definition, water undergoes electrolysis. When the electrolysis of water occur, oxidation and reduction reactions take place in

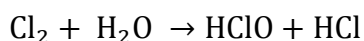
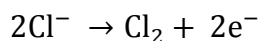
the vicinity of both the anode and the cathode. The oxidation process occurs at the anode and is responsible for generating oxygen gas from water and follows this reaction:



Oxygen is produced at the anode and is accompanied by an acidification of the water near the anode. On the other hand, the reduction process occurs at the cathode, which contributes to the generation of hydrogen gas from water and follow this reaction:



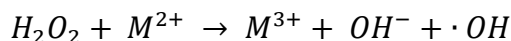
Hydrogen is produce at the cathode which causes the water near de cathode to become alkaline. The electrolysis of chlorine occurs as well and it takes place in the anode, were the chloride ions are oxidized at the anode, producing chlorine gas. Then the chlorine hydrolyses in water which forms hypochlorous acid (Kraft, 2008). The reactions are as follows:



A new type of water purification device was used on research using alternating current were 6000V, 50Hz were applied to a flow of deionized water (Johnstone, 2000).. The disinfection system consisted of a valve that served as the inlet, to control the water flow. Next the water flowed through two deionising resin cartridges in order to reduce the conductivity of the water. An air trap removes undesired bubbles present in the water in order to prevent air reaching the electrode chamber. The Electrode chamber consisted of two square parallel plates, 10 x 10mm separated by a distance of 2mm. The electrode material was titanium because of its hardness and resistance to corrosion (Johnstone, 2000). The efficacy of the electro-disinfector was tested through the inactivation of a bacteria called *Serratia marcescens*. After some testing, the resin had to be removed because it was acting as a filter, capturing the bacteria. The

disinfection obtained was of 99.9% for a detention time of 17ms. The claim of the paper is that a high intensity of electric field disrupts the bacteria cells and kill them. No observation on temperature or chlorine generation were reported.

On the report presented by Barashkov et al., alternating current was the source of electrochemical disinfection as well. Deionized (DI) water polluted with *Salmonella* Typhimurium (S. Typhimurium) bacteria was disinfected by alternating current and ammonium sulfate was used as electrolyte to increase the deionized water conductivity. Since the treated water contained no sodium chloride, the investigation falls under the classification of chlorine free disinfection. Stainless steel electrodes were used and according to this paper, the use of metal electrodes is what makes the hydrogen peroxide produced by electrolysis to react with said metal and decompose into a metal precipitate, a hydroxide ion ( $\text{OH}^-$ ) and a hydroxyl radical ( $\cdot\text{OH}$ ) (Barashkov et al., 2010). The chemical reaction is as follows:



Since the life span of the hydroxyl radicals is very short, it is difficult to detect the radicals presence in the effluent by conventional methods such as the electron spin resonance. For this reason the  $\cdot\text{OH}$  were measured using N,N\_dimethyl\_p\_nitrosoaniline (RNO) as a spin trap for hydroxyl radicals. The concentration of OH radicals resulting from electrolysis was estimated with a spectrophotometer. An electric current of the range of 0.21A was used with voltages varying from 40V to 170V with respect to the electrolyte used to avoid electrode corrosion (Barashkov et al., 2010).

In the investigation done by Park et al., the indicator bacteria was *Vibrio parahaemolyticus*. It was inactivated by alternating low-amperage electricity. In this research, low amperage alternating current was applied to treat effluent seawater to be used in a large-

scale disinfection. The authors reported that using alternating current they were able to avoid the typical problems related with high quantities of chlorine generated when continuous direct current is used. Their results showed that alternating current treatment inactivates *V. parahaemolyticus* in effluent seawater while minimizing the generation of chlorine and that this AC treatment is therefore suitable for practical industrial applications (Park et al., 2004). In this research it was demonstrated that as the frequency of the alternating current decreased the chlorine generation increased. This was because as the frequency approached zero, the polarity of the current would start being similar to the one in direct current. When the frequency used was 50Hz - the normal frequency range for alternating current - very small concentrations of chlorine were reported.

In Senftle et al. both AC and DC were applied to a reactor which used electrode made of graphite. During experiments using alternating currents, no gas formation was observed and higher values of alternating current had to be applied to achieve similar results to ones obtained when direct current was used (Senftle et al., 2010). In a different research, chlorine free water was treated to demonstrate that disinfection occurs due to the presence of reactive oxygen species. The study showed that reactive oxygen species (ROS) are additional disinfectants. Such species as  $\cdot\text{OH}$  and  $\text{O}_3$  are formed by electrolyzing water and can cause a significant inactivation of microorganism, as much as chlorine in the electrochemical disinfection (Jeong et al., 2006). Since the potential role of  $\cdot\text{OH}$  out of the ROS, has oxidizing potentials higher than that of chlorine, it must be noticed that the it might be treating the spore forming microorganisms that are difficult to inactivate by only using chlorine.

## Section 3

### Methodology

#### 3.1 Wastewater sample collection

The wastewater samples used for this research were collected from the Marrero Wastewater Treatment Plant, located at 6250 Lapalco Boulevard, Marrero, LA on Jefferson Parish. The samples taken were from the overflowing effluent of the secondary clarifier; the effluent overflows from the tank's weirs and is later transported to the chlorine basin to be disinfected. About eighty liters were taken and stored on plastic containers for easier transportation to the laboratory located at the Center for Energy Resource Management (CERM) which is based on the Research Technology Park of the University of New Orleans, in New Orleans, Louisiana. Since the E. Coli located in the wastewater have a short life span, it was not possible to collect more water and store it in the laboratory. New water samples had to be taken on each day experiments were being run to ensure that there were live bacteria in the water. The following figure shows the secondary clarifier located at Marrero's Wastewater Treatment Plant.



**Figure 3.1: Secondary clarifier**



**Figure 3.2: Wastewater overflowing from weir**

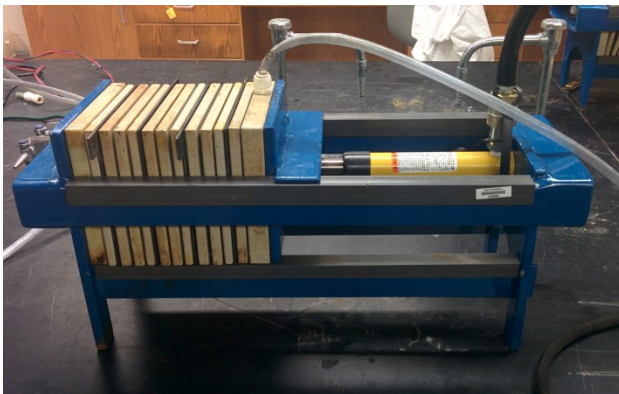
### **3.2 Experimental Setup**

Since an alternating current power supply was needed, a 3 Amp Variac Variable Transformer, 300va Max, 0-130 Volt Output was purchased to conduct the respective experiments. The following figure shows the unit used as a power supply for this research.



