MIXING AND AERATION PERFORMANCE OF A SINGLE PLATE VORTEX RING GENERATOR IN A NATURAL POND

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by

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ABSTRACT

This thesis describes the study of plate vortex ring generators invented and developed by Latto and modified and constructed by E.S.Fox. The vortex ring generator has been applied to destratify and aerate a natural pond in this research. Experiments were conducted to mix and aerate a stagnant and stratified pond in a natural, outdoor setting. Mixing times, temperatures, dissolved oxygen, BOD, COD and pH were measured for each experiment trial. A fluctuating single plate vortex ring generator was constructed and used in four of the five experiments with the depth of the vortex ring plate varied to determine the effect on mixing and aeration. A final experiment used a dual plate vortex ring mixer to examine the advantages of multiple plates with regard to mixing and aeration as well.

It was found that the single plate vortex ring generator with an operating range of 1/2 to 4/5Hz effectively destratified and mixed the pond within a 12 hour mixing duration. The generator aerated the pond by establishing a flow pattern in the pond such that the water at the surface of the pond experienced increased contact with the atmospheric air thereby transferring oxygen to the water. The impact of atmospheric air temperature proved to be a significant factor as a heat source to the pond which affected the time taken to destratify the pond. The increased oxygen transferred to the pond increased dissolved oxygen in the pond. The microbial organisms present in the pond experienced increased

activity due to the increased dissolved oxygen available in the water because of the mixing action provided by the vortex ring generator.

The summary of calculated results for all five experiments with the vortex ring mixer is as follows:

		(1/hr)	(kgO_2/hr)	(kgO_2/kWh)
	Mixer Type	K_La_{20}	SOTR	SAE
EX #1	5 Feet Deep	0.0098	0.0674	0.0274
EX #2	5 Feet Deep	-0.0022	-0.151	-0.0062
EX #3	7 Feet Deep	0.0114	0.0784	0.0319
EX #4	3 Feet Deep	0.012	0.0826	0.0336
EX #5	Dual Plate	0.0014	0.0099	0.004

On the basis of the experimental results it was determined that the vortex ring generator has a bright future as a tool to improve water quality in natural water courses.

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TABLE OF CONTENTS

NOMENCLATURE

Symbol	Definition	Dimension
a	vortex ring core radius	L
BOD	biological oxygen demand	ML^{-3}
C	bulk-liquid dissolved oxygen concentration	ML^{-3}
C_b	dissolved oxygen bulk liquid concentration	ML^{-3}
C_c	critical or lowest oxygen saturation concentration	ML^{-3}
C_i	dissolved oxygen concentration at the interface	ML^{-3}
C_O	dissolved oxygen concentration at time 0	ML^{-3}
COD	chemical oxygen demand	ML^{-3}
C^*	dissolved oxygen concentration at equilibrium	ML^{-3}
C_f^*	field water dissolved oxygen concentration equilibrium	ML^{-3}
C_{sT}^*	dissolved oxygen concentration tabular value	ML^{-3}
C_{s20}^*	standardized dissolved oxygen concentration tabular value	ML^{-3}
C_∞^*	steady state dissolved oxygen saturation concentration	ML^{-3}
d	orifice equivalent diameter	L
d_e	effective saturation depth	L
d_M	mean bubble diameter	L
d_{min}	minor diameter of the vortex ring oblate spheroid	L

d1	oblate spheroid major dimension	L
d2	oblate spheroid minor dimension	L
D	orifice plate overall diameter	L
D	dissolved oxygen deficit	ML^{-3}
Dm	generating orifice diameter	L
DO	dissolved oxygen	ML^{-3}
f	vortex ring generation frequency	T^{-1}
f	mixing frequency	T^{-1}
g	acceleration of gravity	LT^{-2}
k_g	gas film coefficient	LT^{-1}
K_H	Henry's Law Constant	ML^{-3}
k_L	liquid film coefficient	LT^{-1}
K_La	volumetric mass transfer coefficient	T^{-1}
K_La_f	field water volumetric mass transfer coefficient	T^{-1}
K_La_{20}	standardized transfer coefficient	T^{-1}
L_e	equivalent slug length	L
N	minimum number of mixer strokes to mix	-
N_O	mass transfer flux rate	$ML^{-2}T^{-1}$
p_b	oxygen bulk gas phase pressure	$ML^{-3}T^{-2}$
p_b	barometric pressure	$ML^{-3}T^{2}$
pH	acidity/base measurement	-
p_i	oxygen interphase gas pressure	$ML^{-3}T^{-2}$
p_s	standard atmospheric pressure	$ML^{-3}T^{2}$
p_v	saturated vapour pressure of water	$ML^{-3}T^{2}$
p^*	equilibrium oxygen bulk gas phase pressure	ML^{-2}

Q_g	gas flow rate	L^3T^{-1}
R	vortex ring radius	L
R	vortex ring rotation circle radius	L
Ri	dimensionless Richardson number	-
s	piston stroke	L
St	dimensionless Strouhl number	-
t	mixing time	T
T	mixing time	T
V	volume	L^3
V	vortex ring velocity	LT^{-1}
V	liquid basin holding volume	L^3
V	vortex ring volume	L^3
Vf	volume of fluid to be mixed	L^3
$\forall$	volume per cycle	L^3T^{-1}

Greek Symbols

α	volumetric mass transfer coefficient correction factor	-
β	oxygen concentration correction factor	-
γ	water density at test water temperature	ML^{-3}
γ	shear rate	$ML^{-1}T^{-3}$
η	fluid viscosity	$ML^{-1}T^{-1}$
κ	displaced volume fraction	-
θ	transfer coefficient correction factor	-

ρ	vortex ring density	ML^{-3}
$\Delta\rho$	fluid density difference	ML^{-3}
τ	oxygen saturation correction factor	-
τ_S	surface shear stress	$ML^{-1}T^{-2}$
Ω	pressure correction factor	-
ζ	critical ratio	-

LIST OF FIGURES

LIST OF TABLES

PHOTOGRAPHS

CHAPTER 1

INTRODUCTION

1.0 Overview

Aeration of natural water bodies including rivers, streams, lakes and ponds is necessary to reduce the effect of pollution discharged into these water courses. Pollution in the form of untreated industrial waste and sewage as well as run-off from surrounding lands all put demands on the final water course. Wastewater discharges contain solids and numerous microorganisms which consume oxygen. If there is too much microorganism activity the level of dissolved oxygen increases ultimately reducing the amount of dissolved oxygen available for marine life. Aeration and agitation are viable methods to increase dissolved oxygen such that the microorganisms found in the wastewater can be treated while sufficient levels of dissolved oxygen for natural aquatic life can be maintained. The process of agitation and aeration through mixing is important to industrial waste water and is the focus of this thesis.

1.1 Aeration

1.1.1 History

Initial attempts at aeration began in England in 1884 and in 1904[1] with the first patent granted for a perforated metal plate aerator. These early aeration experiments were plagued with clogging of the diffuser pores which decreased their effectiveness and thus increased maintenance costs. Large orifice-type diffusers were developed in the 1950's as an alternative to the perforated diffusers developed earlier but the larger holes cause oxygen transfer efficiency to suffer in spite of reduced maintenance costs. In the early 1920's mechanical aeration was introduced to alleviate clogging problems experienced with diffuser aeration equipment. Mechanical aeration devices have been installed in wastewater plants since the 1920's and appear to be an alternative means to aerate and treat waste. However, both methods are energy consumptive and have their detractors.

The importance of aeration cannot be underestimated since it represents one the most energy intensive operations in wastewater treatment. Aeration frequently consumes between 50 to 90% of the energy costs at a treatment facility. The treatment effectiveness must provide a reasonable return on the invested capital and operating costs while meeting industrial and government cleanliness standards. The drive to improve treatment efficiency while controlling cost effectiveness has industry continually improving treatment systems while investigating other treatment alternatives. At present, industry is continuing to develop mechanical aeration while also investigating gas diffusion systems[1].

1.1.2 Aeration in Waste Water Treatment

Processes involving oxygen transfer are common to many water and wastewater treatment systems at industrial and municipal facilities. Water supplies are aerated to remove undesirable dissolved gases and dissolved inorganic substances by oxygenation. Uses of aeration in wastewater treatment include preaeration, aerated grit removal, grease flotation, post aeration and aerobic biological treatment applications such as activated sludge, aerated lagoons and aerobic digestion. Raw wastewaters can be aerated for short periods prior to secondary treatment to increase the efficiency of subsequent waste treatment operations. Improved efficiencies of biological oxidation and sedimentation are the result of pre-aeration which is particularly useful in cases where raw wastewaters lack dissolved oxygen or are high in dissolved sulfides. Air flotation is also used for grease and solids removal and to concentrate sludge. Two main purposes for air in biological treatment processes include the supply of metabolic oxygen requirements of treatment organisms and to provide mixing within reaction vessels. Various types of forced aeration are common in activated sludge aeration tanks, lagoons and oxidation ditches.

Oxygen transfer is a significant factor in the reaeration of natural waters and the maintenance of adequate dissolved oxygen to support the ecological balance in natural water courses. Over the last two decades there has been renewed interest in the potential of forced instream river aeration as a means to supplement water quality control. Increasing population density near major watercourses as well as the effects of acid rain and farm runoff have decreased water quality in natural sources. The potential for aeration of natural water bodies providing pre-treatment and rejuvenation of poor quality water is becoming necessary and economically viable due to new technologies[19].

In all industrial aerobic biological oxidation processes, maintenance of sufficient concentrations of oxygen is a primary consideration in process design and operation. In the absence of photosynthetic activity, aerobic oxidation in natural aqueous environments is dependent upon oxygen transferred to the water as a result of its intrinsic contact with the atmosphere. Oxygen transferred is present in amounts sufficient to support normal biological processes in relatively unpolluted waters. In the presence of high concentrations of organic substrates, aerobic biological processes may be limited by the rate at which oxygen is transferred by natural aeration. Environments of greatly accelerated biological activity, such as biological waste treatment operations, require a more rapid replenishment of oxygen than could possibly be provided through normal contact with the atmosphere. This replenishment is most commonly accomplished by bubbling air into the water in treatment basins or by providing rapid agitation and mixing to increase the rate of transfer of atmospheric oxygen.

1.1.3 Aeration Equipment

There are three methods of transferring oxygen from the atmosphere to wastewater commonly used in industry. The three methods include submerged diffused aeration, submerged mechanical aeration and surface mechanical aeration. All methods increase the contact area and rate of oxygen transfer through aeration and mixing. The aeration equipment used to achieve oxygen transfer include air diffusion units, turbine aeration systems in which air is released below the rotating blades of an impeller, and surface aeration where oxygen transfer occurs due to high surface turbulence and liquid sprays.

1.1.3.1 Diffused Aerator

There are two types of diffused air systems which include units that produce large bubbles, and units that produce small bubbles from porous ceramic diffusers, tubes or nozzles. The diffusers are usually placed near the bottom of the treatment basin close to one wall to induce a vertical and transverse roll to the wastewater to maintain mixing. Large or coarse bubble discharge units do not have as high oxygen transfer efficiency as fine bubble diffusers since the interfacial area for the coarse bubbles is less than the fine bubbles. Smaller bubbles have a larger surface or interfacial area for oxygen transfer over the gas-liquid interface hence their increased transfer efficiency over coarse bubble units. A major drawback of fine bubble systems is that they are subject to clogging and require extensive air filtration and frequent maintenance of the filters to prevent the fine pores on the diffusers from clogging.

Coarse bubble systems operate over a wider range of air flow since increased air flow increases oxygen transfer efficiency whereas increased air flow in fine bubble systems beyond the optimum design point will decrease oxygen transfer efficiency. Increased air flow in fine bubble systems causes breakdown of the fine bubbles and eventually bubbles are not produced but rather an air jet from the diffuser which has a lower interfacial area and thus decreased oxygen transfer ability. The transfer of oxygen increases with increasing depth placement of diffusers due to the partial pressure of the entering oxygen and the increased contact time between bubbles and wastewater as they travel from the bottom to the surface. Uniformity of air diffusion is also important to prevent pockets of untreated wastewater collecting and potentially clogging the diffusers over time. Examples of diffused aerators include porous(fine bubble), nonporous(coarse bubble), tubular and jet diffusers.

1.1.3.2 Turbine Aeration

Turbine aeration equipment disperses compressed air by the shearing and pumping action of a rotating impeller that can either be submerged or on the surface. In a typical turbine aerater, air is fed to the turbine through a sparge ring located beneath the impeller blades which are located at the bottom of the treatment basin. The mixing action keeps solids in suspension while dispersing the air bubbles uniformly throughout the wastewater thereby contacting air with the waste and transferring oxygen.

Typical examples of turbine aeration are axial and radial flow submerged turbines. The axial flow impeller drives air down and across the bottom of the wastewater holding tank whereas the radial flow impeller throws the air outwards. The axial type transfers a higher percentage of oxygen while the radial type can handle higher volumes of wastewater to be treated. Between these two types there are design options to be considered such as operational flexibility and the ability to adjust air flow within the wastewater treatment tanks during operation.

1.1.3.3 Surface Aerators

The last method of oxygen transfer is surface aeration which can be accomplished by two types of equipment, one of which employs a draft tube and the other without a draft tube. Surface aerators transfer oxygen by exposing large volumes of surface wastewater with atmospheric air through spraying the wastewater over the holding basin or tank. Oxygen transfer is influenced by the impeller diameter, speed of rotation and the submergence level of the rotating components. The purpose of the surface mounted aerator is to induce mixing flow in the tank while at the same time splashing surface water which increases the contact time of wastewater with atmospheric air thus increasing oxygen transfer. Surface aeration units can be mounted in wastewater lagoons on piers, bridges or on floats which allows for relocation under differing waste loading.

Floating aeration units have also been used to aerate natural water bodies such as streams and small lakes or ponds. These floating aeration units have standard mixing impeller configurations that are either on flotation devices anchored to the bottom or secured to the bank of the stream or lake being mixed. The securing of floating aeration units is necessary to offset the impeller torque which could result in rotation of the entire device if not secured as well as to counter the effects of wind and current. Special attention must be paid to the energy and monitoring lines to the mixer since they are exposed to the elements and are often run along the bottom of the water body being mixed.

Radial and axial flow aerators are surface type aerators that are presently in common industrial use. Radial flow aerators are low speed devices with high oxygen transfer efficiency as compared to coarse bubble diffusers, and can be floating, platform mounted or fixed-bridge configurations with draft tubes or lower mixing impellers. Axial flow aerators are considered high speed surface aerators which must be monitored to ensure that their rotation is not too great to disturb floc formation in biological treatment systems. Axial flow aerators generate a liquid jet that disperses into the air as droplets which contact the air and then mixes with the liquid waste in the treatment vessel to transfer the oxygen gained from the surface. Another surface aerator type is a horizontal brush rotor consisting of a horizontal cylindrical rotor with a vaned impeller. This impeller agitates the wastewater surface and drives water jets and droplets into the air after which oxygen is transferred into the water when the jets and droplets fall back and mix with the wastewater.

1.1.3.4 Aerator Development

Two new aerator design configurations include the dual impeller radial flow turbine and the vortex ring generator both developed by Latto.

The impetus behind the dual-radial flow turbine was the need for a device to provide sufficient mixing to maintain biological floc agitation and suspension while providing a means to introduce air or pure oxygen into the wastewater[24]. The turbine consists of two identical radial flow impellers with a semi-circular draft tube and an enclosed radial flow impeller at the end that are slid together to create the entire unit. During operation air and surface liquid is drawn down the upper draft tube and radially ejected from the lower impeller while liquid is drawn from the lower levels up the draft tube to be ejected by the upper impeller causing the two ejected streams to meet in the region between the impellers. This creates a situation for liquid-gas contact and oxygen transfer. This transfer occurs when the impeller causes a free vortex formation at the liquid surface as the upper draft tube sucks in atmospheric air which is discharged from the lower impeller to generate air bubbles. The bubbles are coarse but the rotating impeller breaks them into smaller bubbles.

The vortex ring generator comes in three configurations which include suspended plate mixers, self-contained plate mixers and tube type mixers. The mixers generate vortex rings which have efficient mass transfer making them effective for mixing. The tube type vortex ring mixer can be modified as an aerator by allowing air through holes in the generating tube during the suction stage of mixing. Oxygen transfer occurs when air is sucked into the injection tube and is agitated with the liquid. The aerated water is then ejected in the form of a vortex ring which reaches the bottom of the wastewater tank and breaks up either on impact or self destructs before reaching the bottom which introduces the highly aerated liquid into the wastewater solution. The air bubbles from the destroyed or collapsed vortex ring form bubbles which float to the surface due to buoyancy effects and transfer oxygen as they travel upward making continuous contact with the wastewater.

Suspended plate mixers can also be used for aeration as they provide excellent mixing due to the turnover of wastewater in treatment basins which increases contact at the surface with atmospheric air. The increased contact and faster circulation of the wastewater increases oxygen transfer within the liquid solution. Placing the vortex generating ring at the bottom will churn up bottom sediments and provide excellent mixing while also aerating the wastewater due to surface contact. Placement of the vortex ring generator at the surface decreases mixing efficiency somewhat but significant splashing of liquid at the surface occurs which increases contact with atmospheric air and thus oxygen transfer within the solution. An advantage of the vortex ring generators is that they do not have the torsional problems associated with floating rotary surface aerators.

1.1.4 Measurement and Application

Measurement of oxygenation in wastewater due to aeration includes both unsteady and steady state tests.

The unsteady state test involves the reoxygenation of deoxygenated water. Removing oxygen from the water is accomplished by adding sodium sulfite with a catalyst or stripping with nitrogen gas. This unsteady state method is the most accepted test method in industry. The degree of reoxygenation of the water is measured with either dissolved oxygen probes or by laboratory analysis of water samples taken from the wastewater.

Steady state tests include excess sulfide oxidation, off-gas oxygen balance and the biological uptake rate. In the excess sulfide oxidation method, the oxygen transfer rate is measured when sulfite is oxidized to sulfate with a cobalt catalyst. This method is not popular because the cobalt catalyst may affect the results. The off-gas oxygen method is a mass balance on oxygen in the liquid and gas streams and is generally used for measuring performance in submerged aeration devices. The biological uptake rate is based on the uptake rate of oxygen by microorganisms present in wastewater and is the most popular of the steady state tests.

Due to recent improvements in aeration efficiencies and new technologies there are no general rules of thumb to follow thus air requirements for wastewater treatment should be based on the oxygen transfer coefficients for the aeration and mixing method and device used for each application[25]. The efficiencies of aeration devices are rated on oxygen transfer efficiency and are expressed as kilograms of oxygen transferred per hour and kilograms of oxygen transferred per kilowatt hour for clean water. Standards for measurement of oxygen transfer efficiency vary according to government jurisdiction with ratings for clean water being the most recognized current standard in North America[20].

1.2 Mixing

1.2.1 Definition of Mixing

The process by which a fluid is mixed may appear to be simple at first but the physical relationships involved certainly require more than a passing glance. It often seems in industry that two liquids are thrown into a vessel and mixed with an impeller without giving any thought to the actual mechanics of the mixing process. This frequently results in inadequate mixing, inefficient use of power, excessive mixing time, and, in high rate chemical processes, incomplete and undesirable reactions. Mixing is an operation by itself but more important it is used in conjunction with overall plant processes. Municipal wastewater treatment can be looked at as a process with aeration and mixing as two components used to achieve the final result of treated and cleaned wastewater. The importance of mixing cannot be overlooked in industrial processes due to the capital and energy costs used to achieve the desired final result. The most efficient mixing process that achieves complete mixing is the one that requires the least amount of energy or power density in the least possible time.

Mixing can be defined as the process by which either a discontinuity or a gradient in physical or chemical properties in a mass of fluid is reduced or eliminated[2]. Fluid mixing is a unit operation carried out to homogenize single or multiple phases in terms of concentration of components, physical properties and temperature[16]. The fundamental mechanism of mixing operations involves physical movement of material between various parts of the whole mass. Spontaneous mixing can occur in single phases due to molecular diffusion or free convection but this is inherently slow and of little practical importance. Fast mixing must therefore be achieved by transmitting mechanical energy to force the fluid motion to move and thus mix to achieve eventual complete homogeneity. This is especially the case for multiphase solutions and slurries.

1.2.2 Mixing Mechanisms

The mixing process has three mechanisms that occur simultaneously and include convection, macromixing and micromixing. The first process is convection which is the large scale transportation of fluid elements from high concentration regions to regions of low concentration and vice-versa. Convection occurs with liquids in their natural state at rest due to temperature and current effects. The addition of mechanical agitation increases the rate of convection.

The direct role of mixing in biological systems can be considered on the macro and micro scales within the treatment system. Macro-scale or macromixing is the second component of mixing and is the influence of flow patterns on mixing and is established by means of flow patterns in the mixing vessel. Fluid velocity is represented by the deforming and subdividing actions of turbulent eddies and concentration blotches generated by the relative movement of mechanically induced flow. The fluid motion helps to establish the concentration distribution within the reaction which in turn influences reaction rate and sensitivity. Macromixing promotes uniformity of concentration and provides contact between reactants. The solids present in the fluid are thus kept in suspension and all reactants are dispersed uniformly across the cross-section of the holding basin. Complete mixing exists when uniformity is attained throughout the reaction volume[6].