**Figure 3.3: 3 Amp Variac Variable Transformer**

An electrochemical disinfectant and manual hydraulic fluid pump from previous researches were reused for this investigation. An approximately  $0.1893\text{m}^3$  (50-gallon) water tank was used to feed the reactor (electrochemical disinfectant) and a mechanical air-driven stirrer was used to ensure that the bacteria were evenly distributed in the wastewater. The electrochemical disinfectant was manufactured by Ecolotron Inc. and is made of steel with internal dimensions of 30.48cm height, 17.78cm depth, and 52.07cm length (McCraven, 2009).



**Figure 3.4: Electrochemical disinfectant**



**Figure 3.5: Tank and stirrer**

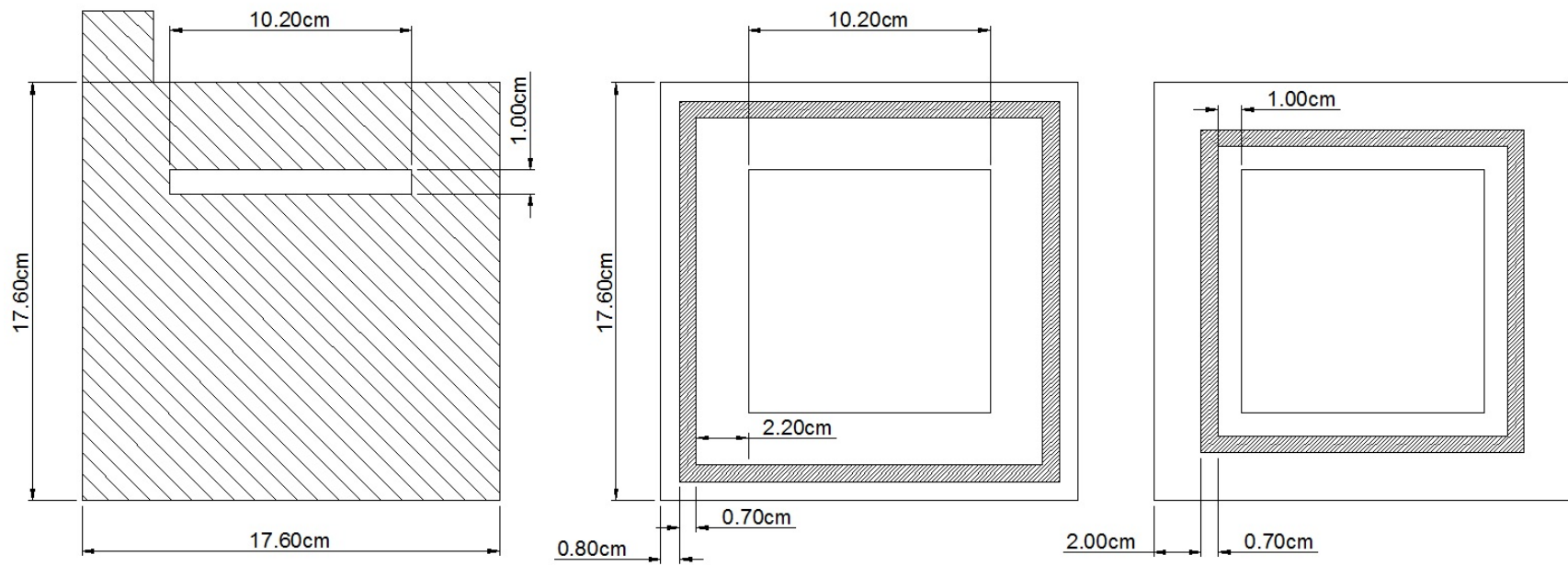
Different arrangements of electrode plates and plastic plates were used to have a desired reactor volume. The electrode plates used for this research were made from titanium coated with iridium oxide (Ti/IrO<sub>2</sub>). Each electrode plate had a dimension of 17.6cm x 17.6cm x 0.3cm with a 1.0cm x 10.2cm opening to allow the wastewater to flow. The electrodes were used with the opening in a vertical position for the electrolysis gases to exit in a more efficient way. These plates were placed parallel inside the reactor with their openings opposite to one another to simulate a plug flow through the reactor. The plastic plates had a dimension of 17.6cm x 17.6cm x 1.30cm and had an opening of 10.2cm x 10.2cm. The plastic plates were used not only to keep the electrodes apart from each other but also to increase the volume of each electrolytic cell, which in turn increased the volume of the reactor. Increasing the distance between electrodes provided a greater electrical resistance due to the wastewater between electrodes. The plastic plates had a 0.7cm insulator seal on both sides of the plate. Once the desired configuration of plastic plates and electrodes was decided, a manual hydraulic pump was used to move a piston that would apply pressure on one of the ends of the reactor by pushing the plates against each other. The plastic plates had to be carefully placed against one another by making the correct insulator seal coincide on each side to have the reactor sealed and avoid having wastewater

leaking. Once the reactor was properly sealed, the tank's valve would be opened and the reactor would start getting filled. When the wastewater started flowing on the effluent side, the reactor would be tilted and shaken to evacuate the air trapped inside, minimizing the dead spaces and air pockets inside the reactor. After each trial the reactor was purged and checked for the presence of precipitates on the electrodes or their vicinity.

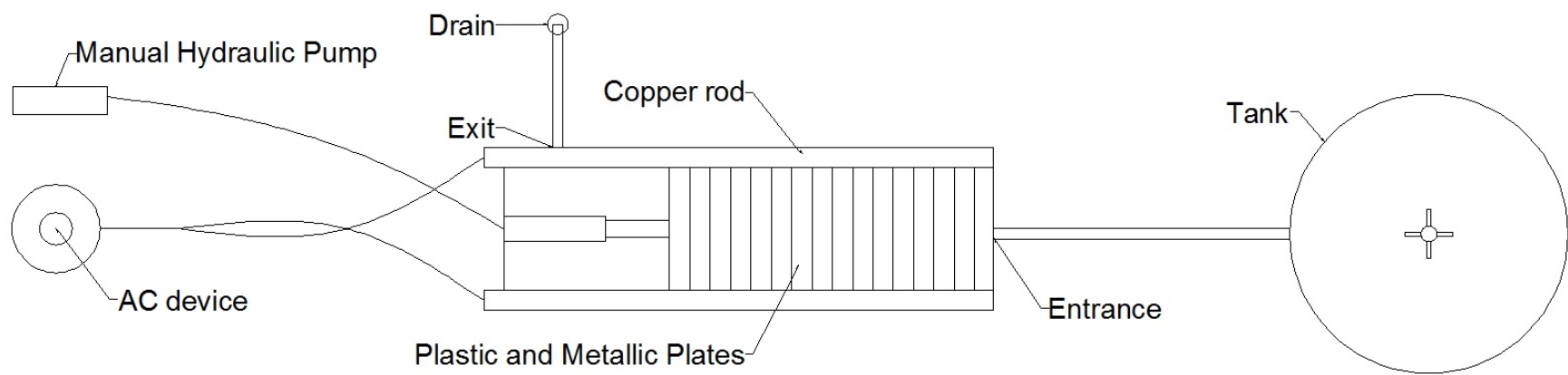
The alternating current power supply was used to regulate the voltage and indirectly regulate the current flowing through the system as well. A three prong plug was connected to the output of the power supply and alligator clamps were connected to the positive and negative wires; a banana plug was connected to the ground wire which was in turn, connected to the ground of the wall power outlet. Since the wires used were less than 0.32cm in diameter and less than 2m long, it can be assumed that the loss of electricity could be ignored. The voltage input necessary to get a desired value of current depended on the number of electrodes connected to the power supply, the more electrodes connected, the lower the voltage and the higher the current.

Since it was recommended to keep the wastewater completely mixed, before, during and after the tests, the best available choice was to use a  $0.1893\text{m}^3$  (50 gallon) tank with a mechanical stirrer. A needle valve was attached at the effluent of the reactor to make handling the flow a bit of an easier task. Because the flow varied with the water level on the tank, the needle valve had to be constantly monitored to keep the flow as steady as possible. After at least two and a half detention times had passed in the reactor, three samples were taken for bacterial count purposes and another sample was taken for chlorides and chlorine testing. Figure 3.6 shows the CAD drawing dimension details of the plastic plates and the metal plates. Figure 3.7 shows a layout diagram for the reactor, the tank and the power source.





**Figure 3.6: Metallic Plate and plastic plates details**



**Figure 3.7: Reactor Layout**

### **3.3 Experimental Plan**

The experimental plan was designed to determine the most efficient values of voltage and current in conjunction with the best electrode configuration to achieve a percentage of disinfection in which there was no more than 200 E. Coli colonies per 100mL of effluent. This objective would mean that the regulations are being followed and in the most economical way possible due to the high cost of the titanium electrodes.

### **3.4 Identification of Escherichia Coli**

The method employed to analyze the effluent samples was based on the United States Environmental Protection Agency "Method 1603: Escherichia coli (E. coli) in Water by Membrane Filtration Using Modified membrane-Thermotolerant Escherichia coli Agar (modified mTEC)." This is a modification of EPA Method 1103.1 in which the mTEC media required the filtered sample to be transferred to another substrate. Method 1603 is a bacterial count method to detect and enumerate Escherichia Coli bacteria in ambient waters and disinfected wastewaters (USEPA, 2009).

### **3.5 Modified mTEC agar preparation**

To prepare the agar, 11.4g of modified mTEC agar were added to 250mL of reagent grade water placed in a previously sterilized flask. The solution was then moved to a hot plate with stirrer until the solution was completely mixed. The solution was then autoclaved at 121°C (15 PSI) for 15 minutes, and cooled in a 50°C waterbath. The pH was adjusted to  $7.3 \pm 0.2$  with 1.0N hydrochloric acid or 1.0N sodium hydroxide. The medium was poured into  $9 \times 50$  mm culture dish to a 4-5 mm depth (approximately 4-6 mL), and allowed to solidify to be stored in a refrigerator (USEPA, 2009).

### **3.6 Chlorides, free chlorine and total chlorine**

In order to detect the presence of chlorides in the wastewater samples a titration method was performed using Hach Drop Kit 8-P which consists of a easy to use method. Depending on the chlorides concentration, the method has a low range procedure and a high range procedure. A specific wastewater volume sample was taken and mixed with the contents of a Chloride 2 Indicator Powder Pillow. The Silver Titrant was added drop by drop until the solution changed from yellow to orange. The number of drops added was then multiplied by a factor that depends if it is the low or high range method. Report the results as mg/L as Cl. To express the results as mg/L as sodium chloride, the mg/L chloride found in the test had to be multiplied by 1.6.

To determine the free chlorine and total chlorine in the effluent samples, Hach methods 10231 and 10232 were used. TNT 866/867 vials were used with Hach's spectrophotometer DR 5000. First the zero vial was taken and introduce in the DR 5000, to zero the equipment. The TNT 867 vial was filled until a mark, shaken, and allowed to rest for the minute. After the minute had passed, the vial was cleaned with a cloth and inserted in the DR 5000 to get a reading. A blank vial of TNT 919, containing an effluent sample was used to correct the reading due to turbidity. A drop of potassium iodide solution was added to the same TNT vial. The vial was shaken and allowed to rest for 3 minutes. After the three minutes had passed, the vial was cleaned with a cloth and inserted in the DR 5000 to get a reading. A blank vial of TNT 919, containing an effluent sample was used to correct the reading due to turbidity.

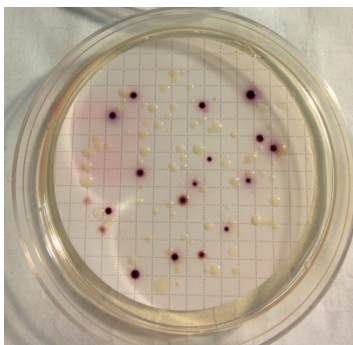
### **3.7 Sample processing**

After a minimum of two and a half detention times of flow through the reactor, three samples were taken for bacterial count purposes, using sterilized test tubes each time. An sterilized beaker was also used to take another sample for chlorides and chlorine testing. The Petri dish to be used was labeled with sample identification to prevent confusion between samples. To begin, a sterile membrane filter was placed on a previously sterilized filter base, grid side up. A previously sterilized funnel was attached to the base so that the membrane filter was held between the funnel and the base. Clamps were used to secure the filter base the and the funnel.

To prepare the wastewater sample, the test tubes were shaken vigorously and then 2 micro liters, 10 micro liters or 10mL were taken depending on the desired dilution, using sterile pipette tips or a sterile graduated cylinder for the bigger sample volume. The sample volume to be filtered was determined by growing E. Coli colonies for different sample volumes. The volume that resulted in an easy to count sample was the one taken to prepare the rest of the petri dishes. A volume of 200mL of deionized (DI) water was measured and poured into an autoclaved beaker; the wastewater sample was added at the same time as the DI water to ensure completely mixing. The sample was filtered, and the inside of the funnel was rinsed with 20mL of sterile buffered rinse water to ensure the bacteria were evenly distributed on the filter. The vacuum was then turned off and the funnel removed from the filter base. Sterile forceps were used to remove the membrane filter from the filter base and the filter was then rolled onto the modified mTEC agar medium to avoid the formation of bubbles between the membrane and the agar surface. The filter membrane had to be resealed if bubbles occurred.

The dish was closed, inverted, and incubated at  $35^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$  for  $2 \pm 0.5$  hours to resuscitate injured or stressed bacteria. After a  $2 \pm 0.5$  hour incubation at  $35^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ , the

plates were transferred to Whirl- Pak® bags, the bags were sealed and submerged in a  $44.5^{\circ}\text{C} \pm 0.2^{\circ}\text{C}$  waterbath for  $22 \pm 2$  hours. After  $22 \pm 2$  hours, the plates were removed from the waterbath; the number of red or magenta colonies were counted and recorded (Mosquera, 2013).