The final component of mixing is micromixing which is the segregation and influence of diffusion of liquid. The fluid velocity described as turbulent eddies and concentration blotches for macromixing does not influence the path of fluid disintegrating and intermingling or turbulent eddies and concentration blotches which describes micromixing. The mixing by disintegration of turbulent eddies and by the molecular diffusion is important for micromixing but is generally negligible for macromixing. Each zone is divided into a series of backmixed or plug flow cells by turbulent diffusion. Transfer occurs by convection between adjacent cells of the same zone or between cells of adjacent zones. Micromixing causes complete intermingling of molecules which is the desired condition for reaction systems and enhancement of interphase mass transfer. Micromixing is pertinent to molecular diffusion because shear intensity influences the film thickness across which molecules must migrate and also determines the time history of a molecule in relation to other molecules[6]. The convection and macromixing components of mixing are studied most frequently in industry as compared to micromixing.

1.2.3 Mixing Operations

Mixing involves the convective transportation of fluid elements within a containment vessel. The movement of fluid can be accomplished in two methods. The first method is circulating the liquid in the containment vessel by means of an external recirculation pump. This method is called jet mixing since the turbulence and overall mixing of liquid is attained by the discharge jet of the pump which is often used in large scale blending and mixing operations. The second mixing method is the mechanical agitation of the entire liquid mass to attain circulation and turbulence within the containment vessel. This method is often used on small to medium scale applications and is more effective than jet mixing in terms of concentration uniformity.

The application of the above methods to practical situations involves the consideration of three elements. The liquid or liquids to be mixed, vessel geometry and dimensions, and the type of agitator or pump to be used are the critical elements. Each characteristic alone is important to effective mixing while the three elements as a whole are critical. Elements vary for each application and several attempts at the proper mixer for the application may be necessary to achieve the desired mixing quality with the least amount of energy input.

1.2.4 Fluid Mixing Classes

Fluid mixing can be characterized by five groups of fluid and solid pairs listed in Table 1.1[21]. Each of the ten basic mixing areas in Table 1.1 have separate rules of thumb, scale-up procedures, research data and methods of application. It is often helpful to take a complicated process and break it down into its basic components that are measurable and meaningful. The physical and chemical processing pairs illustrate differences between degrees of uniformity and some type of chemical reaction that characterize the application class.

Table 1.1

Application Class	Physical Processing	Chemical Processing
Liquid-Solid	Suspension	Dissolving
Liquid-Gas	Dispersions	Absorption
Immiscible Liquids	Emulsions	Extraction
Miscible Liquids	Blending	Reactions
Fluid Motion	Pumping	Heat Transfer

Usually most mixing processes involve several of the five basic application classes so each type must be examined for the role it plays in achieving the desired process result. Wastewater treatment through mixing and aeration, the subject of this thesis, is classified as a liquid-gas operation that disperses oxygen in the liquid waste which is eventually absorbed by microorganisms present in the wastewater.

1.2.5 Mixing Measurement

The criterion for measuring completeness of mixing is an important consideration when mixing methods are tested and implemented. The criterion used is often a subjective decision based on the observation of variables during mixing operations. The measurement of mixing results has been accomplished by four major techniques[17]. The first technique is concentration measurement of the mixture. The use of an electrolyte as a tracer while measuring the concentration change with probes at various locations achieves this result. Mixing is considered to be complete when the liquid density becomes homogeneous over time.

The second method of measurement is temperature variation and discontinuity in the liquid volume which can be measured over time to determine mixing of stratified liquids. Temperatures at several points throughout the containment vessel are continuously recorded with mixing achieved when there is little or no temperature variation between each probe. One drawback to this method is the susceptibility to external temperature fluctuations which can transfer heat to the liquid and effect the overall mixing effectiveness. Certain chemical reactions also generate heat during mixing which effects the measurement results as well.

The addition of dye, decolourization and neutralization processes that cause colour variations in pH indicators is the third method to measure mixing. Visual inspection of the uniformity of the dye in the liquid mixture indicates when a homogeneous solution is achieved.

The final technique are optical methods for turbidity which are commonly referred to as the Schlieren technique[21]. This method uses light refraction to measure blending by the disappearance of optical nonhomogeneity caused when two liquids are not completely blended. Differences in refraction caused by liquid differences can be detected on a screen and serve to provide a good indication of when blending is completed. As with the temperature method, this technique is applied only to stratified blending.

1.2.6 Agitator Design

Transmitting mechanical energy via a mixer to force fluid motion is required to achieve mixing. Mechanical mixers are used to agitate liquids and usually consist of an impeller, driver and a gear box. The selection of an agitator involves reviewing mixing environmental factors that include the physical properties of the fluid medium, vessel size and geometry, impeller location relative to vessel and fluid boundaries and to other impellers or obstructions in the mixing basin, and the presence or absence of baffles including their design and location.

The calibration of a geometrically similar series or family of mixing impellers determines the effect of the mixing environment on the energy and capital costs of the particular agitator selected. The factors and considerations which help to determine the most suitable and economical type of impeller for a given duty are often interrelated and mutually dependent. Mixing does not directly affect chemical reaction but the rate of chemical reaction taking place can be influenced by the agitation only if the reaction itself is controlled by one or more of the primary effects. The factors which influence the rate and degree of mixing as well as the efficiency may be classified as follows:

1) Characteristics concerned with the rotating impeller such as shape, speed, dimensions and position in the wastewater basin.

2) Physical properties of the materials concerned including density, viscosity and physical state.

3) Shape and dimensions of the containing vessel and any of the fittings which may be immersed in the fluid.

Although mixing is concerned with obtaining the primary effects listed above, it is not easy to specify the exact circumstances needed to achieve them efficiently. This is because the physical properties of the fluids being processed are themselves the main factors which determine the choice of impeller because these properties vary widely. For equipment of low cost and power consumption, efficiency is often of secondary importance provided the required effect is produced.

1.2.7 Agitator Selection

There are four general considerations or factors which are to be taken into account before selecting a given type of impeller and speed for a specific duty.

The first consideration is the type of impeller of which there are seven basic types. These include impeller with disc and flat blades, radial bar turbine impeller, radial anchor impeller, axial marine impeller, axial flour blade impeller, axial three blade impeller and the axial double spiral impeller. These types are common in industry for mixing and there are numerous variations of each of these types. Aerators mentioned in Section 1.1 are also agitators but since their primary purpose is aeration they may not be classified as a pure agitator in some literature references. Agitators such as the dual radial flow turbine and the vortex ring generator are relatively new and as such there is little engineering data available from which to size and select a unit for industrial use. One of the main purposes of this thesis is to demonstrate the mixing effectiveness, in addition to the aeration capabilities, of the vortex ring generator to provide experimental data for other applications.

The second consideration are baffles in the holding basin. Baffles are useful where the application requires high turbulence and high power absorption with relatively low speeds of rotation. Baffles can be used with all mixer types but it has been shown that with the vortex ring mixer they are not necessary due to the vortex ring mixer's agitation effectiveness.

The rotation speed is the third consideration. The tip effects of all impellers will be found to be much the same for the same agitating effects except in the case of propellers where the speed is much higher and anchors where it is slightly lower. Consequently, for a given effect, smaller agitators need to run at higher speeds. If small agitators are desired the effects of higher speeds on erosion, bearing wear, gland difficulties, vibration and allied effects must be tolerated. Vortex ring generators do not have their speed as such measured by the tip speed but rather by the frequency and stroke of the up and down action of the moving vortex ring.

The fourth and final consideration is the impeller size and number of impellers in the fluid basin. For the same vessel a large agitator operating at low speed produces relatively more mass flow and less turbulence than a smaller but geometrically similar agitator which operates at high speed and transmits the same power. Additional agitators versus a single large agitator is another option which would require testing to determine if the additional impellers are economically viable in terms of capital and energy costs while providing the same mix quality.

1.3 General Comments

The main thrust of aeration and mixer development is the operation of a device such that more effective mixing at the lowest capital cost and energy usage can be attained. The subjects of aeration and mixing are complex in that many processes require mixing somewhere in the treatment process. Effective mixing not only improves quality but it decreases process cost through shorter mixing times and lower power costs based on proper impeller selection and implementation.

The one piece of information, not explicitly stated in engineering literature and selection guides, is that it appears the most successful aeration and mixing operations resulted more through trial and error with engineering data used as a starting point, rather than lengthy calculations determining mixing parameters, with final adjustments being made after implementation. The obvious drawback with trial and error during system start-up is time and cost so it is suggested to obtain as much information from reference and industrial sources before aeration and associated mixing applications proceed on a full scale basis.

1.4 Objectives

The objective of this research is to investigate the use of a new technology of vortex ring generation for the mixing and aeration of natural bodies of water. In particular, to investigate the effect of depth of location of the mixer impeller and the mixing and aeration performance of the mixer. The vortex ring mixers used in this investigation have been internationally patented, developed and pursued by Latto.

Most literature sources site laboratory results for standard mixers with little information on vortex ring mixers in industrial applications. Similarly, aeration devices have industrial and municipal research data available but there is very little data for applications in natural water courses. The purpose of the thesis experiments were twofold. The first being the testing of the vortex ring mixer in a natural setting and the second to see how effective the vortex ring mixer was at aerating a natural water body.

Several experiments were carried out with the mixer impeller at different depths in the pond to investigate its mixing and aeration capabilities. Temperature probes were used at the bottom and surface of the pond to indicate complete mixing. Oxygen transfer in the pond was measured by taking water samples at regular intervals with laboratory results giving the final readings. Time, temperature, mixing and aeration effects associated with the vortex ring mixer outside of the usual laboratory set-up were recorded and compared to show the general mixing and aerating effectiveness of the mixer in the pond application.

CHAPTER 2

THEORY

2.1 Aeration Theory Introduction

The principal categories of biodegradable organic matter in wastewater are proteins, carbohydrates and lipids. Proteins are high molecular weight compounds composed of amino acids. Carbohydrates are polyhydroxylated compounds such as sugars, starches and cellulose. Lipids refer to a variety of organic substances such as fats, oils and grease. If organic matter is present in wastewater, microorganisms in the water or in the environment will oxidize the organic matter using molecular oxygen as the oxidizing agent. The transformation is frequently represented by[17]

$$\text{Organic Matter} + O_2 \rightarrow \text{bacteria \& nutrients} \rightarrow CO_2 + \text{new bacteria} + H_2O$$

If organic matter is untreated and discharged into a body of water the bacteria in the water will proceed to decompose the organic matter and in the process remove the dissolved oxygen from the water. If the reaeration capacity of the body of water is insufficient to supply the oxygen required by the bacteria, the oxygen level will drop and fish, amphibians, and other aquatic life may die.

The need for artificial aeration to increase oxygen levels in natural water courses therefore becomes very important for maintaining acceptable water quality.

2.1.1 BOD

The Biological Oxygen Demand (BOD) is a measure of the presence in aqueous solution of organic materials which can support the growth of microbial organisms. BOD is commonly used as an indirect measure of the quantity of dissolved oxygen consumed in the aerobic microbial oxidation of the water sample within a specified time and at a specified temperature[27]. The BOD of wastewater is related to the quantity of oxygen which must be supplied to the wastewater either by aerators during treatment or by natural aeration of the receiving water[26].

The laboratory process of measuring BOD involves taking water samples which are seeded with bacteria and other nutrients, if necessary, and incubated at 20°C for 5 days. After incubation, the change in the dissolved oxygen concentration in the sample is measured and the five day BOD or BOD_5 is expressed as mg O_2/litre of wastewater. The oxygen consumed in a BOD test is the sum of two phases consisting of the oxygen used for synthesis of the organic material present and the endogenous respiration of the microbial cells. The rate of oxygen utilization during the first phase occurs over a period of 24 to 36 hours which is 10 to 20 times longer than the second phase[8].

The BOD test has many limitations since the seed bacteria must be acclimated to the particular wastewater which can be a problem for many industrial wastes as well as natural bodies of water including rivers, streams, lakes and ponds. In the laboratory, the measurement of BOD_5 is a static batch process whereas in a river or stream the microbial oxidation occurs within the body of water and is a dynamic and continuous process. It is normal to assume that the laboratory test is reasonably representative of the natural processes that occur in a natural body of water although recent evidence suggests that the rates of oxidation can be much higher than the laboratory tests for rivers and vice-versa for slow moving natural bodies of water such as ponds and small lakes[27]. The long period before test results are obtained makes the BOD test of little value in continuous process control monitoring of wastewater[26].

There are many organic materials which are not biodegradable and hence are not recognized in a BOD_5 test. Dissolved oxygen is consumed in reactions which produce new microbial cells from the organic material in the water. With time the older cells die and the organic materials associated with them are themselves consumed in further reactions. This synthesis of the cells continues until the number of viable cells is greatly reduced and only relatively stable organic materials such as humus remain. A high BOD removal in water treatment can mean little if the organic fraction in the water is non-biodegradable. The BOD_5 clearly measures only part of this overall process which is better characterized by the rate constant for the reactions and the overall quantity of oxygen consumed[26]. The main benefit from measuring BOD_5 is that it provides historical records of treatment in wastewater. True benefits cannot be realized until sufficient tests for a water course are completed to determine the characteristic BOD_5 curve for that particular water body including the waste stream.

2.1.2 COD

To overcome some of the shortcomings of the BOD test a Chemical Oxygen Demand (COD) test is frequently done along side the BOD test. The COD test measures the total organic content of a waste which is oxidizable by a strong chemical oxidant. The oxidant usually used is a boiling mixture of potassium dichromate and sulfuric acid. The test is performed by refluxing a sample of wastewater with the oxidant for 2 to 3 hours and measuring the change in the oxidant. The reaction can be represented as[25]

$$\text{Organic matter} + Cr_2O_7^{2-} \rightarrow CO_2 + H_2O + Cr_2O_4^{2-}$$

Organic nitrogen is converted to either ammonia or nitrates depending upon the type of organic compound in the sample. Some aromatic compounds are not oxidized by the test. Chloride ions will react with the potassium dichromate but can be removed by adding mercurate sulfate to the refluxing mixture. A silver sulfate catalyst is often added to aid in the oxidation of certain compounds such as fatty acids. When the silver sulfate catalyst is used the recovery for most organic compounds is greater than 92 percent[7].

The COD of a wastewater sample is usually larger than its BOD level because more compounds can be chemically oxidized than biologically oxidized[26]. Correlation of COD and BOD is not easy and depends on the nature of the organic material in the sample. Some organic compounds are degraded biologically but are not attacked by acid dichromate as is the case with acetic acid while the reverse is true for compounds such as cellulose. The main advantage of a COD test versus a BOD test is that it is much quicker than a BOD test as it only takes a matter of hours and not days to carry out a COD test[27].

Since a COD test will report virtually all organic compounds, many of which are either partially biodegradable or nonbiodegradable, it is proportional to BOD for only readily assimilable substrates such as sugar. Because the BOD_5 will represent a different proportion of the total oxygen demand for raw wastes than for effluents, the BOD/COD ratio will vary for effluents and for untreated wastes. This is important when discharge is to a natural water body such as a stream or lake since a history of BOD/COD measurement on discharges and the final water body will establish a baseline from which process control can maintain water cleanliness.

There is no correlation between BOD and COD when organic suspended solids are present in the waste stream, such as with pulp and fibre from paper mill waste, since these are only slowly biodegradable in the BOD bottle . There will also be no correlation between BOD and COD in complex waste effluents containing substances such as ABS. For this reason treated wastewater effluents may exert virtually no BOD and yet exhibit a substantial COD[27]. Measurement of both BOD and COD is therefore important to obtain a clearer picture of wastewater and overall water quality. Data plotting of BOD and COD over long periods of time is a useful measure from which to monitor what is being treated by natural water bodies.

2.1.3 pH

Industrial or domestic wastes often contain acidic or alkaline components which may require neutralization before discharge. For wastewater discharges to natural water bodies a pH between 6 and 9 is often required by regulatory agencies. Wastewater entering biological treatment processes such as treatment lagoons should have the pH maintained between 6.5 and 8.0 for optimum growth of microorganisms. When wastewater is treated by aeration the aerobic biological process generates CO_2 as microorganisms consume oxygen which also effects the pH of the system. Monitoring of pH levels is therefore required to ensure that dissolved oxygen consumed by BOD does not alter pH levels which can severely effect marine life.

Neutralization is often difficult since acids or bases may be required to treat wastewater before it is discharged into natural water bodies. The addition of acids or bases may present an additional problem with wastewater treatment that may not be treatable by aeration of the water course.

2.1.4 Dissolved Oxygen

2.1.4.1 Oxygen Saturation

Aeration is the most important factor in waste water treatment and involves the transfer of oxygen to biological treatment processes as well as the natural reaeration of watercourses such as streams and ponds. Dissolved oxygen in water has a saturation concentration of 9.09mg/l at 20°C. The dissolved oxygen level decreases with an increase in temperature and decreases with an increase of the dissolved solids content. It also has a solubility in domestic waste water of approximately 95% of that of clean water. The solubility data given in Table 2.1, given at the end of this chapter, is from the ANSI/ASCE Standard 2-91[25] and based on calculations from Henry's law.

2.1.4.2 Two-Film Model

The rate of reaeration of a moving body of water with oxygen from the atmosphere depends upon the rate of absorption through the air and water interface and on the rate of dispersion through the body of water below the air and water interface. The driving force of the oxygen transfer is the difference between the dissolved oxygen concentration at saturation and the actual concentration present in the water. This two-film model is used to describe the oxygen transfer from the atmosphere to the water.

The two film model concept considers stagnant films at the gas and liquid interfaces through which mass transfer must occur. For sparingly soluble gases such as oxygen, the liquid-film resistance controls the rate of mass transfer. Since most of the mass transfer applications in waste water treatment are liquid-film controlled, an increase in the fluid turbulence will decrease film thickness and therefore increase mass transfer[8]. Figure 2.1 at the end of this chapter schematically represents the gas-liquid film interface of the two film model. Assuming that there is steady-state operation and that there is instantaneous equilibrium between the gas and liquid at the surface interface then the mass transfer flux rate in one direction becomes[26]

$$N_O = \frac{\text{moles of Oxygen transferred}}{\text{area hour}} = \frac{\text{driving potential}}{\text{resistance}} \tag{2.1}$$

$$= \frac{p_b - p_i}{1/k_g} = \frac{C_i - C_b}{1/k_L} \tag{2.2}$$

Where

p_b = partial pressure of Oxygen in the bulk gaseous phase

p_i = partial pressure of Oxygen at equilibrium at the interface

C_b = dissolved Oxygen concentration in the bulk of the liquid

C_i = Oxygen concentration at the interface assumed to be in equilibrium with p_i

$1/k_g$ and $1/k_L$ = gas and liquid resistance

Since the interface values of p_i and C_i are rarely if ever known they are estimated using Henry's law, $p_i = K_H C_i$(K_H = Henry's Law Constant). If C^* and p^* are taken in equilibrium with the bulk potentials of p_b and C_b, or at saturation concentration, then using Henry's law

$$N_O = \frac{p_b - p_i}{1/k_g} = \frac{C_i - C_b}{1/k_L} \qquad (2.3)$$

$$= \frac{K_H(C^* - C_i)}{1/k_g} = \frac{p_i - p^*}{K_H/k_L} \qquad (2.4)$$

Equating the above expressions, solving for p_i and substituting into the first equation gives

$$N_O = K_g(p_b - p^*) = K_L(C^* - C_b) \qquad (2.5)$$

The expressions $1/K_g$ and $1/K_L$ are the overall resistance when the driving potentials are in either the gaseous or liquid forms and are commonly referred to as the overall mass transfer coefficients expressed as K_g and K_L. Most waste water purification systems involve oxygen transfer from bubbles generated from an aerator into the water which is controlled by the liquid film resistance. The main reason, however, that oxygen transfer is liquid phase controlled is that the Henry's Law constant is very high. Because of this , $p_b \approx p_i$, $K_L \approx k_L$.and $1/K_L = 1/k_L+1/(K_H k_g)$. The most widely used coefficient of mass transfer is expressed as K_L. The rate of transfer in Equation 2.1 is the flux rate of oxygen and the interface area is required to determine the amount of gas transferred. Designating a as the surface area of the bubbles divided by the volume of liquid, the volumetric gas absorption rate of gas the water becomes

$$N_O = K_L a(C^* - C_b) \tag{2.6}$$

The above can also be expressed as[5]

$$\begin{array}{ccccc} \text{Rate of Mass Transfer} & & \text{Volumetric} & & \\ \text{per Unit Volume of} & = & \text{Mass Transfer} & \text{X} & \text{Driving Force} \\ \text{Liquid} & & \text{Coefficient} & & \end{array}$$

Actual aerated systems are more complicated than indicated by the previous expression since K_L varies from point to point requiring averaging to produce meaningful results. Because of this averaging, the product $K_L a$ referred to as the volumetric mass transfer coefficient is used to compute the transfer rate[8].