**Figure 3.8: Magenta dots are E. Coli colonies**

### **3.8 Bacterial count method**

Counting the E. Coli colonies was a difficult because it was very easy to make mistakes when counting. If special attention was not paid when counting, the person counting could make mistakes like ignoring colonies or counting them more than once. For this reason pictures were taken from every petri dish sample and uploaded to a computer. A program called Mouse Clickr.exe was downloaded to count the number of left and right click made between each bacterial count. To ensure that the bacteria were not counted twice, the pictures were opened in an image viewer called IrfanView which allowed to use a paint dialog. The right click was configured so that every time the right button was clicked, a small white circle would be drawn on top of a particular bacterium, reducing the chance of making a mistake. The click counter was reset between each sample.

Since three samples were taken per experiment, an average had to be made between the three bacterial counts made for each run. The standard way of reporting the results of the bacterial count is in cfu/100mL which means colony forming units per 100 milliliters of effluent.

Since the sample taken was by far less than 100mL the following formula had to be used to estimate the number of bacteria that would be present in a hundred milliliters of effluent.

$$\text{Count per 100mL} = \frac{\text{No. of colonies counted}}{\text{Volume sample filtered in mL}} * 100$$

Due to the fact that the filtered volumes in most of the trials performed were 2μL, the final count per 100mL could only be reported as an estimation of the bacterial count. The bigger the volume filtered, the more accurate the estimate would be. When taking sample volumes to be filtered, a reasonable volume had to be taken because if it was too small, as it was in some cases, an apparent 100% removal efficiency could be achieved. When comparing the bacterial growth for the same effluent, but a bigger volume, the cfu/sample filtered was too numerous to count. If the percentage of removal was not high enough and the sample filtered was large, the bacterial growth would be similar to the one shown on the following figure.



**Figure 3.9: 10mL filtered sample, low log removal**

### 3.9 Cost Estimate

The cost of operation of any process is a very important factor that helps determine whether it is going to be used or not. For a disinfecting technology to be selected amongst all the others, it must not only have a high bacteria inactivation rate, but also must be economical enough to have a good benefit to cost ratio. To determine the cost of treating wastewater in terms of dollars per liter of wastewater disinfected, some equations and factors should be used.

The electric bill that people must pay every month depends on the amount of kilowatts per hour that were used in a billing period. The average cost for the United States per kilowatt-hour according to the United States Energy Information Administration website as of August 2014 is \$0.0738. Kilowatt-hour is an energy unit and it depends on the amount of power consumed in a certain amount of time (usually in hours). To begin making an estimate of the cost that operating the electrochemical disinfecter will represent, the power consumed will be needed. Since the type of current used was AC the following equations applied:

$$V_{rms} = I_{rms} * R$$

$$R = \frac{V_{rms}}{I_{rms}}$$

The power consumed by the system can be determined by:

$$P = I_{rms} * V_{rms}$$

The units for the above mentioned variables are shown in the table below:

<b>Table 3.1: Unit for voltage, current and power</b>	
$V_{rms}$	Volts
$I_{rms}$	Amps
P	Watts

The equations used are the same as the ones used for DC (direct current) circuits. The difference is that the terms such as voltage and current are the rms equivalences of such



variables. The term rms means root mean square; since in alternating current circuits, both voltage and current values vary with time, there is a maximum value and minimum value depending on which part of the cycle the measurement is made. To avoid having to calculate the rms values, each time a measurement was need, a multimeter was used to make the necessary reading. A multimeter is a very versatile tool which measures current, voltage, temperature and many other parameters if it is needed. The readings made by the multimeter when selecting AC as the working parameter, were the rms values of both current and voltages in the reactor. Special care had to be taken because the high voltages and current might cause harm in case of an accident. To measure the voltage using the multimeter, the measurement had to be done in parallel and to measure current it had to be done in series. If this was not done properly, or the multimeter was not correctly configured, short circuits would happen and the fuse would get burned.

To find the time it takes a liter of wastewater to be treated, the inverse of the flow had to be taken into consideration. With all the information presented above, it is possible to make an estimate of what could be the cost of treating water with AC. The calculations used to make the cost estimate are presented below:

$$Cost\ per\ Liter = Power\ [kW] * \frac{\$0.0738}{kWh} * \frac{1}{Q} \left[ \frac{min}{mL} \right] * \frac{1h}{60min} * \frac{1000mL}{1L}$$

Which yields the following equation:

$$Cost\ per\ Liter\ \left[ \frac{\$}{L} \right] = 1.23 \frac{Power}{Q}$$

Where the power consumed is expressed in kilowatts and the flow in milliliters per minute.

The cost per cubic meter would be:

$$\text{Cost per Cubic Meter} \left[ \frac{\$}{m^3} \right] = 1230 \frac{\text{Power}}{Q}$$

The cost per mega gallon would be:

$$\text{Cost per Mega Gallon} \left[ \frac{\$}{MG} \right] = 4656056.489 \frac{\text{Power}}{Q}$$

## Section 4

### Results and Observations

#### 4.1 Trial 1

For the first trial, seven different experiments were performed. For the same flow and detention time, different voltages and hence different values of current were used to analyze if a high degree of disinfection could be achieved. The sample volume for filtration was the same for all the runs, the volume selected was 0.002mL (2 $\mu$ L) because this sample volume produced colony forming units that were not so difficult to count. Two titanium electrodes were used, one at the beginning of the reactor and one at the end. Creating a reactor volume of approximately, one liter.

<b>Table 4.1: Trial 1: Removal efficiency of the electrochemical disinfectant</b>								
Overall Run	Trial Run	Flow [mL/min]	Detention Time [min]	Voltage [V]	I <sub>ave</sub> [A]	cfu/Sample Filtered	Estimated cfu/100mL	Disinf. %
-	0	-	-	-	-	125.33	6.27E+09	-
1	1	200	5	40	0.248	146.67	7.33E+09	None
2	2	200		60	0.387	0.00	0.00E+00	100.0%
3	3	200		80	0.536	174.67	8.73E+09	None
4	4	200		100	0.7	153.67	7.68E+09	None
5	5	100	10	40	0.265	134.33	6.72E+09	None
6	6	100		60	0.387	60.00	3.00E+09	52.1%
7	7	100		80	0.536	47.00	2.35E+09	62.5%

As can be seen on Table 4.1, most of the results were not satisfactory, there was no disinfection achieved for a five minute detention time. The hundred percent achieved for five minutes and sixty volts is not significant due to the volume filtered. If a much larger volume like ten milliliter would have been filtered, the amount of bacteria would have been too numerous to count. A higher detention time yielded better disinfecting results but not enough, to comply with the regulations.

## 4.2 Trial 2

This trial consisted in repeating the experiment in which a 100% removal was achieved, i.e., using 5-min detention time and 60V. Since in the last experiment some degree of disinfection was accomplished with 10-min as detention time, several voltages were used for this trial. The same amount of plates (2 plates) and the 2 $\mu$ L as a filtered volume were the working parameters.