2.1.4.3 Bubble Diameter

While it is difficult to measure interface or bubble diameters, there are methods to predict bubble diameter. Both size and velocity of bubbles rising in an aeration tank are dependent upon the rate of air flow from the diffuser. When the air flow is low, bubble size is directly proportional to the diameter of the orifice at which the bubbles are formed[8]. From experimental data[25], below diameters of 1.5mm, bubbles are spherical in shape while above 1.5mm, the shape of bubbles resemble the top of a mushroom. As the mean diameter increases above 1.5mm, the diameter of the mushroom head increases even faster, causing viscous forces to dominate over buoyant forces. The mass transfer coefficient K_L reaches a maximum for bubble diameters between 1.5mm and 2.5 mm[25]. For the general range of flow rates employed in aeration the mean bubble diameter, d_M, varies exponentially with the gas flow rate, Q_g, expressed as[8]

$$d_M \approx Q_g{}^n \tag{2.7}$$

where $0.10 \leq n \leq 0.44$

The above can be used to measure and predict bubble diameters but in practice it is difficult to measure interface areas in aeration processes. The product K_La is therefore used as an industry standard to calculate and compare oxygen transfer rates.

2.1.4.4 Volumetric Mass Transfer Coefficient

The overall volumetric mass transfer coefficient K_La is the common design parameter used to specify the rate of aeration of waste water. Assuming that the aeration system is completely mixed where the oxygen is transferred throughout the volume with C and K_La being uniform, an unsteady-state balance can made on the oxygen concentration in the waste water. Assuming that there is no consumption of oxygen in the liquid phase, Equation 2.6 can therefore be integrated over the tank volume with $N_O = dC/dt$ giving[5]

$$\frac{dC}{dt} = K_La(C^* - C) \tag{2.8}$$

Equation 2.8 is the basic model recommended for analysis of both surface and subsurface clean water. Integration of Equation 2.8 using the boundary conditions of $C = C_0$ at $t = 0$ becomes

$$\ln\frac{(C_\infty^* - C)}{(C_\infty^* - C_0)} = K_Lat \text{ (logarithmic form)} \tag{2.9}$$

or

$$C = C_\infty^* - (C_\infty^* - C_0)\exp(-K_Lat)\text{(exponential form)} \tag{2.10}$$

Where

C = DO concentration [M L^{-3}]

C_∞^* = determination point value of the steady state DO saturation concentration as time approaches infinity [M L^{-3}]

C_0 = DO concentration at time zero [M L^{-3}]

K_La = determination point value of the apparent volumetric mass transfer coefficient [T^{-1}]

t = time [T]

The above model has been shown to adequately fit the majority of data observed from both surface and subsurface clean water aeration tests. The model applies to a given aeration system in a given tank under steady state hydraulic conditions and can be viewed as a completely mixed system with uniform dissolved oxygen values in which oxygen is transferred throughout the water volume.

The logarithmic method fits Equation 2.8 to the experimental data linearly but requires that a value of C_∞^* either be assumed, measured, or determined from book values to calculate the oxygen deficits. Recent work on this method has shown that with good data the computed results are close to those determined from the exponential method.

The exponential method fits Equation 2.9 to the experimental data using the nonlinear least squares procedure. The main advantage of this method is that the computational procedure provides least squares estimates for all three parameters without placing any constraints on the data used or on assumed values of the parameters. The parameter estimates appear to be more precise than those from other procedures and requires the use of a computer to give accurate results.

2.1.4.5 Factors Affecting K_La

The volumetric mass transfer coefficient K_La is affected by the physical and chemical variables characteristic of the aeration system including the waste being treated. The four major factors affecting K_La are[8]

1. Temperature. The liquid film coefficient will increase with increasing temperature. The size of air bubbles generated from the aeration device are also affected by temperature thus affecting mass transfer. The influence of temperature on the transfer coefficient and saturation value are expressed in terms of the temperature correction factors theta and tau defined by[5]

$$K_La_{20} = K_La\theta^{(20 - T)} \qquad (2.11)$$

$$\tau = C_{sT}^*/C_{s20}^* \qquad (2.12)$$

Where T = field temperature

θ = Temperature correction factor on the transfer coefficient which is 1.024[20] unless proven to have a different value for the aeration system and tank tested.

τ = Oxygen saturation correction factor is the ratio of the tabular oxygen concentration at the test temperature to the standard temperature.

Equations 2.10 and 2.11 are somewhat empirical since they require measurement of oxygen for their computation which involves measuring devices whose performance in process or untreated water can vary significantly from performance in clean water. The amount of difference will depend on the device, on how it is applied, and on the nature of the untreated water. The values of K_La and τ are therefore influenced by the quality of the oxygen samples originally taken.

2. Waste Water Characteristics. The presence of surface active agents can act as a barrier to diffusion by decreasing surface tension which thus affects K_La. A decrease in surface tension will decrease the size of bubbles generated from an air-diffusion system. The presence of suspended solids and other matter requiring oxygen from waste reduction also affects the K_La of a system. To apply clean water test parameters to the design or evaluation of field respiring systems it is necessary to correct for the influence of water characteristics and temperature on the transfer coefficient and saturation value. The effect of waste water characteristics are commonly accounted for by the alpha and beta factors.

$$\alpha = \frac{\text{field water } K_La^*}{\text{clean water } K_La^*} = \frac{K_La^*_f}{K_La^*} \tag{2.13}$$

$$\beta = \frac{\text{field water } C^*}{\text{clean water } C^*} = \frac{C_f^*}{C^*} \tag{2.14}$$

Where f = the field water condition

The above factors can be expected to increase or decrease and approach unity during the course of water treatment since the substances affecting the transfer rate are being removed in the biological process.

3. Liquid Depth. It is necessary to correct C^* for differences in atmospheric pressure between the test, standard and field conditions. The value of C^* is not a linear function of total atmospheric pressure but instead a linear function of the

partial pressure of dry air at saturation depth, except for the case where the gas phase is depleted of oxygen. The pressure correction factor is defined as

$$\Omega = \frac{C_\infty^* \text{ at } p_b}{C_\infty^* \text{ at } p_s} = \frac{p_b + \gamma d_e - p_v}{p_s + \gamma d_e - p_v} \qquad (2.15)$$

Where p_s = the standard atmospheric pressure of 760mm Hg at 100 percent relative humidity.

p_b = the barometric pressure

γ = water density at the test water temperature

d_e = effective saturation depth

p_v = saturated vapour pressure of water

4. Turbulence. Increasing the degree of turbulent mixing will increase the overall transfer coefficient. Turbulence increases the formation of bubbles which transfers oxygen to the wastewater. Small bubble diameters have a larger interfacial area than large bubbles which increases oxygen transfer. The K_La coefficient also depends on the rigidity of the bubble and its relative velocity within the wastewater.

2.1.5 Dissolved Oxygen Sag

The dissolved oxygen concentration in a stream is a balance between processes trying to oxygenate the stream and other processes that are using up the supply of oxygen. The amount of self purification that can occur in a natural water body depends upon water flow rate, oxygen content and reaeration capacity. The main balance is between oxygen uptake from the atmosphere and oxygen consumption by the BOD of the stream. Green plants in the water have an effect since oxygen is produced by photosynthesis during the day and absorbed at night with the release of carbon dioxide. This action of plants causes daily variation in the amount of dissolved oxygen in the water course. When waste is discharged out into a body of water the BOD in the waste uses the photosynthetic oxygen as it is formed so the oxygen peaks in the clean water do not build up. Downstream or away from the wastewater discharge is where the dissolved oxygen (DO) levels drop until a point is reached where the waste BOD uses up more oxygen than is produced which may lead to a reduction in aquatic life.

When the reaeration capacity of the natural water exceeds the microorganism demand of the waste water, oxygen levels once again build up and approach the original level. This phenomenon is known as the oxygen sag of a water course. The unit of measure is the dissolved oxygen deficit rather than concentration[26,27] and is expressed as follows:

$$D = C_0 - C_c \tag{2.16}$$

Where C_o = Initial oxygen concentration

C_c = Critical or lowest oxygen concentration

A plot of oxygen versus distance from waste discharge is recorded to determine the extent of oxygen reduction as well as the critical point where oxygen levels are the lowest in the natural water course. The purpose of recording the oxygen sag is to view the relationship between BOD and DO in the water course and how a satisfactory level of oxygen can be maintained to provide sufficient oxygen for aquatic life while treating waste through aeration.

2.1.6 Standard Oxygen Transfer Rate and Efficiency

Two measures that are often used to indicate the overall effectiveness of a treatment system are the Standard Oxygen Transfer Rate (SOTR) and the Standard Aeration Efficiency (SAE). The purpose of standardizing treatment systems is to allow engineers to compare the amount of oxygen transferred in a particular wastewater treatment system to other systems. Data from several different systems generated from real time operating conditions are useful to other engineers and designers when new systems are being proposed. Data can also be consulted for the direct comparison of existing systems to determine if they are performing at the proper efficiency levels.

The oxygen transfer capacity of an oxygenation system is expressed as the rate of oxygen transfer in clean water at zero dissolved oxygen under standard conditions of temperature and pressure which are 1.00 atmosphere or 101.6 kPa and 20 degrees Celsius[20].

$$\mathrm{SOTR} = K_La_{20} \ \mathrm{X} \ C_\infty{}^*{}_{20} \ \mathrm{X} \ V \qquad (2.17)$$

The standard aeration efficiency is the standard oxygen transfer rate expressed in terms of the power input to the aeration treatment system and is expressed as follows:

$$\mathrm{SAE} = \mathrm{SOTR}/\,\mathrm{Power} \qquad (2.18)$$

The SAE is expressed as the kilograms of oxygen transferred per kilowatt hour of energy consumed or kg/kWh.

2.2 Mixing

2.2.1. Mixing of Liquids

The agitation or mixing of liquids and liquid-solid suspensions or slurries are important processes to many industries including wastewater treatment. The achievement of a homogeneous distribution of liquid and solids in liquids with the least amount of capital and energy cost is the main objective for industrial and municipal wastewater treatment systems. Poor mixing increases the time and energy input to mixing operations such that increased costs will result. Costs such as additional processing steps, too much sedimentation that must be removed, and the potential reprocessing of materials may be experienced if mixing is substandard.

There are many methods to mix and agitate liquids including, recirculating pumps, rotating and oscillating impellers, air injection through perforated plates, gas sparging, inline mixing devices such as vanes in pipes and ducts and vortex ring generators. The numerous mixing devices developed arose from the need to address the many factors involved in mixing mentioned in Chapter 1, i.e., physical and chemical properties of the substances to be mixed and vessel geometry. Texts by Nagata and Oldshue address the subject of mixing in detail and should be referenced for particular agitator types and applications.

2.2.2 Vortex Ring Mixers

There are different methods to generate mixing such as turbulence for mass transfer or the transport of fluid slugs. The mixer type used for the experiments in this thesis is the vortex ring generator which utilizes the generation and transport of vortex rings to create mass transfer and convection and therefore mixing[15]. The reason for choosing the vortex ring mixer are it's excellent mixing capabilities with low energy input and the lack of industrial or municipal application experience thus justifying further research. The basis for most applied information on vortex ring generators is recent and one of the purposes of this thesis is to further contribute knowledge and experience on the subject.

A vortex ring is an annular toroid of rotating fluid which creates a self-contained oblate spheroid structure as shown in Figure 2.2. Once a vortex ring is created it will travel relatively large distances with very little energy expenditure. This occurs because the internal rotation of the fluid in a ring has a relative velocity which is almost zero at its outer surface and consequently the shear stress around it is quite small and thus the drag as well. This can be visualized as equivalent to a tire rolling along a surface as compared to a non-rotating tire sliding over a surface[12]. The progress of the ring through the fluid is relatively unhindered and it can be used as a device for the efficient transport of material from one location to another which as stated previously is one of the primary goals of mixing.

2.2.3 Viscous Shear

The viscous shear at the outer surface is given by:

$$\tau_S = \eta\gamma \tag{2.19}$$

Where τ_s = Surface shear stress

η = Viscosity of the fluid

γ = Shear rate which is du/dr

The ratio du/dr is the radial velocity gradient and when the velocity of the free stream fluid approaches zero, then τ_s approaches zero which is independent of η. This is significant because after a vortex ring is generated the transport of a laminar vortex ring is relatively insensitive to the viscosity of the fluid involved.

2.2.4 Critical Ratio

Figure 2.3 illustrates the vortex ring generation from an orifice plate similar to the type used in this thesis. Literature references based on recent experiments state that an important parameter for vortex ring generation is the ratio L_e/d. When conditions are such that $L_e/d > L_e/d_{crit}$, it has been shown that a primary vortex ring is generated which leaves the orifice approximately when L_e/d reaches L_e/d_{crit}. The generating motion is still occurring at this point and the generating orifice produces a second vortex ring which leaves the orifice when it is stopped. The second ring is smaller than the first ring and therefore travels faster. The second ring soon catches up with the first ring and is ingested by the first ring which results in the destruction of the combined ring.

The ratio L_e/d is often referred to as the critical ratio even when L_e/d is less than L_e/d_{crit}. The critical ratio is expressed as:

$$\begin{aligned} \zeta &= L_e/d \qquad (2.20) \\ &= \{(\pi/4 \times D^2 \times s)/(\pi/4 \times d^2)\} \times 1/d \\ &= (D^2/d^3) \times s \end{aligned}$$

Where ζ = Critical ratio

L_e = equivalent slug length

d = Orifice equivalent diameter

D = Orifice plate overall diameter

s = Piston stroke

Literature references attributed to Baird and Latto state that the critical ratio experimentally has been found to be $L_e/d \leq 2.8$. Further research by Latto has shown that:

$$0.4 \leq \zeta \leq 3.8 \tag{2.21}$$

The above equations for the critical ratio hold true if it is assumed that all the fluid passes through the orifice and not around the periphery of the orifice plate. A fraction, κ, of the displaced volume that passes through the orifice can be included in the critical ratio equation to account for this. This fraction is 1.0 for a tube type generator and can be as low as 0.5 for a plate type orifice unit. The critical ratio can then be expressed as:

$$\zeta = (D^2/d^3) \times s \times \kappa \tag{2.22}$$

2.2.5 Richardson Number

The Richardson number is a vital parameter for vortex ring generation. The Richardson number represents the buoyancy constraints of a fluid which is especially important with stratified liquids. The Richardson number is expressed as[27]:

$$Ri = (\Delta\rho/\rho)(gR/V^2) \tag{2.23}$$

Where $\Delta\rho$ = Density difference in the fluid
ρ = Density of the vortex ring
R = Radius of vortex ring
V = Velocity of vortex ring
g = Acceleration due to gravity

The density, radius and velocity of the vortex ring are the conditions of the ring just prior to the velocity gradient or stratification interface. For a vortex ring to completely penetrate a stratification layer, the Richardson number approaches zero. A reasonable number stated in the literature by Latto is $Ri = 0.01$. As the density of a fluid increases the forward velocity of the vortex ring must be increased such that the Richardson number is less than 0.01.

2.2.6 Strouhal Number

The frequency of vortex ring generation is represented by the Strouhal number. The parameters shown in Figure 2.4 are the basis for the Strouhal number:

$$St = (V/f)/d_{min} < 1 \tag{2.24}$$

Where V = Forward velocity of vortex ring

f = Frequency of ring generation

d_{min} = Minor diameter of the oblate spheroid of the vortex rings

The distance between the generated vortex rings is represented as V/f. To avoid collision between rings the distance which must not be exceeded is $V/f < d_{min}$. It is difficult to determine the exact relationship between V and f for a particular vortex ring generator but observations suggest that V and f are related and may be constant. If V and f are related then d_{min} is related to piston stroke and the factor κ if $Le/d < Le/d_{crit}$. When the situation exits such that V is not directly related to f then d_{min} must decrease as f increases.

2.2.7 Design Calculations

Based on Equation 2.7, $dC/dt = K_La(C^*-C)$, several practical equations can be derived from which an engineer can use to determine the usefulness of a vortex ring generator. The size of generator, mixing time and power consumption for a particular application can thus be determined. The equations listed below do not appear in many literature references and have been supplied by Latto and verified on several laboratory experiments with the vortex ring generator apparatus. All equations assume that the liquid to be destratified and surrounding environment are adiabatic. There is also no allowance for aspect ratio(depth/diameter) or surface roughness in each equation.

1) Volume Per Cycle Mixed:

$$\forall = \pi/4 \times D^2 \times s \times f \times 2 \times \kappa \qquad (2.25)$$

2) Mixing Time:

$$T = V/\forall \qquad (2.26)$$

3) Power Consumption:

$$P_{Dot} = (\pi/4 \times D_p^2) \times P \times \zeta \times (d^3/D^2) \times f \times 2 \qquad (2.27)$$

Where $\forall$ = Volume per cycle..

D_p = Mixing or orifice plate overall diameter.

f = Mixing frequency

κ = Displaced volume fraction.

s = Piston stroke.

ζ = Critical ratio.

T = Mixing time.

V = Liquid holding basin volume.

The above equations appear in the sizing calculations in Chapter 4. These calculations were used to scale the vortex ring mixers that were constructed for use in the experiments that were conducted as part of this thesis. Because there is little information on vortex ring mixers, confirmation of the vortex ring mixers' performance will be verified by the experiment results.

Table 2.1: Solubility of Oxygen (mg/l) in Water Exposed to Air Saturated Air at Atmospheric Pressure = 101.3 KPa and Chlorinity 0.

ANSI/ASCE 2-91 Standard, Second Edition, June 1992.

Temp - Degrees Celsius	Dissolved Oxygen - mg/l
0.0	14.62
1.0	12.33
2.0	13.83
3.0	13.46
4.0	13.11
5.0	12.77
6.0	12.45
7.0	12.14
8.0	11.84
9.0	11.56
10.0	11.29
11.0	11.03
12.0	10.78
13.0	10.54
14.0	10.31
15.0	10.08
16.0	9.87
17.0	9.67
18.0	9.47
19.0	9.28
20.0	9.09
21.0	8.91
22.0	8.74
23.0	8.58
24.0	8.42
25.0	8.26
26.0	8.11
27.0	7.97
28.0	7.83

FIGURE 2.1

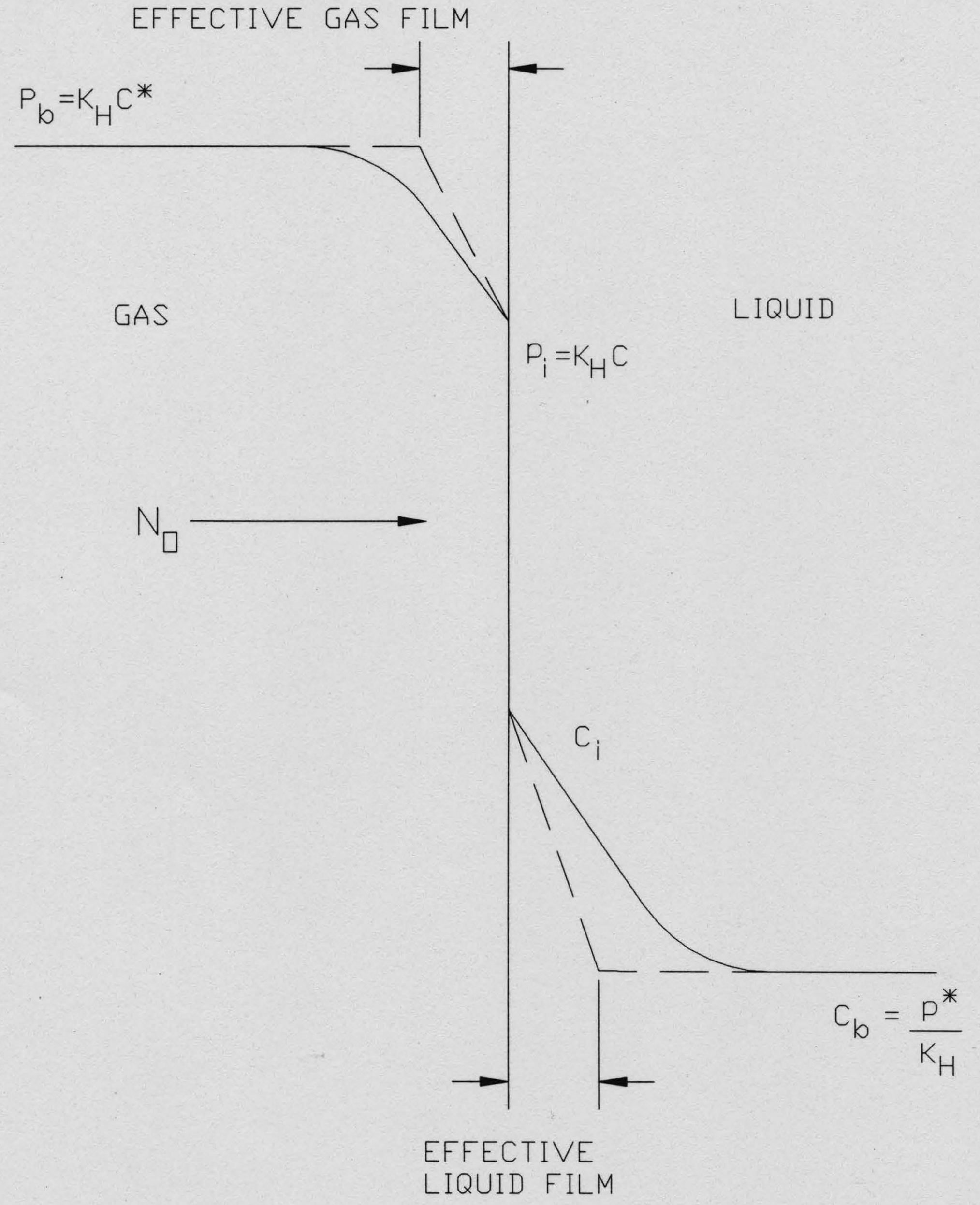

EFFECTIVE GAS FILM
$P_b=K_HC^*$
GAS
LIQUID
$P_i=K_HC$
N_0
C_i
$C_b = \frac{P^*}{K_H}$
EFFECTIVE
LIQUID FILM

FIGURE 2.2

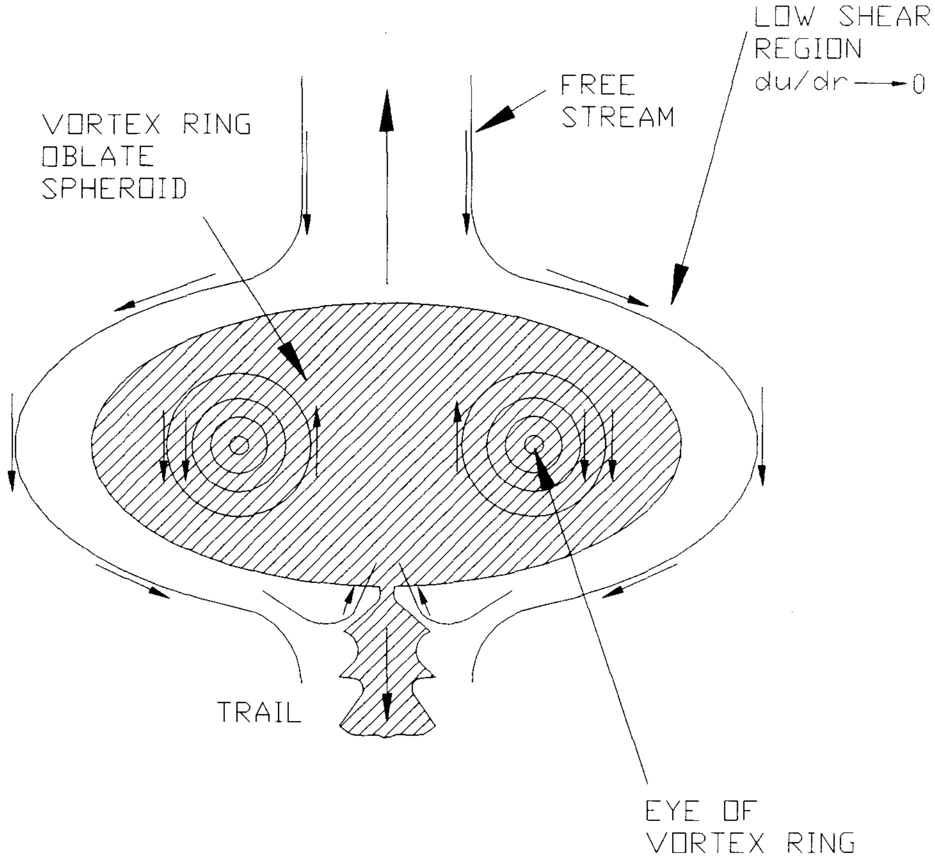

LOW SHEAR
REGION
du/dr ⟶ 0
FREE
STREAM
VORTEX RING
OBLATE
SPHEROID
TRAIL
EYE OF
VORTEX RING

FIGURE 2.3

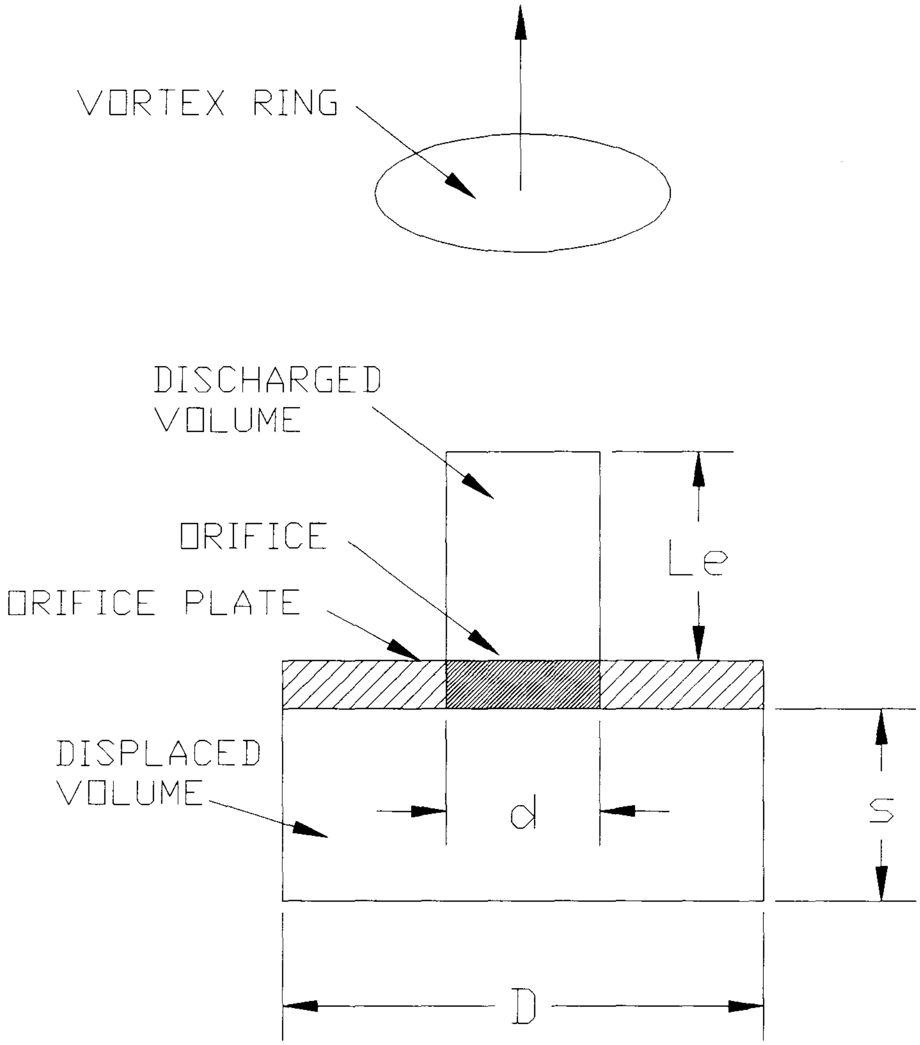
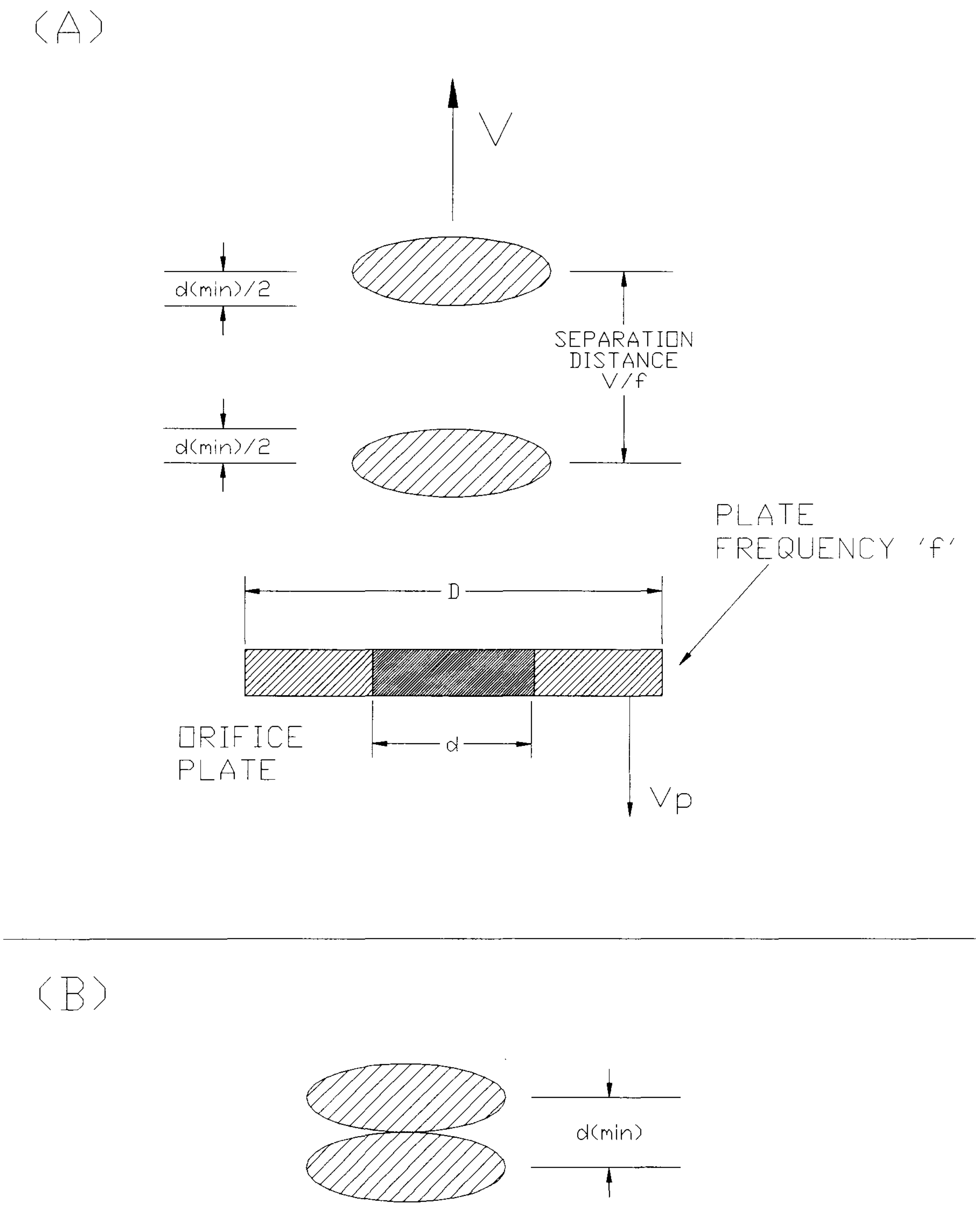

VORTEX RING
DISCHARGED VOLUME
ORIFICE
ORIFICE PLATE
Le
DISPLACED VOLUME
d
s
D

FIGURE 2.4


(A)
V
d(min)/2
SEPARATION
DISTANCE
V/f
d(min)/2
PLATE
FREQUENCY 'f'
D
ORIFICE
PLATE
d
Vp
(B)
d(min)

CHAPTER 3

LITERATURE REVIEW

3.1 Aeration References

The subject of aeration is almost exclusively related to industrial and municipal wastewater treatment. The aims of process industries are to produce intermediate and final products from raw materials dug from the earth or taken from water or atmospheric air. It is inevitable that there are waste products to be disposed of from these processes and if they are of no use in other industrial processes then they must be returned to the air, water or land environment. The return of wastes should be carried out in such a way as to minimize any adverse effects on the environment[26]. Municipal wastewater treatment focuses on treatment of water after use from domestic, farm or industrial sources. Social and political problems, in addition to economic and technical ones, often dictate the quality levels that effluent discharges must meet. Aeration of wastes and the transfer of oxygen are therefore critical in the attempt to meet such varied criteria.

3.1.1 Oxygen Transfer

Municipal water treatment facilities have been in existence for the last 75 years with McKinney and O'Brien[19] commenting that papers written on the subject of aeration in activated sludge treatment systems number in the hundreds. They also commented that the tremendous diversity of available information poses a dilemma for engineers since it is almost impossible to read all of the published information on aeration and biological treatment systems much less to evaluate the merits of different methods.

In a paper on biological treatment of ferric compounds resulting from mining operations, Liu, Branion and Duncan[17] investigated the effect of pH on the rate of oxygen transfer. The authors recognized that the rate of oxygen transfer into the wastewater solution containing the microbial organisms used in biological treatment of the waste was important. They also recognized that the performance of any proposed aeration device must be examined carefully due to problems with scaling-up from laboratory or bench apparatus to plant sized equipment.

With respect to Liu, Branion and Duncan's original premise, pH was found to not have a significant effect on the value of K_La. They did note that the effect of temperature on K_La was more significant than pH with K_La increasing with increasing temperature. The authors also stated that the rate of transfer of oxygen from a gas to a liquid is proportional to the dissolved oxygen in the liquid and to the interfacial area per unit volume. Equation 2.8 in Chapter 2 representing the overall volumetric mass transfer coefficient K_La was developed from this criteria and confirmed by the authors in the article.

Research by Barnhart[4] investigated the mechanism of oxygen transfer in pure water and waste water to attempt to define the parameter, alpha, that relates the oxygen transfer rate in waste to the transfer rate in waste water. Using Henry's law, Barnhart developed the logarithmic form of the volumetric transfer coefficient found in Equation 2.9 of the previous chapter. From this basis various investigators found that the oxygen transfer rate is altered from that in pure water in the presence of surface active agents or other contaminants. The magnitude of the change depends on the concentration of the contaminant, the nature of the aeration and the characteristics of the aeration surface. Those surface active agents which quickly reach equilibrium have a far more profound effect on oxygen transfer than those which slowly reach equilibrium. In like manner, a continuously renewed surface will exhibit less effect than a long exposure surface such as occurs during a bubble rise through a deep tank. Organic materials in low concentrations principally influence transfer by changing the bubble size in the system which is related to changes in surface tensions. From these investigations, Equation 2.11 for temperature effects and Equation 2.13 for waste effects represented by alpha were confirmed.

A cautionary note from Barnhart is that in most sewage solutions the reduction in surface tension is small and the change in oxygen transfer characteristics can probably be related directly to the change in bubble characteristics. The vast majority of data available on the effect of surface active materials on bubble size has been obtained on bubbles considerably smaller than those employed in conventional practice. A conclusion can be drawn from this statement that laboratory scale experiments usually employ much smaller bubbles than are produced by commercial equipment and therefore provide misleading information for such systems. The selection of a treatment system should therefore be based on data generated from actual commercial full plant scale systems and not from laboratory results.

3.1.2 Oxygen Transfer Data

Brown and Baillod[5] did extensive research on modelling and interpreting oxygen transfer data. The unsteady state clean water oxygen transfer test is widely used to determine the oxygen transfer capacity of aeration equipment. Frequently, this evaluation is based on shop tests concluded in tanks which are more or less similar to recommended field installations. In other cases, this evaluation is based on data collected in full scale installations. Although the test is straightforward, the validity of the results is influenced strongly by the experimental procedures. Moreover, the design parameters resulting from the test are affected by the techniques employed in analyzing the test data. Modelling and interpretation of these data are important for the design of aeration systems and especially for field performance acceptance tests.

Brown and Baillod stated the basic model recommended for the analysis of both surface and subsurface clean water unsteady state-oxygen transfer test data can be represented by the following:

1) Differential Form:

$$\frac{dC}{dt} = K_La(C^* - C) \tag{3.1}$$

2) Logarithmic Form:

$$\ln\frac{(C_\infty^* - C)}{(C_\infty^* - C_0)} = K_Lat \tag{3.2}$$

3) Exponential Form:

$$C = C_\infty^* - (C_\infty^* - C_0)\exp(-K_L a t) \qquad (3.3)$$

These equations also appear as Equations 2.8, 2.9 and 2.10 in Chapter 2. This model has been shown experimentally to fit adequately the vast majority of observed data from both surface and subsurface clean water aeration tests.

3.1.2.1 Differential Method

The direct or differential method of Equation 3.1 is linear in K_La and does not require that a value of C_∞^* be specified to do least squares analysis. The main disadvantage of this method is that it magnifies the noise in the data. The estimates of K_La are more imprecise than the other two methods and it is often necessary to discard substantial portions of the data at both high and low values of C to get a good fit. Because of this the direct or differential method is not recommended.

3.1.2.2. Logarithmic Method

The log deficit or logarithmic method is linear in K_La allowing linear least squares regression to be used for parameter estimation but it requires that a value of C_∞^* either be assumed, measured or determined from book values in order to calculate the deficits. The estimate of K_La will be biased to the extent that the value of C_∞^* is selected incorrectly.

3.1.2.3 Exponential Method

The exponential method fits Equation 3.3 to the experimental data with the values of dissolved oxygen concentration used directly to fit the data employing non-linear least squares regression. The main advantage of this method is that the computational procedure provides least squares estimates for all three parameters without placing any constraints on the data used (truncation) or on assumed values of parameters. The parameter estimates from this method appear experimentally to be more accurate than either the differential or logarithmic methods.

3.1.3 ASCE Clean Water Standard

The Brown and Baillod article mentioned previously is referenced in the 1992 American Society of Civil Engineers' (ASCE) standard, second edition, on the measurement of oxygen transfer in clean water[20]. Brown and Baillod were members of the committee that came up with the standard and Equation 3.3 is the reference model used to determine the dissolved oxygen levels in clean water. The ASCE standard covers the measurement of the oxygen transfer rate (OTR) as a mass of oxygen per unit time dissolved in a volume of water by an oxygen transfer system. The oxygen transfer represented by Equations 3.1, 3.2 and 3.3 are applicable to laboratory scale oxygenation devices with small volumes of water as well as the full scale systems and a wide variety of mixing conditions.

The result of using the exponential method found in the ASCE standard is the Standard Oxygen Transfer Rate (SOTR) expressed as Equation 2.17 in Chapter 2. The SOTR is a hypothetical mass of oxygen transferred per unit time at zero dissolved oxygen concentration, water temperature of 20°C and barometric pressure of 1.00 atm. The method outlined in the standard is intended primarily for clean water which is achieved by removing the dissolved oxygen in the water by sodium sulfite and then reoxygenating to near saturation level by the reaeration method under test. The dissolved oxygen is measured throughout the test either by probes or taking samples. Data from the reoxygenation is analyzed using the exponential method of Equation 3.3 to estimate the apparent volumetric mass transfer coefficient K_La and the steady state dissolved oxygen concentration C_∞^* using regression analysis.

Baillod, Paulson, McKeown and Campbell[3] researched the accuracy of the method outlined in the first edition of the ASCE standard. The test procedure outlined in the standard is based on widely used clean water unsteady-state tests in which deoxygenation is followed by oxygenation to saturation. The ASCE standard gives details with regard to water quality, sulfite addition, sample point location, sampling times and dissolved oxygen measurement. The purpose of the research paper was to determine the degree of agreement between the test procedures in the authors' candidate test data and those prescribed by the ASCE standard. The resulting test data were analyzed by the simplified mass transfer model given as the differential, logarithmic and exponential forms outlined in Equations 3.1, 3.2 and 3.3.

The authors found that the results of the replicate shop and plant-scale clean water oxygen tests conducted in agreement with the ASCE standard showed that the SOTR measurement is very good. The data was fit using the logarithmic and exponential methods represented as Equations 3.2 and 3.3. It was found that comparison of SOTR values given by these two methods generally agreed within plus or minus 3% of each other and that the exponential method generally gave more accurate SOTR values than the logarithmic method. The ASCE standard was also successfully applied to wide variety of aeration equipment and tank configurations including coarse and fine bubble diffused air, single and multiple surface aeration, oxidation ditches and static tubes.

3.1.4 Destratification of Water Reservoirs.

A paper by Busnaina and Lilley[7] focused on predicting local destratification in reservoirs. During the hot summer months thermal stratification may occur in reservoirs. The lower layers of water become severely anaerobic or oxygen deficient with corresponding harm to water quality. When this occurs three main layers of water with different characteristics may be observed. The top layer or epilimnion contains warm low density water usually rich in oxygen because of atmospheric reaeration and photosynthesis and thus considered to be high quality water. The hypolimnion or bottom layer consists of cold high density water which is often poor in oxygen and thus considered as a low quality water. The region of rapid temperature change between the other two layers is called the thermocline or metalimnion. This stratification presents a serious problem for reservoirs with low level release structures in that the quality of water released as characterized by its oxygen content may be poor since most of the exit flow comes from the bottom layer of the reservoir. Many old reservoirs have release structures located near the bottom and there are many problems associated with finding suitable and economically feasible alleviation techniques.

Possible approaches suggested by the authors include artificial destratification, structural modification and localized mixing to improve the release water quality. Artificial destratification can either be mechanical pumping or diffused air pumping. These mixing devices unfortunately consume substantial amounts of energy to destratify large bodies of water. Structural modifications of dammed reservoirs ito allow some of the water to be drawn from the epilimnion is effective although extremely costly. The authors also commented that localized mixing of the epilimnion water into the hypolimnion has been found to be effective and economical in enhancing the quality of water release from low level release gates.

The fact that the article was written in 1983 is poignant since Busnaina and Lilley commented that there has been continued interest in local mechanical destratification of reservoirs to improve water quality. The authors quoted experiments in reservoirs in the states of Oklahoma and Mississippi that used a low energy axial flow propeller positioned just below the water surface. This provided a downward directed jet of water and thereby locally mixed the reservoir in the vicinity of the release structure of the dam thus transporting the high quality epilimnion water downwards to improve water quality and reduce stratification. The authors research discovered that release water quality increases with higher jet velocities from mechanical destratification devices and a lower degree of stratification within the reservoir.