<b>Table 4.2: Trial 2: Removal efficiency of the electrochemical disinfectant</b>								
Overall Run	Trial Run	Flow [mL/min]	Detention Time [min]	Voltage [V]	I <sub>ave</sub> [A]	cfu/Sample Filtered	Estimated cfu/100mL	Disinf. %
-	0	-	-	-	-	115.33	5.77E+06	-
8	1	100	10	80	0.750	104.67	5.23E+06	9.2%
9	2	100		100	0.956	107.67	5.38E+06	6.6%
10	3	100		130	1.316	94.33	4.72E+06	18.2%
11	4	200	5	60	0.558	72.33	3.62E+06	37.3%

The repetition of the five minutes and sixty volts did not reached a hundred percent disinfection this time. This means that human error might have been one of the reasons why an apparent disinfection was reached before. For a higher detention time and voltages, no significant degree of disinfection could be achieved. For this reason it was determined that using just two electrodes (plates) was not a good working parameter.

### 4.3 Trial 3

For trial number three, three electrodes were connected to the alternating current power supply. A detention time of approximately ten minutes was chosen for a reactor with a volume of approximately eight hundred milliliters. Because of numerous inconsistencies in the ending results and bacterial count, trial three was not taken into consideration in the discussion of this research. While the results were not consistent enough, this trial gave insight as to what was happening to the resistance of the system. As can be seen above, in the first and second trials, a higher voltage was needed to get a high current. In the third trial, far less voltage was needed to get a current near to three amperes, which was the maximum current the power supply could handle. This means that the higher the number of electrode plates the lower the voltage needed to get a higher current, which means that the resistance was decreasing. Another important thing that was noted with the results of this trial was that there was an increase in the effluent temperature. For this reason, temperature readings were taken into consideration for the coming trials.

Table 4.3: Operating conditions for Trial 3					
Overall Run	Trial Run	Flow [mL/min]	Detention Time [min]	Voltage [V]	$I_{ave}$ [A]
-	0	-	-	-	-
12	1	100	10	25	1.5
13	2	100		35	2.192
14	3	100		48	2.95

#### 4.4 Trial 4

In trial number four, a reactor volume of approximately eight hundred milliliters and three electrode plates were used. To determine the voltages to be used with this reactor configuration, the multimeter was used to check how the effect of voltage on the current intensity. For a flow of approximately one hundred milliliters per minute, different voltages were used. One run was performed with the highest permissible value of voltage and a higher detention time. The volume of sample filtered was two micro liters.

<b>Table 4.4: Trial 4: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Trial Run	Flow [mL/min]	Det. Time [min]	Vol t. [V]	I <sub>ave</sub> [A]	cfu/Sample Filtered	Estimated cfu/100mL	Disinf. %	T [°C]
-	0	-	-	-	-	107	5.35E+06	-	26.5
15	1	100	8.00	25	1.568	104.33	5.22E+06	2.49%	28.5
16	2	100		35	2.073	15.33	7.67E+05	85.67%	30.5
17	3	100		45	2.747	105.67	5.28E+06	1.25%	33.5
18	4	70	11.43	45	2.947	57.33	2.87E+06	46.42%	37

As can be seen on Table 4.4, as the values of voltage and current increased, the effluent temperature increased as well. For the 100mL/min flow, the results were not good, while for 25v there was a very low disinfection, for 35v the degree of disinfection increased to almost 86% and for a higher value of 45v it decreased to 1.25%. In the other hand, when the flow was decreased to 70mL/min, hence increasing the detention time, an increase in disinfection was noted. Since these values were not consistent, they were only taken as an indicator that at higher detention times, better results might be achieved.

## 4.5 Trial 5

For this trial, higher detention times with smaller flows were used as the working conditions. The maximum value of voltage was used and the temperature was recorded. Three electrode plates were used and the reactor volume was approximately eight hundred milliliters. The volume of sample filtered was two micro liters. The results were the following:

<b>Table 4.5: Trial 5: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Trial Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %	T. [°C]
-	0	-	-	-	-	34.33	1.72E+06	-	
19	1	50	16.00	55	2.660	3.33	1.67E+05	90.29%	51.5
20	2	33.33	24.00	55	2.660	0.00	0.00E+00	100%	41
21	3	33.33	24.00	55	2.660	1.33	6.67E+04	96.12%	67.5

In this trial excellent disinfection results were obtained for a higher detention time. The voltage was a little higher than in the fourth trial and the flow was decreased. While these results are good, there is a concern regarding the increase in temperature. The high degree in disinfection might have been achieved due to the elevated temperatures, even though the water did not reach the boiling point, it was hot enough to kill many of the E. Coli in the effluent. For the third run, while purging the reactor after the completion of the second run, a much warmer effluent was noted and a sample was taken and labeled run 3. Another factor that should be taken into consideration considering the bacterial count, is the sample volume filtered. A larger volume (i.e. 10mL) should have been filtered to have a more accurate estimation of the number of colony forming units.

#### 4.6 Trial 6

For this trial, the number of electrode plates used was increased to six plates. The filtered volume sample was the usual two micro liters and two different detention times were used to analyze to variations of the inactivation of E. Coli in the effluent. The reactor volume was approximately 674mL and the results were the following:

<b>Table 4.6: Trial 6: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Trial Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %	T. [°C]
-	0	-	-	-	-	151.66	7.58E+06	-	19
22	1	66.7	10	6	2.700	56.33	2.82E+06	62.86%	25
23	2	33.33	>20	6	2.700	3.33	1.67E+05	97.80%	25
24	3	32	20	6	2.700	44	2.20E+06	70.99%	23.5

As can be seen on Table 4.6, there was a more consistent removal efficiency than in the other trials (except trial 5) and the temperature in the effluent remained relatively low. Since during run number 2 it was very difficult to maintain a regular flow, a higher detention time was used, but could not be determined. Because of this, a third run was done under the same operating conditions with a better control of the valve. The second was not considered significant, even though it had a higher disinfection, because the detention time could not be determined. Also, it is important to notice how much the resistance of the system lowered by increasing the number of plates. A current of 2.7A was measured by inputting a voltage of 6V.



#### 4.7 Trial 7

Trial number 7, was a modification of trial number 6. While the same number of plates and reactor volume of 674mL was used, the detention time was increased to approximately forty minutes and twenty five minutes.

The results are shown on the table below, but cannot be considered significant because as can be seen on Table 4.7, the estimated colony forming units per one hundred milliliters for the untreated sample was lower than the colonies counted for the treated sample in the second run. The first run of this trial got an apparent one hundred percent removal of E. Coli, as has been previously discussed, this means that no bacteria were found in the 2 $\mu$ L of sample filtered. A bigger volume should have been filtered to check the presence of bacteria. Another possible explanation for getting a lower bacterial count, might be due to the lack of the sample being shaken before taking the 2 $\mu$ L. The presence of human error is a factor difficult to deal with, since many complications might arise while running the experiments, it is easy to get distracted and make mistakes. For this reason, the decision to repeat the experiment was made.