The referenced article by Busnaina and Lilley was one of the foundations for the experiments in this thesis. The comments by these two authors of the need to improve water quality through destratification with an economical method was one basis for the idea of using the vortex ring generator as a mixer to destratify a natural water body. Since this article first appeared in 1983 the need for improvement of existing man made reservoirs and the preservation and remediation of natural water courses is increasing. The application of the relatively new vortex ring generator to this situation was felt to be a current and realistic application for study.

Commercial information has recently been obtained from a Swiss company, Locher[18], on a restoration system first employed in the restoration of several lakes and reservoirs in Switzerland. This firm specializes in sewage treatment and was awarded a contract to develop a system to aerate low altitude lakes with unacceptable phosphorus and oxygen levels. The apparatus used was a typical mixing and pumping arrangement that uses capital and energy intensive equipment. The equipment was necessary to penetrate and mix the epilimnion and hypolimnion with higher oxygen water to reduce stratification and thus increase oxygenation of the water body. Government regulation and sponsorship developed this process and proved that aeration of large lakes is achievable. The major drawback is the capital and energy expense of the equipment. It is one of the goals of this thesis to show that by mixing natural water bodies with a vortex ring generator with inherent lower capital and energy cost is more process and cost effective than existing rotating and pumping technologies such as the Locher apparatus.

3.1.5 Aeration Conclusion

The subject of aeration is well known and there is plentiful data available on applications from municipal and industrial waste treatment. The extent of this information was the basis for the ASCE standard on clean water. Using the information from this standard the tests conducted as part of this thesis were analyzed for K_La and eventual SOTR and SAE values of the vortex ring mixer in a natural pond setting. Since the information found in the ASCE standard is well established, results based on this standard are meaningful and can be readily compared to other applications analyzed in a similar manner.

3.2 Vortex Ring Generation and Mixing References

A search for literature on the subject of vortex ring generators applied to mixing proved that there are few sources of technical reference on the subject. The majority of information was found in recent research papers from several authors. At present, there is no one source or definitive textbook on the subject because, in my opinion, research is still evolving the knowledge of vortex rings and until sufficient plant scale applications in mixing and aeration are established over the long run there will not be such a reference source possible and available. In Chapter 2 much of the information describing the theory behind mixing and vortex ring generation was obtained from research papers and will be discussed further in this section.

3.2.1 Recent Vortex Ring Research

Ongoing research by Latto over the last ten years has been concerned with vortex ring generation to obtain design parameters of vortex ring generators and mixing equipment. The results of this research has shown that the generation and motion of a vortex ring is complex and difficult to accurately predict analytically. It is also difficult to predict the motion of a vortex ring adjacent to a wall or the effects of adjacent vortex rings on each other[12].

The volume of fluid transported in a vortex ring is an approximately oblate spheroid shape. The rapid rotation or vorticity is concentrated in a toroidal core or ring. Figure 3.1[22] shows the core radius dimension with radius a, and the radius of the circle R around which the rotation occurs. The toroidal core of rotating fluid is surrounded by an oblate spheroid region with major and minor dimensions d_1 and d_2, respectively, of lower circulating fluid which moves translationally with the core.

It was found that to generate the vortex rings described above they should have a plug length to orifice diameter within the following range:

$$0.4 \leq \zeta \leq 3.8 \qquad (3.4)$$

Additional parameters that have been determined through research include the volume of the vortex ring immediately after it has been formed and the minimum number of strokes a generator needs to make to transfer the entire volume of fluid to be mixed:[12]

$$\text{Vortex Ring Volume} = V = 1.6D_m^3 \qquad (3.5)$$

$$\text{Mixer Strokes} = N = 0.625\ Vf/D_m^3 \qquad (3.6)$$

Where: V = Volume of fluid in a vortex ring immediately after generation.

D_m = Diameter of the generating orifice.

N = Minimum number of mixer strokes to translate entire fluid volume to be mixed.

Vf = Volume of fluid to be mixed.

3.2.2 Vortex Ring Generator Types

The main thrust of the research by Latto[9-16] has been the development of vortex ring mixers that can be applied to practical industrial and municipal mixing situations. The emphasis on mixer design has been ease of operation and installation with low capital, maintenance and energy costs. Based on this criteria, two classes of mixers have been developed and include the tube type and plate type mixers.

3.2.2.1 Tube Vortex Ring Generators

Figures 3.2 and 3.3 show tube type mixers which share the common characteristic of ejecting a slug of fluid from the mixer by a piston activated by an electronic, mechanical or pneumatic drive system. Aside from the vortex ring generation, the heart of the vortex ring generator is the control system that governs the mixing rate and effectiveness. The control box can be pneumatic, electro-pneumatic or electronic which continuously varies the power input and the frequency of vortex ring generation over the 0 to 10 Hertz range found most effective by Latto.

One of the tube type mixers' main advantage is the ability to inject gases into liquids or slurries due to the inherent ability to seal and entrain gas in the mixer tube. Gases can be pumped or automatically drawn into the tube when agitation produces high absorption rates of the injected gas into the liquid. The gas then mixes with the liquid in the tube and the resulting highly gasified liquid is ejected from the tube mixer in the form of a vortex ring which travels into the surrounding liquid until the vortex ring ultimately disperses. The vortex ring transports the injected gas into the liquid and often a ring of gas at the eye of the vortex ring can be observed during mixing. Another advantage is that tube type mixers are outside the liquid being mixed or the mixing vessel thereby greatly increasing maintainability.

Tube type mixers have wide applications in areas such as sealed vessels for noxious liquids and for the efficient introduction of additives such as deoxidizers, dyes, and use with liquid or molten metals like aluminum or steel. Recent practical equipment development of tube type mixers has shown great promise in the ability to be installed and retrofitted on existing pressure vessels and pipelines without cutting new access points as shown in Figure 3.3. The tube mixer can be installed in pressure vessels through existing access hatches or external nozzles during plant shutdown and also when the vessel is in operation through valved nozzle connections. This application is also beneficial when there is a particularly hazardous process occurring in a vessel since the tube mixer does not have to project into the vessel to be effective. A parallel application is the installation of tube mixers in pipelines. This configuration allows the mixer to be out of the stream flow while allowing installation and removal at valved connections when the pipeline is in continuous operation which is critical in liquid and gas transmission.

3.2.2.2 Conical and Flat Plate Vortex Ring Generators

The other major class of vortex mixers are plate type mixers which have been produced in several configurations. Figures 3.4 through 3.8 illustrate some of the types that have been trial tested in industrial settings.

The cone type configuration outlined in Figure 3.4 has shown to have less effective mixing characteristics than the flat plate design outlined in the remaining figures even though the conical design can have a more mechanically simplistic design. A single drive piston can be more readily used for the conical mixer since the entire conical concept is more hydrodynamically stable than a flat plate.

Figure 3.5 shows multiple conical units submerged in a large tank to provide mixing. Sophisticated control systems can be used in such an application to adjust individual mixers to provide increased or decreased mixing throughout the tank if concentration differences are significant. These same control systems can also be used to decrease or throttle back mixing frequency once a tank is mixed and also detect when increased mixing is required to maintain the desired process concentration in the tank.

Figure 3.6 shows the typical flat plate vortex ring generator configuration. This flat plate set-up is completely submerged in a tank and produces vortex rings both upward and down. As with the tube type mixers, the drive piston can either be pneumatic, electro-pneumatic or electronic. The main advantage of having the mixer at the bottom of the tank is to mix sediments that concentrate at the bottom. This type of mixer also can be located at the tank axis at any angle or in the horizontal such that the vortex rings can be projected at virtually any angle across the liquid being mixed. The disadvantage to this configuration is maintainability since the mixer must be removed from the tank for service which can often be difficult if the mixer malfunctions thereby allowing thick and heavy sediments to form on top of the mixer making retrieval difficult.

Figure 3.7 illustrates a plate mixer that is suspended at the top of a mixing tank. This allows for easier removal while still maintaining the ability to mix the entire tank volume including bottom sediments. Figure 3.8 shows a flat plate mixer with multiple pistons supported by a flotation collar in a large holding tank. Several small pistons have found to be more effective since they can provide a more abrupt and non-sinusoidal stroke as compared to a larger piston since a large piston cannot effectively move fast enough during the downward stroke to generate an effective vortex ring.

The mixer used in the experiments of this thesis was a combination of the mixers shown in Figures 3.7 and 3.8 consisting of a flat plate mixer driven by a single piston supported on a flotation collar in the test pond. Recent developments in mixer design include flexible membrane vortex generator mixers made of reinforced plastic sheet or woven fiberglass cloth which provide acceptable low mixing times and energy consumption. The flexible membrane configuration offers low weight, easy installation in areas with small access holes and the flexing of the surface to give self adjusting orifice shape.

3.2.3 Mixing Performance

Performance characteristics for vortex rings over a wide range of test facilities and liquids and slurries have been investigated by several authors including Latto, Papple, Shoukri and Baird[11]. As indicated above, experiments have also been conducted on the generation and propagation of vortex rings in a variety of solutions. Empirical studies have concentrated on optimal generating conditions for homogenous liquids, stratified liquids, suspensions or slurries and liquid-liquid dispersions. In all cases, the practical experiments were done to obtain operating characteristics for the mixers in various vessels or tanks with differing geometry.

3.2.3.1 Homogenous Liquids

Homogenous liquids were investigated to determine the formation and propagation of vortex rings. Latto had determined from these tests the critical ratio expressed as Equation 3.1 mentioned in section 3.1.2. Other observations included that there is almost immediate vorticity at distant regions from the vortex ring generator which is rarely observed for propeller impellers. Latto in 1987 reported that the velocity of the plate is only required to be large enough such that the vortex ring reaches the liquid surface or an appropriate location in a mixing tank. A high energy vortex ring that vigorously breaks the surface has little value in the mixing process other than creating surface turbulence. It was also reported that a high velocity vortex ring does not grow very fast and thus does not generate significant mixing between the high velocity vortex ring and the surrounding fluid. The disadvantage of this is that increased energy is used to generate a vortex ring with inferior mixing capabilities as compared to a lower velocity ring generated with less energy that provides better mixing.

3.2.3.2 Stratified Liquids

Research described in Section 3.2.1 and more recently by Latto[11] on stratified liquids was the next logical step after propagation studies of vortex rings in homogenous liquids. Stratified liquids often result from temperature and density gradients resulting from homogenous liquids that over time at rest have experienced some sort of separation or destratification. Experiments by Latto and Baird on stratified fluids have produced much of the data available on the use of vortex ring mixers in stratified applications. One particular example is the suggestion by Baird of the use of vortex rings for the de-stratification of water in lakes and the agitation of the floor of lakes. Some preliminary experiments were conducted in Lake Ontario. This suggestion formed the basis of the research for this thesis.

When a vortex ring encounters a density gradient the ring may pass through it, partially penetrate or "bounce" back into the fluid from which it came. Latto in 1991 reported that this phenomenon is related to the Richardson number, Ri, which is an important parameter for stratified fluid systems and indicates the buoyancy effects of a fluid determines if a vortex ring will penetrate the gradient and eventual mixing. The Richardson number expression appears as Equation 2.23 in Chapter 2. When the Richardson number is less than 0.01 repeated vortex rings will penetrate the layer and cause complete dilution of the layer and eventual homogenization of the entire liquid. When the Richardson number is greater than 0.01 only partial penetration occurs and de-stratification may occur but at a much slower rate. Larger Richardson numbers result in vortex rings that do not penetrate but rather bounce back in to the primary fluid. Latto, Papple, Shoukri and Baird in 1990 investigated mixing thermally stratified fluids using Patankar's SIMPLER numerical method technique. The numerical technique was found to be adequate to simulate the formation of vortex rings and confirmed the effect of the Richardson number as described by Latto's research.

3.2.3.3 Suspensions

Liquid suspensions or slurries applications were developed to provide real word applications of vortex ring mixing of liquid and solid sediments. Extensive mixing tests were done by Latto over the last ten years on aqueous coal and lime suspensions with up to 45% concentration by weight. These slurry solutions were left standing for periods up to 24 hours such that the solids sedimented to about one third of the depth of the liquid in the test tank. When the vortex ring mixer was started it was observed that it took a significant number of pulses for the vortex rings to break the surface of the solution and thus begin the mixing process. Once the first ring broke the surface the turbulence in the solution became more violent as the vortex rings broke up the sedimentation and complete homogenous mixing occurred. Additional mixing tests on slurry solutions such as paint, calcium carbonate, magnesium hydroxide and corn syrup were outlined by Latto[15] in a 1992 paper. The resulting mixing times were very short as compared to propeller type mixers under similar applications. Low mixing times and frequencies in the range of 1 to 4 hertz for the mixer stroke also point to significant energy cost savings when compared to the high energy costs and long mixing times usually associated with propeller type mixing devices

3.2.3.4 Liquid-Liquid Dispersions

A recent 1994 paper by Rao, Latto and Baird[22] describe the effect of vortex ring mixing on a stratified solution of brine and kerosene. The mixer used was a tube type immersed in the upper and lighter kerosene layer. Several tests were run where kerosene containing vortex rings penetrated the brine solution. It was recommended that dispersion of the kerosene could be enhanced by locating a fixed baffle or plate near the vortex ring generator or by modifying the orifice or tube to promote turbulence in the rings as they form. The mixing of dissimilar liquids is common in the petrochemical, food and pharmaceutical industries and further investigation has been recommended.

3.2.4 Energy Consumption

The two main advantages of the vortex ring mixer is low mixing time and low energy costs. Results from aqueous coal and lime slurry investigations by Latto show that mixing such slurries in standard 45 gallon drums is usually accomplished in less than one minute. Compressed air consumption rates when mixing in this configuration are 0.085m^3/min as compared to 0.425m^3/min for standard rotary impeller mixers. Mixing tests with slurries in a 2000 litre tank produced mixed contents in less than three minutes with a flat plate mixer using a piston with a 3.8cm stroke. In terms of power consumption, tests using a flat plate mixer operating at 4 Hertz in a 530 litre tank had an energy consumption of 0.112 horsepower or 84 Watts which translates to 0.16 Watts per litre. Typical air powered rotary mixers consume 1 Watt per litre so in effect the vortex ring mixer consumed 88% less energy during mixing operations.

Other experiments in 2000 litre tanks have yielded 0.013 and 0.026 Watts per litre for frequencies of 1 to 2 Hertz. Energy consumption for complete mixing is therefore 1.008 and 0.975 Joules per litre. These figures are again considerably less than normal values for rotating element mixers even though there is a certain minimum energy that must be supplied to overcome the stratification in a given case. It has been found that the with the flat plate vortex ring mixer the optimum frequency is about 2 hertz to provide the minimum energy for complete mixing. Higher frequencies give faster mixing times but once the solution is mixed the frequency can be decreased to maintain mixing at a more economical rate. As the frequency is decreased the role of forced convection increases whereas at high frequencies the mixing process is governed by the mass transfer created by the vortex rings hence the higher energy requirements of higher frequencies.

3.2.5 Vortex Ring Mixer Conclusions.

From the research studied, the vortex ring mixers provide very effective mixing in a short period of time with low energy and capital costs. Mixers have been shown to work in differing mixing tank geometry and capacities without the use of baffles. Mixer control depends on varying frequency and power input which can be quickly and easily varied to fine tune vortex ring mixers for different applications or as mixing characteristics change in a particular application. Computer control and the potential use of new smart controls to automatically sense mixing requirements have shown great promise to automatically control vortex ring mixers in industrial applications. The present thrust of vortex ring mixer development is to move applications from the lab and into the field in varying industries. Mixers are presently being tested by mixing molten metal in metal processing and plating industries, to mixing effluent in sewage digesters, gasification of liquids in food, mineral and petrochemical industries and the mixing or destratification of natural water bodies, the latter of which is the basis of this thesis. Unfortunately, as mixers are applied in industry, results may not be forthcoming since firms may consider this data proprietary process knowledge and not publish the actual results.

FIGURE 3.1

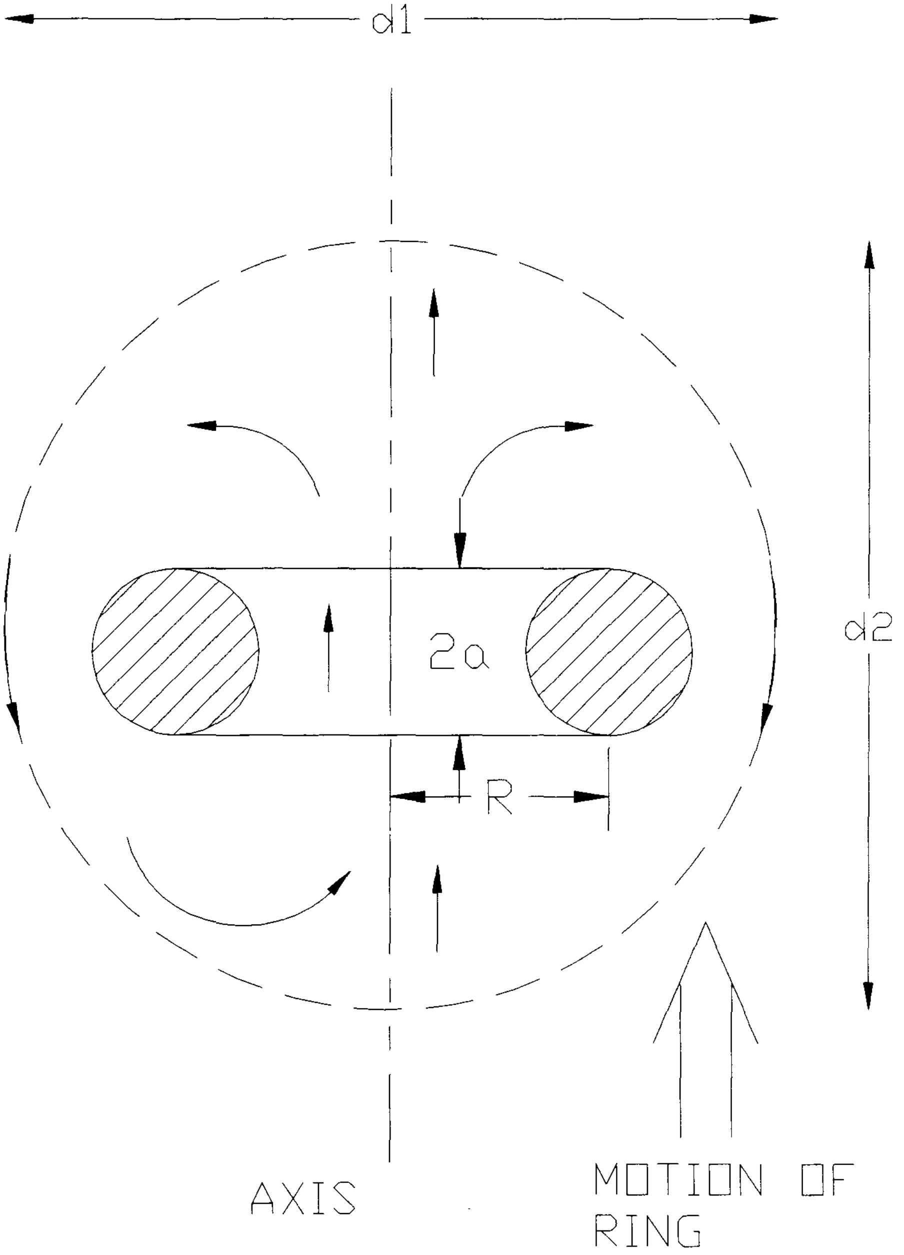


FIGURE 3.2

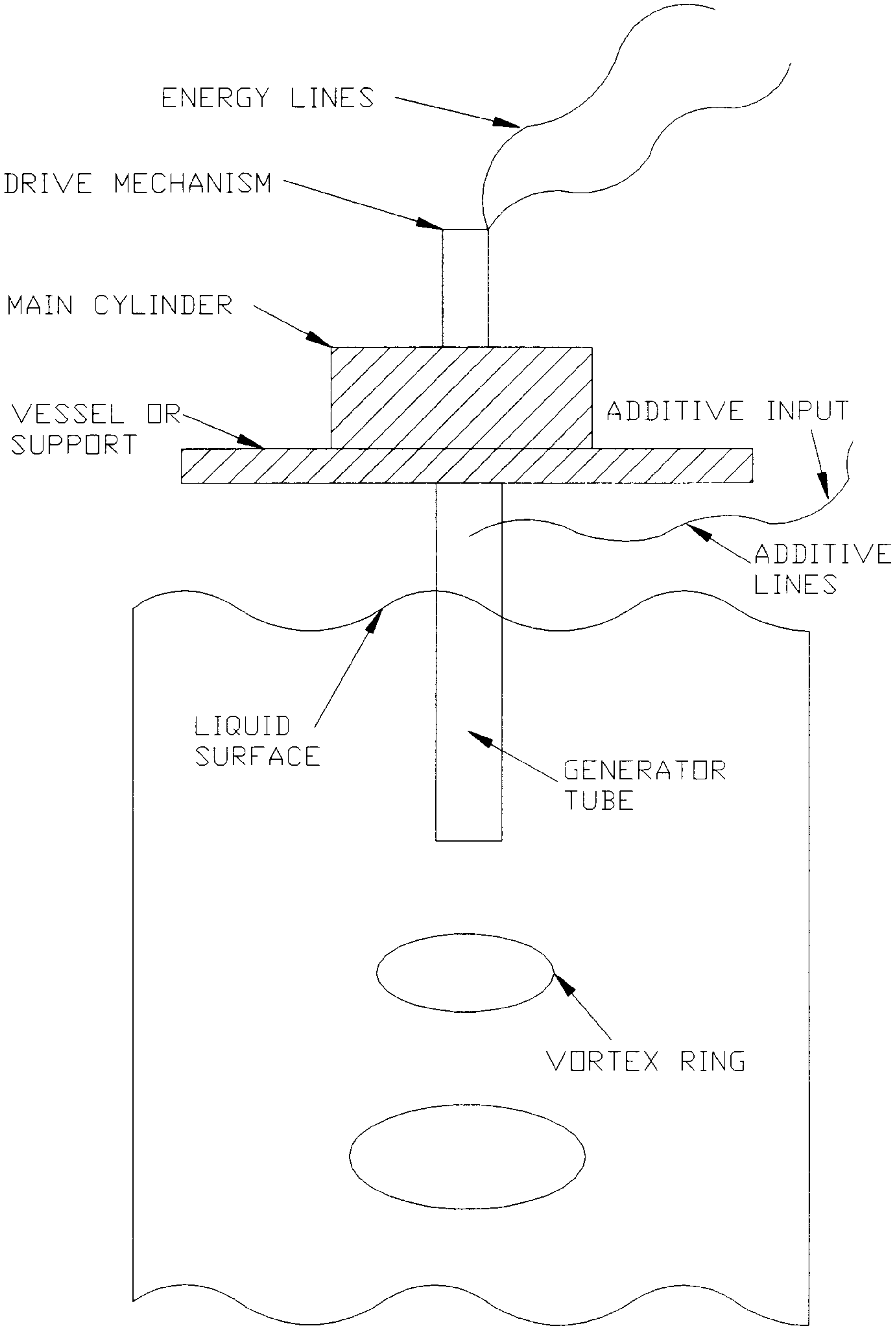

ENERGY LINES
DRIVE MECHANISM
MAIN CYLINDER
VESSEL OR SUPPORT
ADDITIVE INPUT
ADDITIVE LINES
LIQUID SURFACE
GENERATOR TUBE
VORTEX RING

FIGURE 3.3

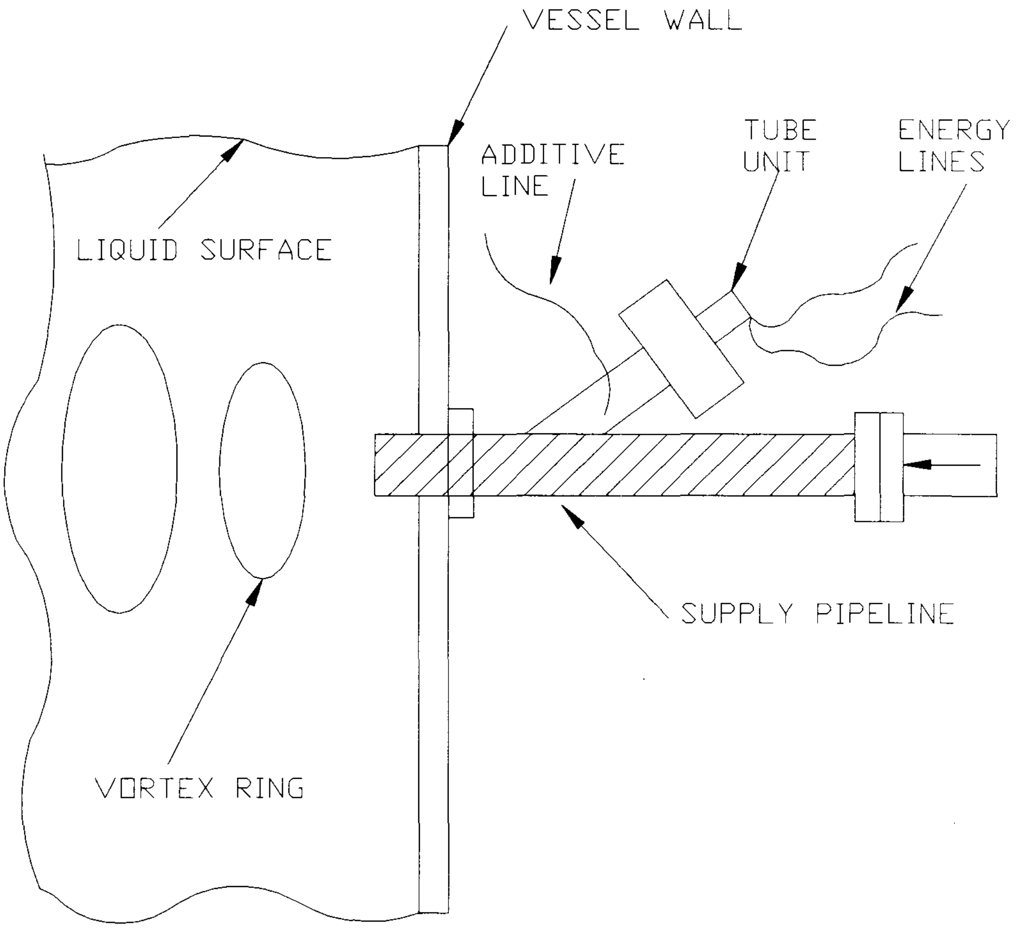
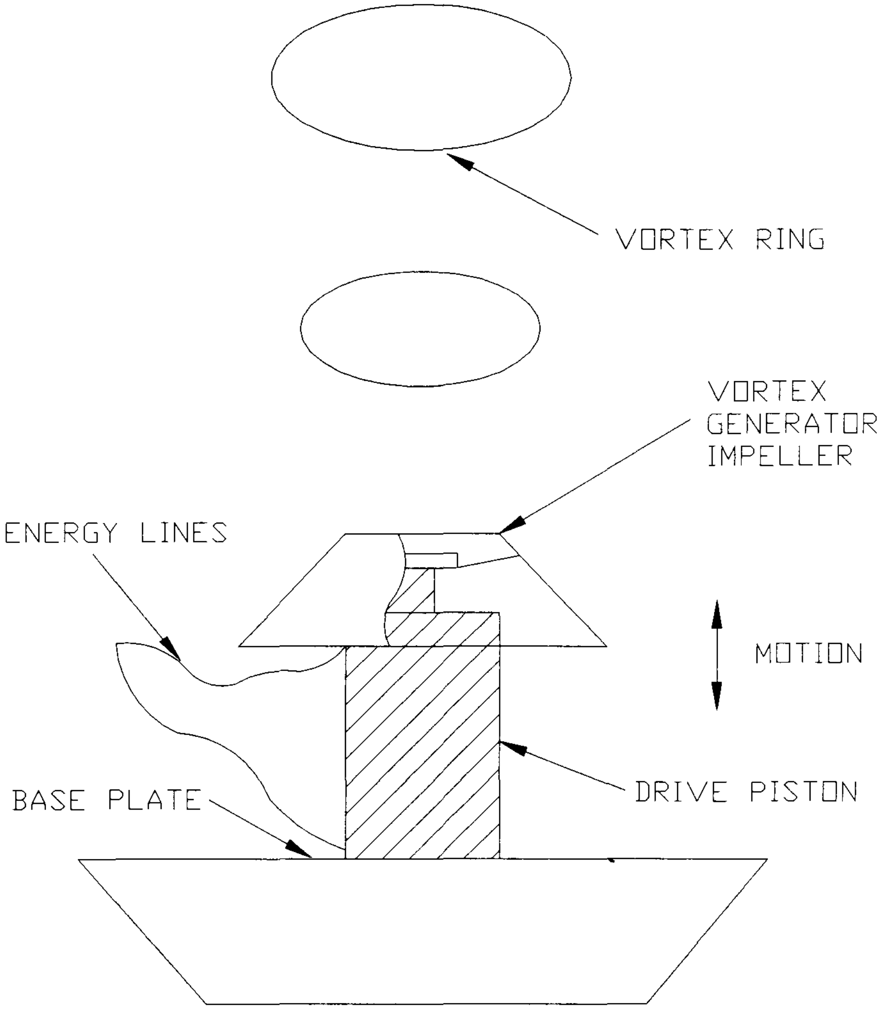
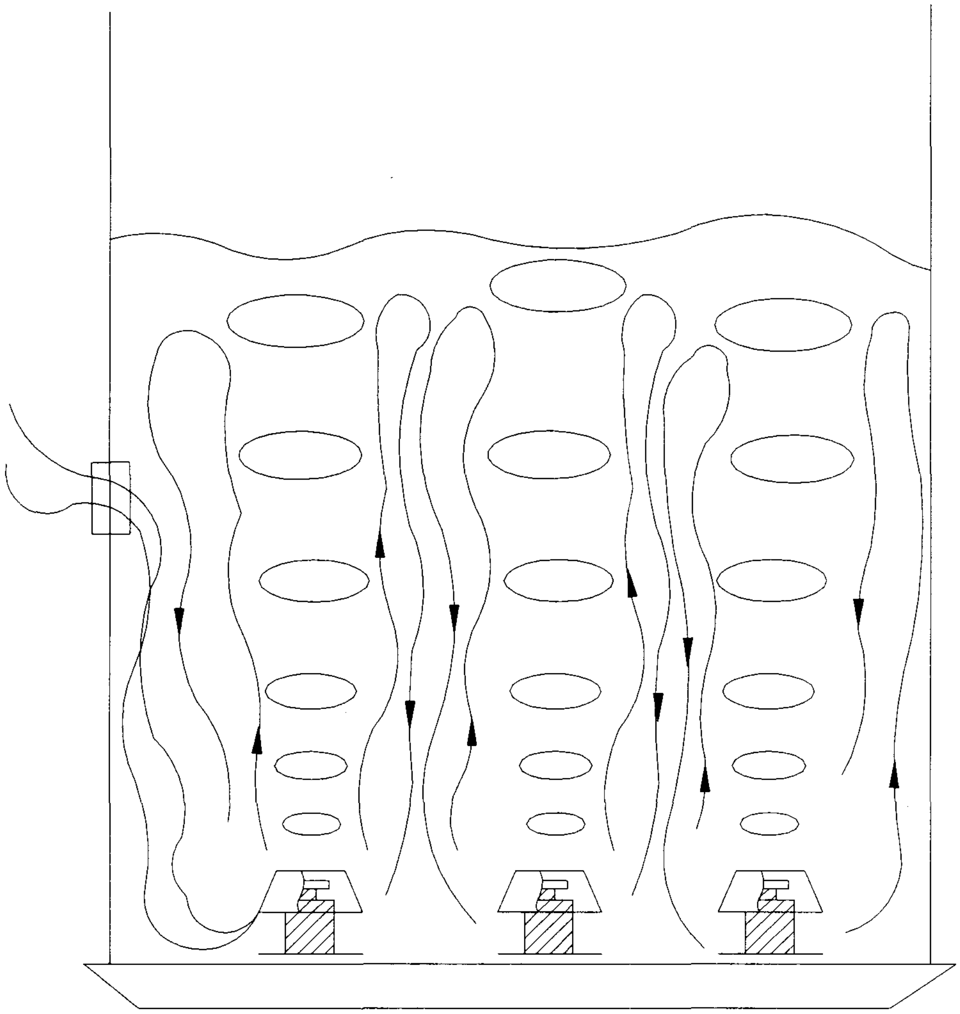

VESSEL WALL
ADDITIVE LINE
TUBE UNIT
ENERGY LINES
LIQUID SURFACE
SUPPLY PIPELINE
VORTEX RING

FIGURE 3.4



CONE TYPE VR MIXER

FIGURE 3.5



MULTI-UNIT SYSTEM FOR A LARGE TANK

FIGURE 3.6

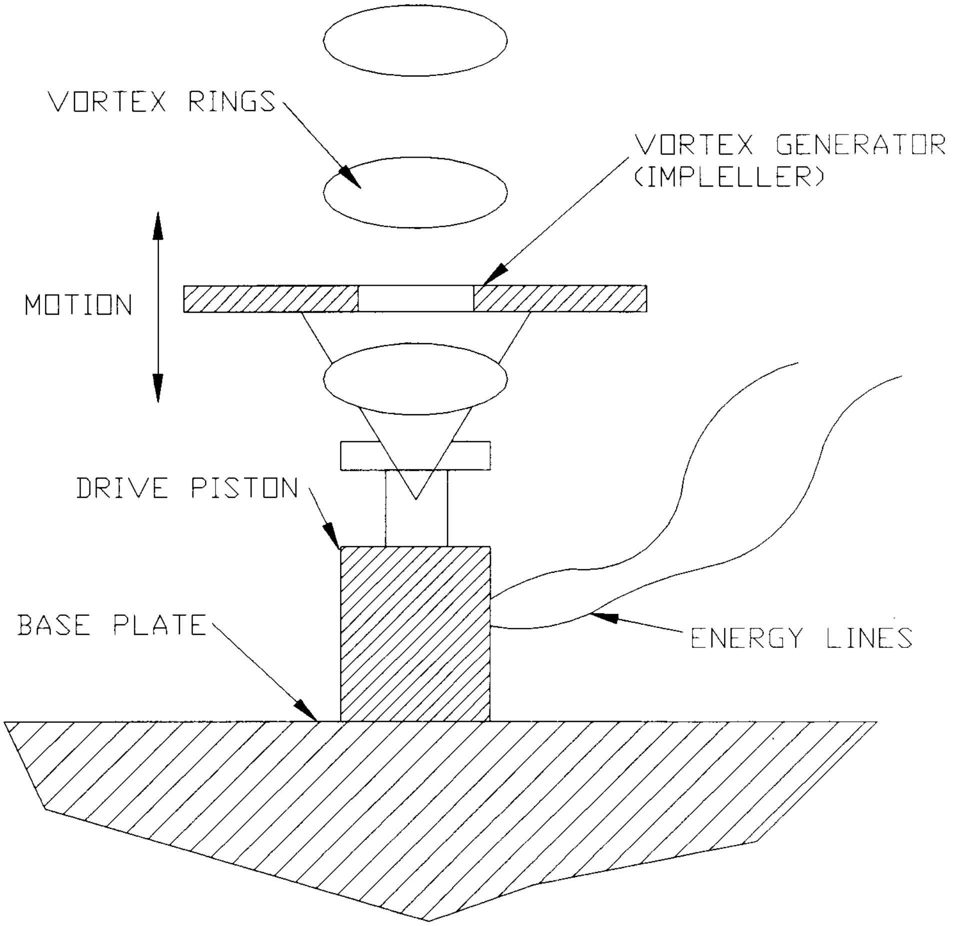
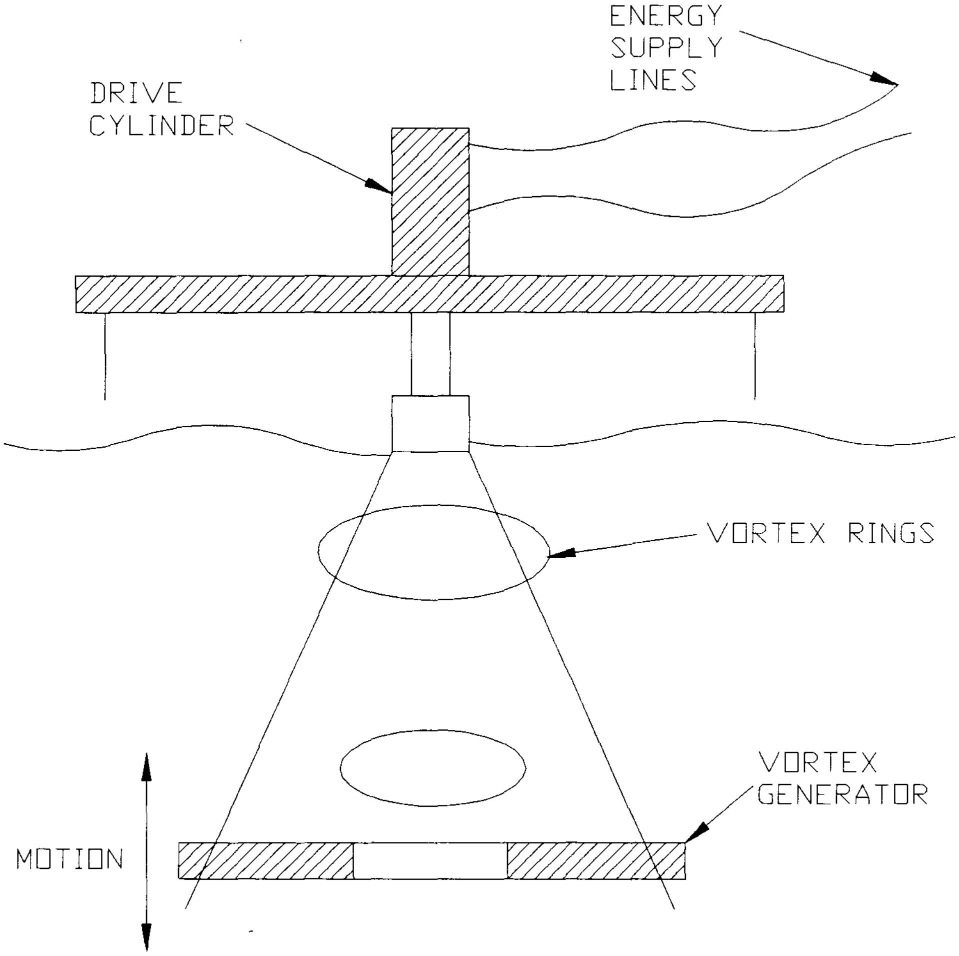


PLATE TYPE VR MIXER

FIGURE 3.7



SUSPENDED PLATE VR MIXER

FIGURE 3.8

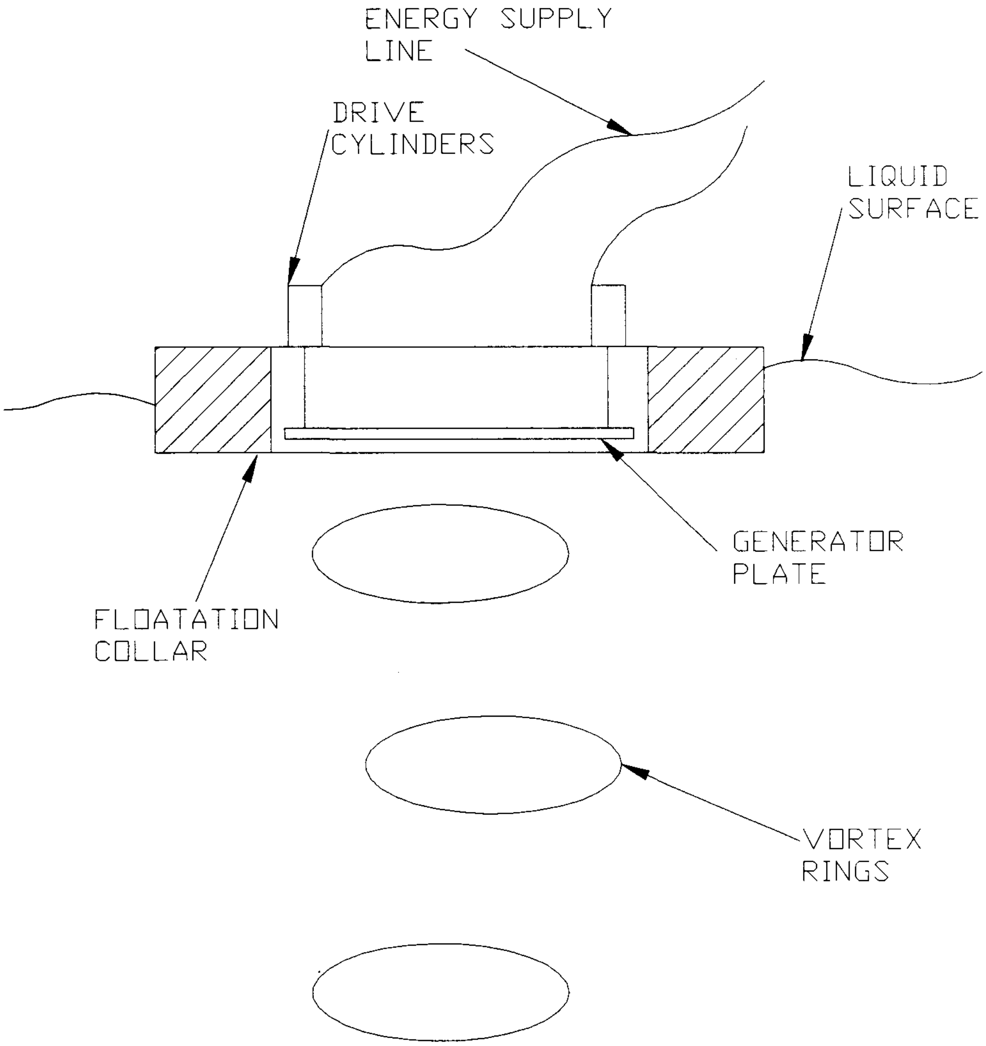


PLATE UNIT WITH FLOATATION COLLAR

CHAPTER 4

EXPERIMENTAL APPARATUS AND PROCEDURE

4.1 Apparatus Overview

The mixing and aeration experiments implemented the use of a flat plate vortex ring generator suspended from a floating platform secured in the centre of a 200,000 US gallon man made pond. A pneumatic cylinder powered by an electrically driven air compressor was used to drive the reciprocating motion of the cylinder. The motion of the drive cylinder was controlled by a pneumatic control box mounted on board the floating mixer. This in turn controlled the motion of the vortex ring generator plate. This chapter describes the experiment apparatus including the mixer sizing calculations, equipment, pond configuration and experiment procedure.