<b>Table 4.7: Trial 7: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Trial Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %	T. [°C]
-	0	-	-	-	-	4.67	2.33E+05	-	23
25	1	16.5	40.8	6	2.621	0	0.00E+00	100%	25
26	2	26	25.9	6	2.621	24.67	1.23E+06	None	25

## 4.8 Trial 8

Trial number seven was repeated and recorded as trial eight, the working conditions were as similar as possible to trial seven. The results are shown on the following table:

<b>Table 4.8: Trial 8: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Trial Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %	T [°C]
-	0	-	-	-	-	32	1.60E+06	-	24
27	1	25.5	26.4	6	2.612	28.67	1.43E+06	10.42%	26
28	2	16	42.1	6	2.612	28.33	1.42E+06	11.46%	26

The results for trial number eight were more realistic and consistent despite the fact that a very low degree of disinfection was achieved. Careful attention was paid during the preparation and processing of the samples to ensure no mistakes were made. Temperature was slightly increased compared to the initial untreated sample's temperature. The flow was not exactly the same as in the previous trial due to the precision and flow handling capabilities of the needle valves. When an approximate flow to the desired one was obtained, the detention time was changed to be adjusted to the new flow. The use of six electrode plates was classified as a unsuccessful working condition because it was not efficient as expected.

## 4.9 Trial 9

For this trial, two runs were conducted, the first using five electrode plates and the second one using four electrode plates. The first run used a reactor volume of approximately 557mL and the second run used a reactor volume of approximately 418mL. Both runs were subjected to a voltage that would yield an average current of 2.65A. Table 4.9 shows the results obtained under the above mentioned parameters.

<b>Table 4.9: Trial 9: Removal efficiency of the electrochemical disinfectant</b>									
Overall Run	Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %	T. [°C]
-	0	-	-	-	-	39	1.95E+06	-	22
29	1	19	29.3	10.7	2.650	17.33	8.67E+05	55.56%	25
30	2	18	23.2	23.83	2.649	0.67	3.33E+04	98.29%	38

As can be seen on the table above, in run number one, using five electrode plates and approximately thirty minutes of detention time, an E. Coli removal of about 56% was achieved and the recorded effluent temperature was 25°C. In run number 2, which used four electrode plates and a detention time of about twenty three minutes, the E. Coli inactivation was of about 98.3% and the recorded temperature was 38°C.

#### 4.10 Trial 10

Trial number ten was the last trial done for this research, in this trial the chlorides concentration, free chlorine and total chlorine values were measured. After analyzing the results from the previous trials it was determined that when high temperatures were recorded along with high percentages of disinfection, the process happening could be compared to wastewater pasteurization. The run that recorded the highest temperature was when three electrode plates and 55V were used as the working parameters of the reactor. Detention times of ten and thirty minutes were used as tests parameters for runs one and two respectively, using three electrode plates and a reactor volume of approximately 780mL. For the third run, four electrode plates were used, but only the end electrode plates (2 plates) were connected to the power supply and the other two electrodes were left disconnected, to work as neutral plates. To ensure that the bacterial count was more accurate when the estimated colony forming units per 100mL was calculated, the volume sample to be filtered had to be increased. For the untreated sample, run zero, the volume taken was 10 $\mu$ L; for runs one, two and three, the volume taken to be filtered was 10mL, which was 5000 times greater than the filtered volume in trials one through nine. The results obtained were the following:

<b>Table 4.10: Trial 10: Removal efficiency of the electrochemical disinfectant</b>								
Overall Run	Run	Flow [mL/min]	Det. Time [min]	Volt. [V]	I <sub>ave</sub> [A]	cfu/filtered volume	Estimated cfu/100mL	Disinf. %
-	0	-	-	-		147.33	1.47E+06	-
31	1	78	10	40.4	2.996	too numerous to count	too numerous to count	low
32	2	26	30	39.9	3.377	1.33	13	99.9991%
33	3	117	10	132.1	1.584	too numerous to count	too numerous to count	low

<b>Table 4.11: Trial 10: Chlorides, Free and Total Chlorine values</b>					
Overall Run	Trial Run	Temp. [°C]	Chlorides [mg/L as Cl <sup>-</sup> ]	Free Chlorine [mg/L Cl <sub>2</sub> ]	Total Chlorine [mg/L Cl <sub>2</sub> ]
-	0	25	160	approx 0	0.08
31	1	37	160	approx 0	0.108
32	2	67	140	0.130	0.273
33	3	44.5	160	0.152	0.342

For this trial, runs one and three gave a bacterial count that was too high to be counted. It is important to notice the difference in temperature between runs one and two. The higher the detention time, the higher the temperature, for a three electrode plate configuration. The overall run number 32 (trial run 2, for trial 10) had a similar temperature as the one recorded in overall trial number 21 (trial run 3, for trial 5) which demonstrates that this experiment can be repeated and very similar results. The average bacterial count in run 3 was of 1.33cfu in the 10mL filtered volume. This is equivalent to an estimate of 13 cfu per 100mL of effluent treated water which is very good.

By using the methods described in section 3.6, the chlorides, free and total chlorine values were determined. From Table 4.11 it can be seen that the use of two electrode plates and two neutral plates with 10min detention time, produce more free and total chlorine concentrations than runs one and two. The voltage required to produce this amount of chlorine was relatively high and the chlorine concentration did not achieved enough disinfection to comply with the NPDES regulations.

#### 4.11 Power and cost estimates

The methods used to determine the power necessary to operate the reactor under certain conditions as well as the estimated cost of treating the wastewater was discussed in section 3.9. Using the formulas described in the previously named section the following values were computed for the runs that yielded the best removal percentages.

<b>Table 4.12: Power and Cost Estimate</b>								
Overall Run	Flow [mL/min]	Volt. [V]	I <sub>ave</sub> [A]	Disinf. %	Power [kW]	Cost [\$ /L]	Cost [\$ /m <sup>3</sup> ]	Cost [\$ /mega gallon]
21	33.33	55	2.66	96.12%	0.146	0.0054	5.40	20437.48
30	18	23.83	2.649	98.29%	0.063	0.0043	4.31	16328.70
32	26	39.9	3.377	99.9991%	0.135	0.0064	6.37	24129.53

Three different types of costs were calculated in the table above. As each volume increases, so does the cost, this means that as the disinfecting procedures are passed to a more real and bigger scale, the cost will increase. In the last column the cost per mega gallon of treated wastewater can be seen. It should be noticed that the most expensive value that was calculated, corresponds to the only run that is accurate and that can be considered significant. A more detailed analysis is described in the discussion section which is presented below.

## Section 5

### Discussion

It is of great importance to identify some of the factors that may have acted as limitations for this research. Such factors were the difficulty to maintain a constant wastewater flow and the limited knowledge in electricity and power conditions that the electrochemical disinfectors were working with. Another less important factor was the required volume of treated effluent needed to make a precise bacterial count. The greater the volume taken to be filtered, the greater the bacterial growth, if the disinfection was not efficient enough. Besides the information found on papers regarding the operating electrical conditions for the reactor, more attempts were done by trial and error. It should be noted that even though the flow rate might have not been entirely constant, the same chemical reactions occurred nonetheless.