4.1.1 Test Pond

The pond is located on a 10 acre parcel of property in the Village of Port Robinson, Ontario approximately three miles from the Welland Canal. This property was farmed at one time and there is a natural swale that provides drainage through the southeast corner of the property as shown in Figure 4.1. When the farm was in operation a pond was dug in this corner astride the swale to provide additional drainage as well as a source of irrigation. It has been approximately 25 years since the land was farmed so the pond has not been in use other than a collection point for rain and snow melt runoff. Also on the property is a house. A portion of the garage was fortunately secured to store test equipment between experiment trials of the vortex ring generator.

When the site was first investigated in the summer of 1993 there was a strong pungent odour emanating from the pond which provided an early indication that the water was stagnant. The only water entering the pond is runoff. Water samples subjected to laboratory analysis in 1993 and 1994 for dissolved oxygen confirmed that the pond was indeed oxygen deficient.

The pond is almost circular with a diameter of 85 feet and a maximum depth of 10 feet 6 inches with an average depth of 10 feet as measured in July 1993. Figure 4.2 shows the location of the vortex ring mixer apparatus and the profile of the pond as measured from a 12 foot aluminum boat using a measuring stick to check depth while connected to the shore with a measuring tape. Based on the profile determined, the pond has very steep banks with an almost flat bottom which was not surprising considering it was man made and not natural. From the depths and shape of the pond shown in Figure 4.2 and 4.3, the volume was calculated to be approximately 200,000 US gallons.

The pond depth varied during to the time of year that testing occurred with a variation of plus or minus 1 foot. The pond was used for all experiment testing of the vortex ring mixer which occurred in 1994.

4.1.2 Sizing Calculations

Once the pond for the investigation was selected, the size of the vortex ring mixer was calculated. Based on research by Latto, a floating single plate vortex ring mixer configuration was selected for the experiments in the pond.

The vortex ring plate diameter and centre hole size was also selected on the basis of Latto's research. From the calculations below, the final configuration of the vortex ring mixer was determined from which design drawings were completed and the unit fabricated.

1) Critical Ratio

The critical ratio forms the basis for the vortex ring mixer design. It was convenient to select a pneumatic drive cylinder having a stroke of 3 inches. Equation 2.20 in Chapter 2 expresses the critical ratio as follows:

$$
\begin{aligned}
\zeta &= L_e/d \\
&= \{(\pi/4 \times D^2 \times s)/(\pi/4 \times d^2)\} \times 1/d \\
&= (D^2/d^3) \times s \\
&= ((36\text{in})^2/(12\text{in})^3) \times 3\text{in} \\
\therefore \quad \zeta &= 2.25
\end{aligned}
$$

Research by Latto indicates that the critical ratio is optimum in the following range:

$$0.4 \le \zeta \le 3.8$$

With the optimum value possibly about 2.0 to 2.8, the value of $\zeta = 2.25$ is in the acceptable range for the single plate mixer that was designed and fabricated.

2) Piston Stroke

The above equation was manipulated to check the measured stroke of the pneumatic drive cylinder used in the vortex ring mixer.

$$s = \zeta \times (d^3/D^2)$$

$$= 2.25 \times ((12in^3)/(36in^2))$$

$$\therefore \quad s = 3 \text{ inches}$$

3) Power Consumption

Equation 2.27 found in Chapter 2 expresses the equation for power consumption of the vortex ring mixer.

$$P_{Dot} = (\pi/4 \times D_p^2) \times P \times \zeta \times (d^3/D^2) \times f \times 2$$

$$= (\pi/4 \times (3.25in)^2) \times 35lbf/in^2 \times 2.25 \times ((12in)^3/(36in)^2) \times 1Hz \times 2$$

$$= 1742.1 \frac{lbf\ in}{s} \times \frac{1ft}{12in} \times \frac{1hp}{550\ lbf\ ft/s}.$$

$$= 0.264hp \times 746W/hp$$

$$\therefore \quad P_{Dot} = 196.9W$$

From the above calculation the air compressor selected was a 1hp air compressor to pneumatically power and control the vortex ring mixer.

4) Volume of Fluid Projected Per Cycle

Equation 2.22 found in Chapter 2 gives the volume of the pond mixed for every cycle of the vortex ring mixer. Assuming a 50% radial loss of fluid, i.e. $\kappa = 0.5$, and assuming only 2 vortex rings per cycle, then,

$$\forall = \pi/4 \times D^2 \times s \times f \times 2 \times \kappa$$

$$= \pi/4 \times (36in \times 1ft/12in)^2 \times (3in \times 1ft/12in) \times 1stroke/sec \times 2 \times 0.5$$

$$= 1.77ft^3/s \times 1m^3/35.3ft^3$$

$$\forall = 0.0501m^3/s$$

5) Theoretical Mixing Time

With the calculated result for the volume per cycle, the mixing time required to mix the pond with the 3 foot diameter single plate vortex ring mixer can be calculated based on Equation 2.26 in Chapter 2.

$$T = V/\forall$$

$$= \{(200{,}000USGal \times 1m^3/264.2USGal)/0.0501m^3/s\} \times 1/3600s$$

$$T = 4.2Hours$$

6) Power Consumption Per Unit Volume

The power consumption calculation above was divided by the pond volume to obtain a value for comparison with published results for performance of other types of mixers.

$$P_{Dot}/V = (196.9W/200{,}000USGal) \times 264.2USGal/m^3$$

$$P_{Dot}/V = 0.26W/m^3$$

4.1.3 Vortex Ring Agitator

The entire agitator, drive and float assembly is detailed in Figures 4.4 through 4.8. The description of the fabrication and overall configuration of the vortex ring mixer will begin by focusing first on the vortex ring plate illustrated at the bottom of Figure 4.4.

The main component of the vortex ring mixer was a 3 foot diameter steel plate with a 1 foot hole in the centre(10). This vortex ring plate was cut on a plasma burning table to get a clean and uniform diameter ring. The ring was connected to the drive shaft by four 5/8 inch threaded rods(22) through four holes punched in the plate. The rods were bent to the angle shown in Figure 4.4 and secured to the plate by 5/8 inch nuts and washers on the rods on both sides of the plate.

The rods were connected to an 18 inch diameter plasma cut plate(11) in a similar manner to that for the 3 foot diameter plate as shown in Figure 4.5. To secure the drive shaft and piston to the vortex ring plate a 3 inch threaded pipe cap(13) with a 9/16 inch hole drilled in the centre was connected in the inverted position to the plate with a 1/2 inch bolt and nut. This 1/2 inch bolt and nut was welded both inside the pipe cap and on the other side of the 18 inch plate to prevent the bolt loosening during mixer operation. The pipe also had a 3/8 inch hole drilled and tapped through the pipe wall for a 3/8 inch set screw(24). The purpose of the set screw was to prevent the drive shaft and pipe cap from unthreading during mixing operations.

A drive shaft made from 3 inch standard wall pipe(12) was connected to the plate. This pipe was machined down 1/8 inch to ensure that the surface of the shaft was smooth and uniform. A standard pipe thread on the lower portion of the shaft was used to connect the shaft to the 18 inch plate. A 1 inch by 3.5 inch plate(8) machined to the configuration shown in detail #1 in the upper right of Figure 4.5 was located at the top of the shaft. This plate was machined from a solid piece of steel to provide the necessary strength to withstand the load caused by the up and down stroking action of the pneumatic piston driving the vortex ring plate. Through this hole a 3/4 inch bolt(17) was welded pointing upward through a 13/16 inch hole such that a threaded coupling could be attached(27). The bolt and coupling had a 3/16 inch hole drilled through both items so a 1/8 inch split or cotter pin could be used to secure the coupling and bolt and prevent the shaft from separating from the coupling during mixing(27).

4.1.4 Pneumatic Actuator (Drive Cylinder)

A Numatics Type P1 fixed clevis floating cushion type actuator with 3-1/4 inch bore and a 3 inch stoke(28) was used to drive the mixer. The vortex ring generator assembly was connected to the pneumatic actuator by the 3/4 inch threaded coupling shown in Figure 4.5. The actuator had a 3/4 inch threaded connecting pin through which a 1/8 inch hole was drilled so that the coupling shown in detail #1 of Figure 4.5 could be secured by a 1/8 inch split pin to prevent unthreading during mixing. The cylinder had a clevis connecting arrangement to connect the vortex ring agitator hanging from the cylinder to the steel support frame. A 0.75 inch diameter clevis shaft with provisions for split pins at either end of the shaft was provided with the actuator to connect the actuator to the steel frame. The overall actuator and shaft/vortex ring plate assembly was connected as shown in Figure 4.4.

4.1.5 Steel Support Structure

The structure that supported the pneumatic actuator and vortex ring mixing assembly was a welded steel structure fabricated from 2 inch by 2 inch by 3/16 inch steel angle(1,2,3,4,6 & 36) as shown in Figure 4.6. The frame was welded using the GMAW or Mig process with 1/8 inch and 3/16 inch fillet welds at all locations as indicated in Figure 46. The frame was designed and fabricated by E.S.Fox Ltd. (Niagara Falls, Ontario). Notable features of the frame include the support angles(6) that allow the frame to rest on the floatation device. Also at this location were four 9/16 inch holes were drilled in the frame to connect the frame to the flotation device with 1/2 inch bolts. At the top of the frame a 0.751 inch hole was drilled in the steel angle support through which the clevis bolt of the pneumatic actuator would be placed to secure the agitator and vortex ring generating device to the support frame during mixing.

Teflon pads shown in Figure 4.7 were used as bearings for the vortex ring generator shaft. Teflon pads require no lubrication and when spaced 8 inches apart on the steel plates, the teflon pads align the shaft during mixing. A critical aspect of the frame are the supports for the teflon pads(16) shown in Figure 4.6. The steel frame had parallel angles(3,4) welded within the frame to support a 1/8 inch steel plate(35) cut to the same configuration as the teflon pad. These plates were welded to the support angles so that the teflon pads are 8 inches apart. The teflon pads were secured with 1/4 inch bolts and nuts to the steel plates. The machined 3 inch shaft passes through the teflon pads during the up and down stroke of the agitator. This provides non-binding operation in all weather conditions with no lubrication and little or no maintenance.

The other notable feature of the steel frame is the 1/4 inch thick steel plate(9) welded on the top of the frame. This plate provides a secure baseplate to secure the pneumatic control box during operation. The entire frame was sandblasted and painted with a coat of primer and a top coat of yellow paint for aesthetic purposes and to prevent corrosion from running onto the teflon pads thereby causing wear of the pads.

4.1.6 Flotation Device

The flotation device to which the steel frame and vortex ring mixing apparatus was attached is shown in Figure 4.8. The Wood support frame was made using 2 inch by 6 inch pressure treated wood(30,32) with two cross members to support the wood deck. The underlying frame was bolted together at the four corners through steel support angles(5) to provide strength. The 2 inch by 6 inch wood deck(31) was secured with galvanized nails to provide a smooth surface to prevent tripping during servicing and adjusting of the mixer. The steel support frame steel tabs welded to each vertical post supported the frame when it sat on the wood frame. One quarter inch coach or lag(21) bolts secured the frame to the wood frame on both sides of the frame.

The floats used were the type used in pleasure craft floating dock construction. These floats were 10 inch by 20 inch styrofoam floats(34) 8 feet in length. Each float is capable of supporting 600 pounds giving a total flotation capacity of 1,200 pounds which was more than sufficient to hold up both the mixer and two people during servicing and operation. The floats had 1/2 inch varnished plywood(33) running the entire width and length along the top of the floats to prevent the securing bolts from pulling through the floats and to prevent damage when people were on the unit during servicing. A 2 inch by 8 inch pressure treated piece of wood(29) ran along the bottom of both floats to provide a sturdy support for the floats when sandwiched between the 2 inch by 8 inch wood beams and the plywood. This 2 by 8 piece of wood also provided protection from gouging when the mixer was launched.

Four 7/16 inch holes were drilled equally spaced through each float. Sleeves made of 1/2 inch diameter pipe(15) cut to the same depth as the floats were put into the holes. This was necessary because it is very difficult to have clean drilled holes in the foam floats The pipes also offer protection for the securing bolts. The securing bolts were made from 3/8 inch threaded rod(23). In two places on each float the rods were cut to secure the 2 inch by 8 inch top wood beam and the plywood on the bottom of the float. The rod was held in place by nuts and washers on the top and bottom of the float. In the other two locations of each float the threaded rod was cut longer so that it would pass through the wood deck to secure the float to the wood frame. The floats were secured perpendicular to the wood platform so that the resulting structure was stable and people could easily climb aboard and walk about the platform and mixer without tipping or undue listing of the entire assembly.

4.1.7 Pneumatic Control Box

The pneumatic control was based on a design originally used by Latto in previous experiments. The internal control schematic of the box appears at the top of Figure 4.9 with the overall dimension of the final control box at the bottom of the figure. The pneumatic control operates by first supplying air to the box from the compressor which starts control TD1 timing. As TD1 times out the piston begins its stroke while at the same time control TD2 begins timing. As TD2 finishes timing the piston is at its full stroke at which point TD2 forces the piston to reverse its stroke also causing TD1 to begin timing once again. The entire cycle will repeat itself as long as air is supplied to the control box. The two control knobs on the top of the box control the timing of TD1 and TD2 to increase or decrease the time it takes to stroke the piston. Controls TD1 and TD2 along with the supply air pressure allows the operator to fine tune the frequency and thus the effectiveness of the mixer.

Figure 4.10 outlines the sequence of operation and the parts list for the control box. The control box has an external silencer to muffle the air exhausting as the piston strokes. It also has three 3/8 inch bulkhead fittings with female quick disconnect ends for the air inlet and the supply and exhaust from the control box to the pneumatic cylinder. Connected immediately to the control box at the inlet and outlet to the cylinder were two Norgren model 10-005 lubricators. Each lubricator was filled with SAE 10W-30 oil and set at the minimum oil feed rate to supply lubricant to the air cylinder during operation. Two 3/8 inch hoses 24 inches long with male quick disconnect ends were used to connect the pneumatic cylinder to the inlet and outlet on the control box.

4.2 Instrumentation and Measurement

All measurement instruments used in the mixing experiments will be outlined in this section according the parameter measured.

4.2.1 Mixing Time and Temperature

Temperature measurement is a parameter that can be used to determine the time to mix the pond. It was desired to have precise measurement at regular time intervals to determine the rate at which the pond was being mixed. The device used was a Barnant Co. Benchtop Scanning Thermocouple Thermometer model number 692-8000, Benchtop, 115 Volts. This device was supplied in Canada by the Cole-Parmer Instrument Company. The scanning thermometer had a noted accuracy of +/- 0.1°F with an automatic and manual calibration mode. The unit came factory calibrated and was compared to a reference temperature source(ice water) to confirm temperature accuracy.

Initially, a temperature difference existed between the water surface and the approximately 10 feet deep pond bottom. Since the pond water temperature varied according to the time of year, wind, sun, clouds and the mixing effectiveness it was critical that temperature be continuously monitored. To measure temperature distribution, 5 iron constantan thermocouples were used. One thermocouple was used to measure atmospheric air temperature and the other four measured water temperature at various locations. Two 3/4 inch diameter copper pipes twelve feet long with two thermocouples attached on each were placed in the pond to measure water temperature. A thermocouple was attached 18 inches from the bottom of each pipe. When the pipes were driven in to the pond bottom, the lower thermocouple on each pipe was 6 to 12 inches off the bottom and measured the cooler water temperature at the bottom. The upper thermocouple was attached 12 to 18 inches from the top of the pipe and was approximately 6 inches below the surface of the water when the pipe was driven into the bottom. The thermocouples were therefore approximately 9 feet apart such that the maximum temperature could be measured between the top and bottom of the pond.

The thermocouples came with twelve foot long leads and a two prong plug. Each thermocouple was secured to the pipe with electrical tape which is water proof. The connecting plugs were taped to the pipes above the surface of the water to prevent water from damaging the connection. Additional thermocouple wire was cut into 75 foot lengths to act as extension leads back to the scanning unit. Each extension had a male and female plug to connect the thermocouples at each pipe and to the scanning unit.

The scanning unit had a digital display which indicated all five thermocouples as they were scanned. The unit scanned the thermocouples every 5 minutes and displayed the temperature in degrees Fahrenheit. The Barnant unit was connected to a NEC Powermate 286 computer via an RS-232 cable. Cole-Parmer supplied computer software titled Data Logger V1.3 that simultaneously logged the temperature readings from the Barnant unit into the computer memory. The software also allowed the computer to display the temperature readings on the monitor thus indicating the degree of mixing occurring in the pond in relation to time. After each experiment was complete the Data Logger software had a conversion utility allowing conversion of the temperature data into Lotus 1-2-3 format for further data manipulation.

Also used to measure temperature was a combination pH meter/thermometer purchased from a hunting and fishing store. The unit was a "Colour C-Lector" thermometer and pH unit with a dial that indicated temperature. The temperature probe was a battery powered resistor with a 50 foot lead. The thermometer was used to quickly check temperature and also to double check the temperature readings given by the scanning thermometer.

4.2.2 Frequency and Stroke

The frequency of the mixer stroke was measured by manual timing with a stopwatch. The actual stroke of the pneumatic cylinder was measured and compared to the manufacturer's value and also by viewing the full stroke during mixing. Measurement of the frequency and stroke provided verification of standard mixer performance comparisons for all experiments.

4.2.3 Dissolved Oxygen, COD, BOD & pH

Water samples were taken every two hours from start to finish of each experiment. Two water sample bottles 500ml capacity were used each time a sample was taken. One water sample was used for COD and the other water sample for DO, BOD and pH. The samples were immediately placed in a refrigerator after sampling and then a cooler packed with ice for transportation to the lab. Walker Laboratories located in Thorold, Ontario supplied the sample bottles and did all laboratory work. This laboratory is accredited by the Canadian Association for Environmental Analytical Laboratories and the New York State Department of Health.

4.3 Ancillary Equipment

In addition to the above equipment there were several other items necessary to conduct all experiments. The most important equipment was related to the supply of electricity and air. The air compressor initially used was a 1hp compressor and the compressor used on all subsequent experiments was an Ingersoll Rand Model 4000 3.3hp compressor. This unit was an oil free compressor with built in regulator with operating range of 0 to 160 psi. Air was supplied to the pneumatic cylinder through a 3/8 inch diameter hose approximately 50 feet long from the compressor along the pond bottom and up to the vortex ring generator.

The compressor was electrically powered which posed a bit of a problem since the pond was approximately 1000 feet from the electrical source. Because of this distance a low resistance cable would have to have been required to overcome the voltage drop over the 1000 feet while still being able to power the 3.3hp compressor motor. The power configuration used was a 5hp gasoline powered Honda generator. This generator allowed independent power supply to the compressor that was more economical than running a large diameter power cord.

The NEC computer and Barnant thermometer were powered by running extension cords from the house to the pond. It was discovered during preliminary trials that connecting the computer and thermometer to the gasoline generator did not provide smooth power. Instead the power delivery fluctuated as the compressor cycled on and off satisfying the pneumatic cylinder's requirements. The problem was cured by using four 250 foot long extension cords connected together to power the computer and scanning thermometer. Despite the 1000 foot distance, the power delivery was sufficient to adequately power both units.

A metal garden shed 8 feet by 6 feet by 7 feet was used to provide weather protection for the computer and scanning thermometer. The shed was erected on a wood platform constructed of scaffold planks and located at the pond's edge on the north side of the pond. A desk provided the workstation for the computer and scanning thermometer. Adjacent to the shed was a portable halogen construction light to light up the area when testing ran into the night. Other seemingly minor necessities were sunblock, since were few shade trees near the pond, and mosquito repellent to provide some relief from the mosquitoes that made the pond their home.

4.4 Experimental Procedure

The basic fundamentals of the experimental procedure remained constant through out all experiments. The details of the experimental procedure are given in the following sections.

4.4.1 Experiment Set-Up

The vortex ring mixer and float assembly was permanently secured in the centre of the pond by four 3/8 inch diameter ropes connected to wooden stakes on the shore. The day prior to an experiment was used to vertically insert the copper pipes with the thermocouples attached into the bottom of the pond. The thermocouple leads were then run and secured at the metal shed on shore. There was no other preparation prior to the day of an experiment since there was no way to secure the site.

All experiments took place on a Saturday and that day brought much activity early in the morning. Several trips were required with the help of a pickup truck to transport all required apparatus from the garage to the pond. The gasoline generator, air compressor, halogen light, desk, chairs, computer and scanning thermometer were first placed at the site. After this the control box was secured on the vortex ring generator and the air supply hose run back to the air compressor. The next step was to connect the power to the computer and scanning thermometer.

The activities listed above required several hours of labour depending if minor malfunctions requiring repair occurred. Once all items were in place the activities that occurred from start to finish of an experiment are as follows:

Experiment Procedure:

1) The computer and scanning thermometer were switched on.