One of the most difficult tasks regarding the development of this project, was to be able to maintain the wastewater flow through the reactor as constant as possible. Once the reactor was assembled with a desired configuration of plastic plates and electrodes, the reactor was filled with the wastewater to be disinfected. Different methods were tried to achieve a desired wastewater flow through the reactor. At first, a positive displacement pump, manufactured by Micropump Inc. was used but a constant effluent could not be achieved. While positive displacement pumps are known for their outstanding performance for delivering a steady flow rate without being affected by differential pressures, the pump available for this research, failed to provide a constant flow. Another option was using a Mariotte Bottle; one was built in order to have a constant flow rate. With the Mariotte Bottle, a less variable flow rate was achieved; but since the bottle had to be sealed and the wastewater needed to be constantly mixed, a mechanical stirrer could not be used. A magnetic stirrer was used, as suggested in previous research done

in the same laboratory, but because the Mariotte's Bottle bottom was not perfectly flat, the Lab-Line Instruments Inc. King Size Magnestir could not create good mixing conditions.

Throughout the duration of this research, thirty three runs (experiments) were conducted with different reactor configurations and different operating parameters in order to determine an effective way of disinfecting wastewater samples taken from the Marrero Wastewater Treatment Plant. In some occasions, an apparent disinfection was achieved but when the experiment was repeated, the same results were not obtained. These events can be explained by human error. For example, between the filtration of each sample, the filter base and the filter funnel were cured with a 10% ethanol solution to kill the remaining bacteria between runs. If the filtration instruments were not cured properly, bacteria would remain in the equipment and the samples could be altered. Another possibility is that the filtering instruments were not rinsed properly and residues of the ethanol solution remained on the equipment, this would cause some bacteria to die, hence altering the possible results. It is also possible that the person responsible for preparing the samples to be filtered forgot to shake the sample to ensure an even distribution of bacteria in the sample collected from the effluent of the reactor. While the best efforts were given to ensure a minimization of human error, it is always possible to get mistakes throughout an experiment. One thing that should also be noted is that the alternating current did not provide a stable output of current, the current reading kept increasing even though the voltage had stopped being increased. For this reason the values for current were presented as an average value, which came from the initial and final readings per run performed.

Regarding the runs taken into account to calculate the power and cost estimate, two of the three values of the overall runs presented in Table 4.12 contain disinfecting percentages that are considered to be apparent. Since the volume samples taken for runs twenty one and thirty were



really small (0.002mL), the estimation for the colony forming units per one hundred milliliters loses its accuracy. The results for overall run 32 are more accurate because the volume taken to be filtered was of 10mL. By analyzing the formula presented in section 3.8 to make an estimate of the bacterial count per 100mL, one can notice how inaccurate the results get. The formula is as follows:

$$\text{Count per 100mL} = \frac{\text{No. of colonies counted}}{\text{Volume sample filtered in mL}} * 100$$

Since the volume filtered for the overall runs 21 and 30, was 0.002mL, when inputting this value in the formula and dividing the 100mL by said volume, the coefficient obtained is  $5 \times 10^4$ . Once that number is multiplied by the number of colonies counted in the filtered volume, the number increases; this is why this is called an estimation. On the other hand, when the filtered volume increases, as in the case of overall run 32, a coefficient of  $1 \times 10^1$  is obtained. When this coefficient is multiplied by the number of colonies counted in the filtered volume, a more accurate estimate is made. The most accurate value for a bacterial count would be obtained when filtering 100mL, in this case the bacterial count can be reported as exactly the number of colony forming units counted per 100mL. Several attempts were made to filter 100mL of effluent but because of the suspended solids in the wastewater samples, the filter got clogged every time. When 10mL of effluent wastewater were filtered, a darker circular shape could be noticed on the filter paper. In order to be able to make a bacterial count when using larger filtered volumes, a high percentage removal of E. Coli must have been achieved, otherwise the colony forming units will be too numerous to count, as can be seen in Figure 3.9. When events in which it is not possible to count the bacteria colonies occur, smaller samples should be filtered to at least be able to make an estimation. As a rules of thumb, an ideal filtered volume which yields no more than 200 bacteria should be found, to make the bacterial count easier to be reported.

When analyzing the concentrations of chlorides found during the last trial, it can be determined that this is a normal value for the wastewater that arrives to the Marrero Wastewater Treatment Plant. These values, were compared to the values found by Julio Acosta, another research assistant who was analyzing the efficiency of the same reactor and electrode plates, but was working with direct current instead of alternating current. The values he found, oscillated between 140 and 160mg/L as  $\text{Cl}^-$  (Acosta, 2014). It is assumed, for simplification purposes that the chlorides found in wastewater water belong mostly to sodium chloride.

Regarding free and total chlorine, when using two connected electrode plates and two disconnected plates (neutral plates) between the connected ones, the highest amounts of free and total chlorine concentrations were obtained. The highest values obtained for free and total chlorine during trial number 10 were 0.152mg/L  $\text{Cl}_2$  and 0.342mg/L  $\text{Cl}_2$  respectively. The voltage used for the configuration mentioned was 132.1V and the current was 1.584A. When comparing these results with the ones found in the research done by Acosta, for the same reactor configuration but different values of current and voltage, different free and total chlorine concentration were obtained. The following results were observed for a detention time of 10min:

<b>Table 5.1: Results obtained using Direct Current by Acosta, 2014</b>								
Volt. [V]	I [A]	Power [kW]	Chlorides [mg/L as $\text{Cl}^-$ ]	Free Chlorine [mg/L $\text{Cl}_2$ ]	Total Chlorine [mg/L $\text{Cl}_2$ ]	T [°C]	Cfu /100mL	Disinf. %
40	0.5	0.02	120	1.34	> 2.0	25	3.3	99.99981
51	0.4	0.0204	140	0.268	0.493	24	1593.3	99.90895
65.1	0.5	0.033	140	0.351	0.837	25	26.67	99.99848
65	0.3	0.019	160	0.061	0.142	25	3.3	99.99981

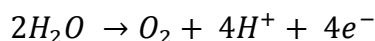
The first thing that can be noticed when comparing the results from this research - which can be seen in Table 4.12 - to the one done by Acosta is the difference in the amount of power required to generate similar concentrations of free and total chlorine. Acosta reported using

values of current between 0.3 and 0.5 amperes and voltages in the range of 40 to 65 volts.

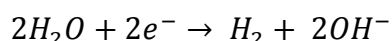
Different reactor volumes were used to perform the runs presented in Table 5.1 but the detention times were very close to 10min. The temperature during each run in Acosta's report, did not change more than 2°C compared to the untreated sample. The temperature in this research for overall run number 33, had an increment of 20°C. The most important difference between this research and Acosta's is the percentage of disinfection obtained based on the estimated colony forming units per 100mL for the same filtered volume of 10mL. Acosta's research obtained a 99.99981% disinfection with free and total chlorine concentrations of 0.06mg/L Cl<sub>2</sub> and 0.142mg/L Cl<sub>2</sub>. This research obtained free and total chlorine concentrations of 0.152mg/L Cl<sub>2</sub> and 0.342mg/L Cl<sub>2</sub> and the colony forming units was too numerous to count and it could only be concluded that the disinfection percentage was not high enough to be determine accurately.

This analysis of great importance because by having a high percentage of disinfection for such small concentrations of total and free chlorine in Acosta's research and having little to no disinfection in this research by having larger amounts of chlorine, it can be seen that the disinfection is not happening only due to chlorine. This means that the disinfection is happening mostly due to the presence of radical species rather than by the amount of chlorine produced by electrolytic processes. It is also important to notice that a high volume of gas was formed during Acosta's experiments, producing bubbles, which made it difficult to stabilize the flow. On the other hand, no bubble formation was observed during the experiments performed using alternating current. This implies that there was no electrolysis of water when an alternating current supply was used.

As was discussed earlier, when water undergoes electrolysis, oxidation and reduction reactions occur. The oxidation process occurs at the anode, the positively charged electrode, which is responsible for generating oxygen gas from water and follows this reaction:



The reduction process occurs at the cathode, the negatively charged electrode, which contributes to the generation of hydrogen gas from water and follow this reaction:



The reactions presented above explain the behavior of water when it undergoes electrolysis and suggests an explanation as to why there were bubbles in the research performed using direct current. It is assumed that the presence of gases can be directly related to the electrolysis of water, and to the formation of oxygen and hydroxyl radicals.

When working with direct current, the polarity of the electrodes does not change; in alternating current, as its name implies, the current changes from positive to negative maximum values 60 times per second. This might be one of the reasons why it appears that the electrolysis of water was not happening during any of the 33 experiments performed for this research. Since oxidation and reduction occur in the vicinity of the anode and cathode respectively, it is possible that the change in electrode polarity was interfering with the formation the of hydrogen and oxygen gases, generating micro volumes that were not detectable by simple inspection. What some studies suggest is that the precipitation of substances will not occur when working with alternating current. This was verified each time the reactor was cleaned by inspecting the electrodes. The only thing that was found in the reactor was a little layer of settled solids from the wastewater, no substance was found attached to the electrodes. When inspecting the

electrodes after the use of direct current, a white precipitate was found attached to the electrodes, possibly calcium carbonate.

The five log removal obtained from overall run number 32, was clearly not due to the electrolysis of chlorine or the presence of hydroxyl radicals - which because there was little to no electrolysis of water its assumed they were not formed- but because of the increase in temperature throughout the reactor. The reason for this increase in temperature to happen was because of the power consumed due to the high values of voltage and current applied to the reactor. The electrodes dissipated the energy into the electrolyte, which in this case was the wastewater. The high temperatures obtained with the use of alternating current can be compared to the pasteurization of wastewaters, which is a method known to inactivate bacteria in a very efficient way.

The pasteurization of wastewater uses the heat produced by turbines or any other heat source to increase the wastewater temperature to a specified temperature for a certain amount of time with the purpose of killing bacteria and other harmful microorganisms. The disinfected wastewater effluent is then used to preheat the water that is going to be disinfected which lowers the temperature of the effluent wastewater. Pasteurization of wastewaters is said to be cost effective because the heated exhaust from different sources that would otherwise be dissipated in the air is used to heat the water. The cost for the disinfection found in overall run number 33, extrapolated to  $3785.4 \text{ m}^3$  (1MG) would be approximately \$24 thousands per day; this means that a plant handling  $7570.8 \text{ m}^3$  (2MG) would spend \$48 thousands every day to disinfect the wastewater if the proposed reactor configuration is to be used. This implies that even though the disinfection obtained is effective, it is not feasible. The main advantage of pasteurization is that because the water is disinfected by heating it, no chlorination and dechlorination processes are

required. Furthermore the risks involved in shipping, handling and storing chlorine, can be avoided when pasteurization processes or effective electrochemical disinfection processes are utilized. The average daily cost for disinfection through chlorination is approximately \$1900 per 3785.4m<sup>3</sup> (1MG) and it includes the dechlorination process (Solomon et al., 1998). Based on the results observed in this research, the high operating expenditures of electrochemical wastewater disinfection using AC make it economically unfeasible.

As was discussed in the literature review section, electrochemical disinfection is an emerging popular alternative to conventional chlorination processes. While some researchers believe that chlorine is what provides the disinfecting effects, others believe that the reactive oxygen species such as hydrogen peroxide and hydroxyl radicals are the ones disinfecting. Several researchers have demonstrated the presence of hydroxyl radicals when alternating current was used for electrochemical disinfection. Many reported achieving good degrees of disinfection. Based on the results that were presented above, certain doubts arise due to the fact that very little disinfection was achieved during the experiments performed for this investigation.

## Section 6

### Conclusions and Recommendations

The electrochemical disinfection of wastewater from the effluent of a secondary clarifier using alternating current as the power source was evaluated in this study. To perform this research, an electrochemical disinfectant was employed using electrode plates made from titanium and coated with iridium oxide. The reactor was subjected to a continuous flow of completely mixed wastewater coming from a 0.1893m<sup>3</sup> (50gallon) tank. To determine the efficacy of this method samples from the effluent of the reactor were taken, processed and filtered. The evaluated parameter, to check for disinfection was the removal of E. Coli from the wastewater. This was done by comparing the number of E. Coli found in the untreated wastewater with the ones found in the effluent of the disinfectant. It is recommended to upgrade some of the laboratory equipment, to facilitate the tasks that need to be done, as well as giving regular servicing to the electronic equipment to always have readings that are as accurate as possible.

After conducting several experiments, it was demonstrated that a removal of bacteria can be achieved using alternating current. However, analyzing the decrease in E. Coli colonies, the removal percentage was too low to be considered an efficient method and the NPDES regulations for wastewater final effluents could not be met. The 5 log removal efficiency obtained was because of the increase in temperature and not because of the presence of chlorine or hydroxyl radicals. This disinfection through elevated temperatures, can be compared to the pasteurization of wastewater, which is an effective method. The drawback of operating the reactor as a water heater by using current to heat up a resistor is the high cost of operation.

Based on the results obtained in this research, it can be concluded that the disinfection of wastewaters by applying alternating current to an electrochemical disinfectant is not a suitable

alternative to replace chlorine as a disinfecting agent. The costs of operation alone, are by far larger than those of chlorination and dechlorination combined. However, it was verified that treating wastewaters with a temperature of approximately 67°C for 30minutes, can in fact achieve a high inactivation of bacteria and pathogens, to the point of complying with the discharge standards of less than 200cfu/100mL. It can also be concluded that using alternating current also produces free chlorine, but to obtain similar chlorine concentrations as the ones obtained using direct current, much higher values of alternating current are needed.



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## **Vita**

Xavier Antonio Chávez Reyes was born in Guayaquil, Ecuador on December 2, 1989. In January 2008, he graduated from High School. In May 2011, he started pursuing a Bachelor of Science degree in Civil Engineering -a 5-year Engineering program- at ESPOL, Escuela Superior Politecnica del Litoral, (Superior Polytechnic Littoral School) in Guayaquil, Ecuador. In August 2011 he transferred to the University of New Orleans, where he obtained his Bachelor of Science in Civil Engineering degree in May 2013. On June 2013 he obtained his Engineer in Training Certification. On August 2013 he was admitted to the Master of Science in Engineering (Environmental Engineering) program at the University of New Orleans.

Throughout the completion of his Master's program he has been working as graduate research assistant under the mentorship of Dr. Enrique J. La Motta for the Department of Civil and Environmental Engineering of the University of New Orleans. The focus of his investigation has been electrochemical disinfection of municipal wastewater using alternating current as an alternative to chlorination.