2) The scanning thermometer was checked for accuracy against the handheld thermometer.

3) The gasoline generator was turned on to warm up for five minutes before switching on the air compressor.

4) As the generator was warming up the first two water samples were taken and transported immediately back to the house for refrigerated storage.

5) Visual inspection of the pond water colour and clarity were noted prior to commencement of a test run.

6) The air compressor was then started up and the regulator set between 35 to 45 psi.

7) Immediately after switching on the air compressor, inspection of the vortex ring mixer took place at the mixer. The control box governing the frequency was fine tuned during the first fifteen minutes at the mixer to ensure that the proper frequency was realized to produce pronounced vortex rings that broke the surface. After the first test run the frequency was set and it took only a few minutes to tune the frequency on subsequent tests.

8) After tuning the mixer, the time and temperature were monitored on the computer screen in the metal shed. Time and temperature were manually recorded in a notebook every 30 minutes in case of a power failure or fluctuation that might damage or erase the data in the computer.

9) Every two hours two water samples were taken and immediately refrigerated. This was done in order to monitor changes in DO, BOD, COD and pH.

10) The pond water was visually monitored closely for the first few hours to record when the water was becoming partly and then completely cloudy to give an indication of mixing.

11) The test duration finished when the pond was completely mixed or when it was approximately 11:00pm at which point the test was halted so the noise from the gasoline generator would not disturb the neighbours.

12) The temperature data generated from the scanning thermometer was stored in the computer for later conversion into Lotus 1-2-3 format.

After the test was shut off the entire setup procedure was reversed such that the experimental apparatus and ancillary equipment was dismantled and stored in the garage for the next experiment.

The day after each experiment(Sunday) was initially spent at the test site to make sure no items were left outside. If the next experiment required that the vortex ring be removed for modification then this would also occur. After returning from the site the NEC computer would be setup and the data converted into Lotus 1-2-3 format to determine the validity of the data and make preliminary data analysis. On Monday the water samples were removed from the refrigerator and placed in a cooler packed in ice for immediate transport to Walker Laboratories for DO, BOD, COD and pH analysis.

4.4.2 Experiment Parameter Details

All experiments used the same methodology for measuring and recording temperature, DO, BOD, COD and pH. The vortex ring mixer was modified three times to vary the depth of mixing to 3, 5 and 7 feet and the resulting change in mixing time and effectiveness monitored. The flow patterns for all experiments were similar and consisted of a vortex ring being fired to the bottom during the down stroke of the mixer and a vortex ring fired to the water surface during the up stroke of the mixer. The effect was to turnover the bottom and surface water of the pond to determine the degree of mixing and aeration.

Preliminary tests established the frequency range of the pneumatic cylinder during operation. The frequency and air supply pressure were not significantly modified since it was desirable to achieve the best vortex ring formation to achieve the best possible pond water turnover. The time of year affected the pond depth which provided some variation in mixing time and the initial oxygen content of the pond water. Weather conditions such as sun, clouds, wind, air temperature, day and night were factors that affected mixing and were recorded prior and during each experiment.

4.4.3 Dual Plate Mixer

The most significant change to the experimental procedure was during the last test which employed the use of a dual plate vortex ring mixer having two 21 inch diameter plates with 7 inch diameter hole in each plate. The plates were 14 inches apart at rest and were propelled by a dual action pneumatic air cylinder. The cylinder's two shafts separately operated one of the two plates. When air was supplied to the cylinder the plates moved in opposite direction during the outward stroke and together during the inward stroke. The effect was similar to the single plate vortex ring mixer in that a vortex ring was propelled both to the pond bottom and to the water surface at the same time. The mixer was constructed of stainless steel and aluminum and was considerably smaller than the single plate mixer used in all other experiments. A round flotation ring 4 feet in diameter was used to float the mixer and was roped to the floating single plate vortex ring mixer platform which was permanently secured to the centre of the pond. The pneumatic control box was secured on top of the single plate mixer apparatus with the supply and return air hoses from the control box connected to the dual plate mixer. All other measurements and procedures were similar to those used in the experiments with the single plate mixer. This mixer had only been tested in the laboratory and was operated in the pond to gain valuable field experience with the unit.

FIGURE 4.1

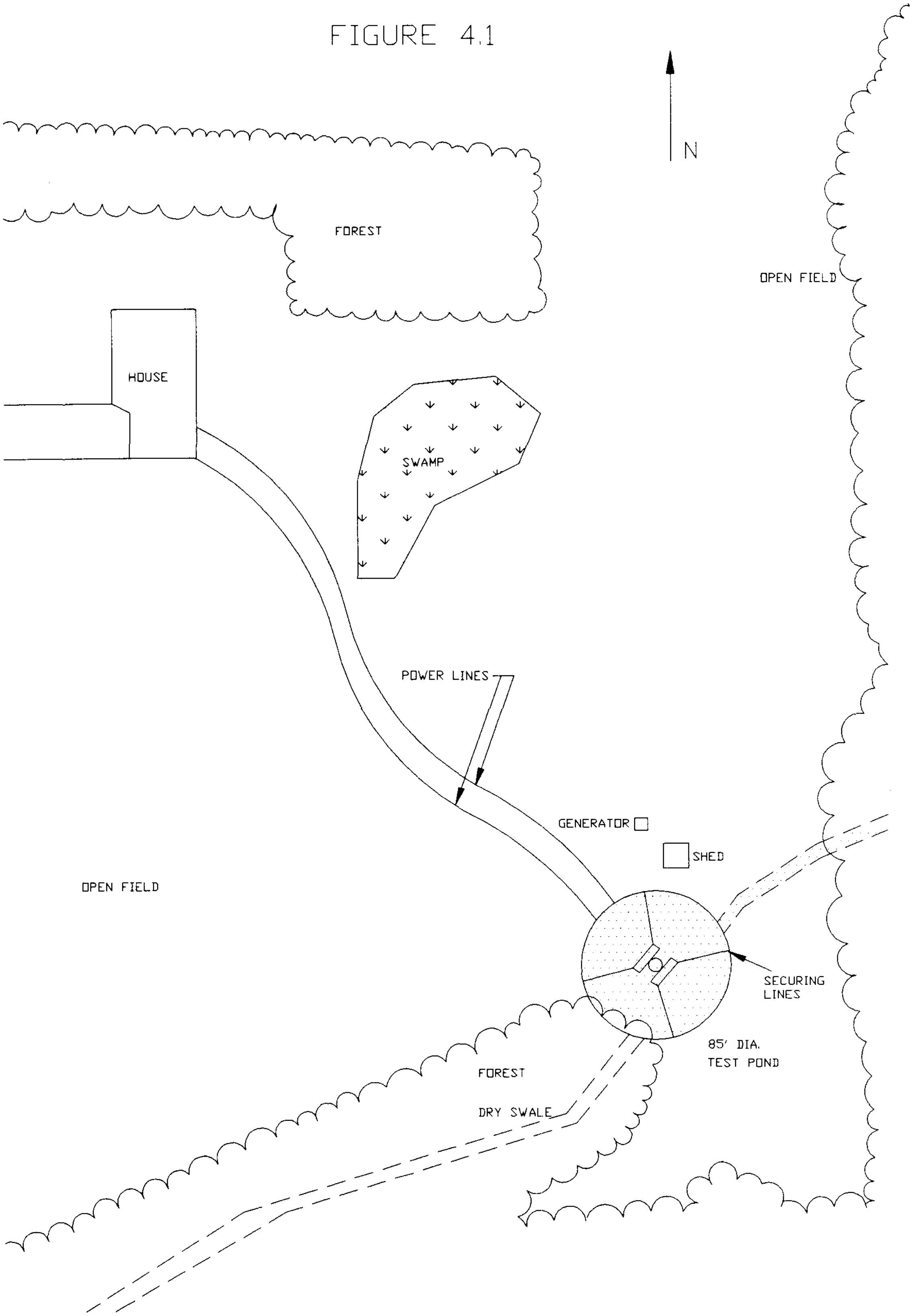
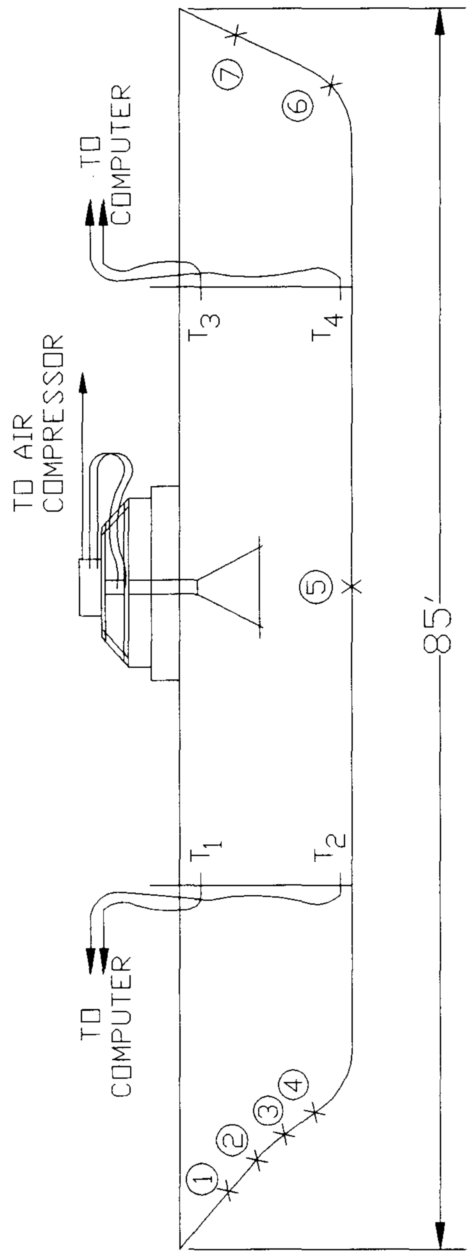

N
FOREST
OPEN FIELD
HOUSE
SWAMP
POWER LINES
GENERATOR
SHED
OPEN FIELD
SECURING LINES
85' DIA. TEST POND
FOREST
DRY SWALE

FIGURE 4.2

	DISTANCE FROM SHORE	DEPTH
①	5′	3′-1″
②	9′	5′-6″
③	12′	7′-10′
④	15′-6″	9′-10″
⑤	41′-6″	10′-6″
⑥	12′-0″	8′-8″
⑦	7′-2″	5′-4″



NOTE: THIS FIGURE IS NOT TO SCALE. IT IS FOR DIAGRAMMATICAL PURPOSES ONLY.

FIGURE 4.3

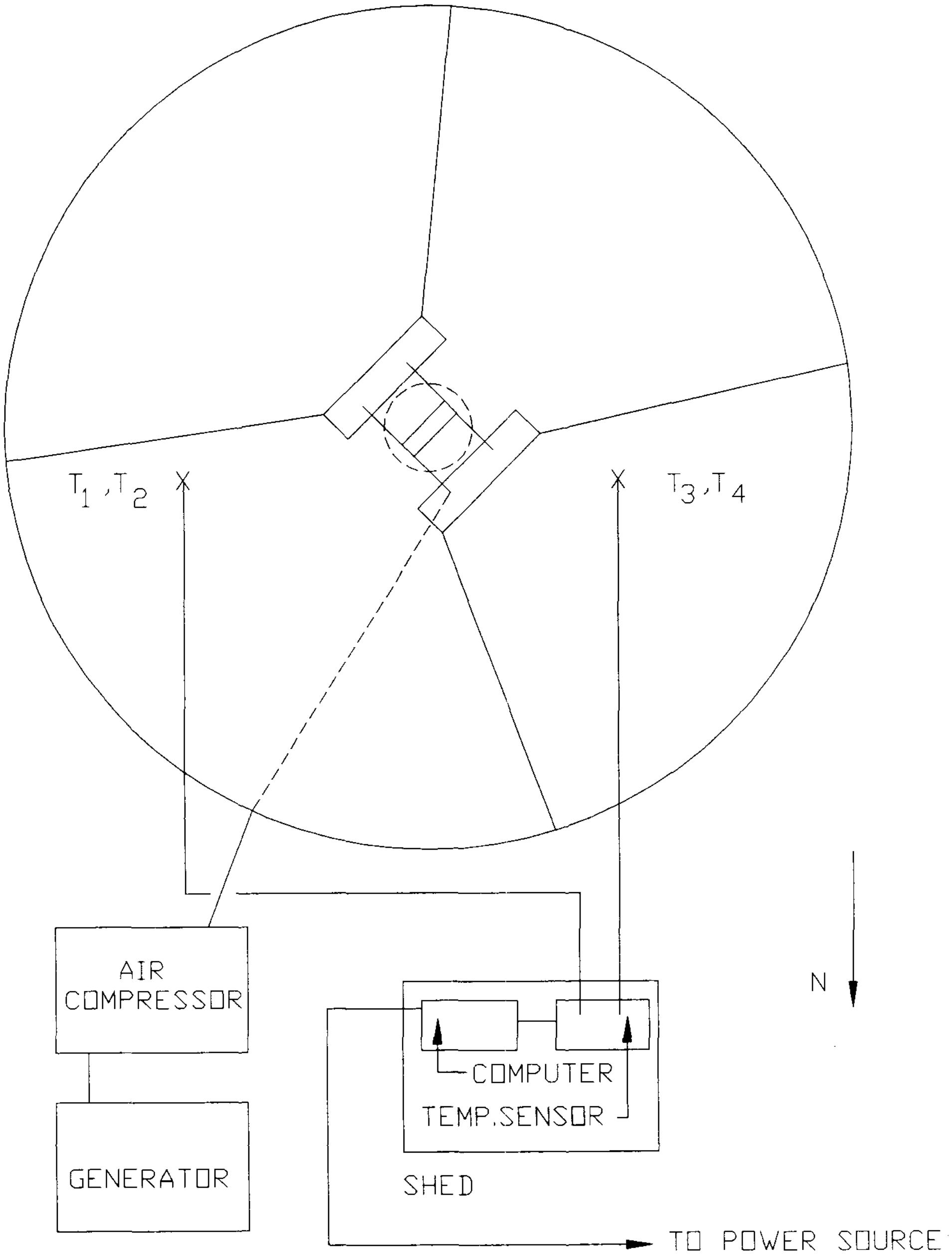

T_1 ,T_2
X
X
T_3,T_4
AIR COMPRESSOR
GENERATOR
COMPUTER
TEMP.SENSOR
SHED
N
TO POWER SOURCE

TABLE 4.1

BILL OF MATERIAL					
ITEM	QTY	MATERIAL	LENGTH	WEIGHT	REMARKS
1	4	L2 X 2 X 3/16	3'-0"	29.28	44W
2	4	L2 X 2 X 3/16	2'-6"	24.40	"
3	6	L2 X 2 X 3/16	1'-8"	24.40	"
4	4	L2 X 2 X 3/16	1'-5"	13.83	"
5	4	L2 X 2 X 3/16	5-1/2"	4.47	"
6	4	L2 X 2 X 3/16	2"	1.63	"
7	1	PLATE 2" X 1"	6"	3.41	"
8	1	PLATE 3-1/2" DIA X 1"	-	2.79	44W, MILLED
9	1	PLATE 8" X 1/4"	8"	4.54	44W
10	1	PLATE 36" DIA X 1/8"	-	32.00	"
11	1	PLATE 18" DIA X 1/8"	-	9.00	"
12	1	3" DIA STD. PIPE	2'-1/4"	15.20	MILLED, SCH 40
13	1	3" DIA PIPE CAP	-		THREADED
14	1	3/4" DIA COUPLING	1-1/2"		THREADED
15	4	1/2" DIA PIPE	10"	2.84	SCH 40
16	2	7-1/2" X 1" TEFLON PAD	7-1/2"		
17	1	3/4" DIA BOLT	2-1/4"	0.52	
18	4	1/2" DIA BOLT	2-1/4"	0.76	C/W NUT & WASHER
19	1	1/2" DIA BOLT	1-1/2"	0.15	C/W NUT & WASHER
20	8	1/4" DIA BOLT	1-3/4"	0.27	C/W NUT & WASHER
21	16	1/4" DIA COACH BOLT	2-1/4"	0.65	C/W NUT & WASHER

BILL OF MATERIAL					
ITEM	QTY	MATERIAL	LENGTH	WEIGHT	REMARKS
22	4	5/8" DIA THREADED ROD	5'-5-1/2"	22.96	C/W 4 NUTS & 4 WASHERS
23	8	3/8" DIA THREADED ROD	1'-1/2"	3.50	C/W 2 NUTS & 2 WASHERS
24	1	3/8" DIA SET SCREW			
25	18	#8 WOOD SCREWS	3"		
26		GALVANIZED NAILS	3"	2.00	
27	1	1/8" DIA SPLIT PIN	1/2"		
28	1	ACTUATOR		5	NUMATICS
29	2	2" X 8" WOOD	8'-0"	53.33	PRESSURE TREATED
30	2	2" X 6" WOOD	8'-0"	40.00	PRESSURE TREATED
31	12	2" X 6" WOOD	3'-3-1/2"	97.50	PRESSURE TREATED
32	4	2" X 6" WOOD	3'-0"	30.00	PRESSURE TREATED
33	2	18" X 1/2" PLYWOOD	8'-0"	30.00	MARINE GRADE
34	2	10" X 20" STYROFOAM	8'-0"		
35	2	PLATE 7-1/2" X 1/8"	7-1/2"	2.00	44W
36	2	L2 X 2 X 3/16	1'-0"	4.88	44W

FIGURE 4.4

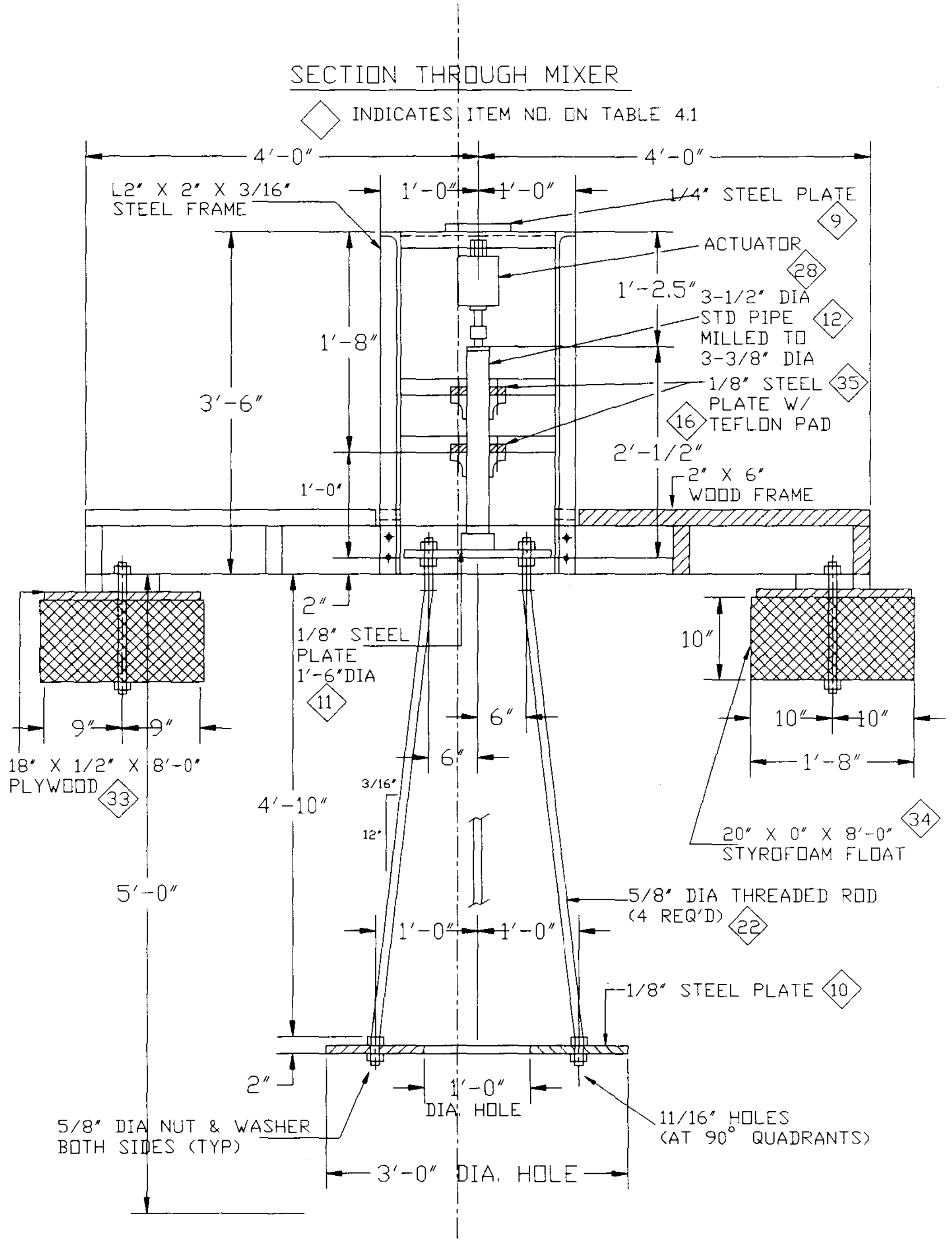
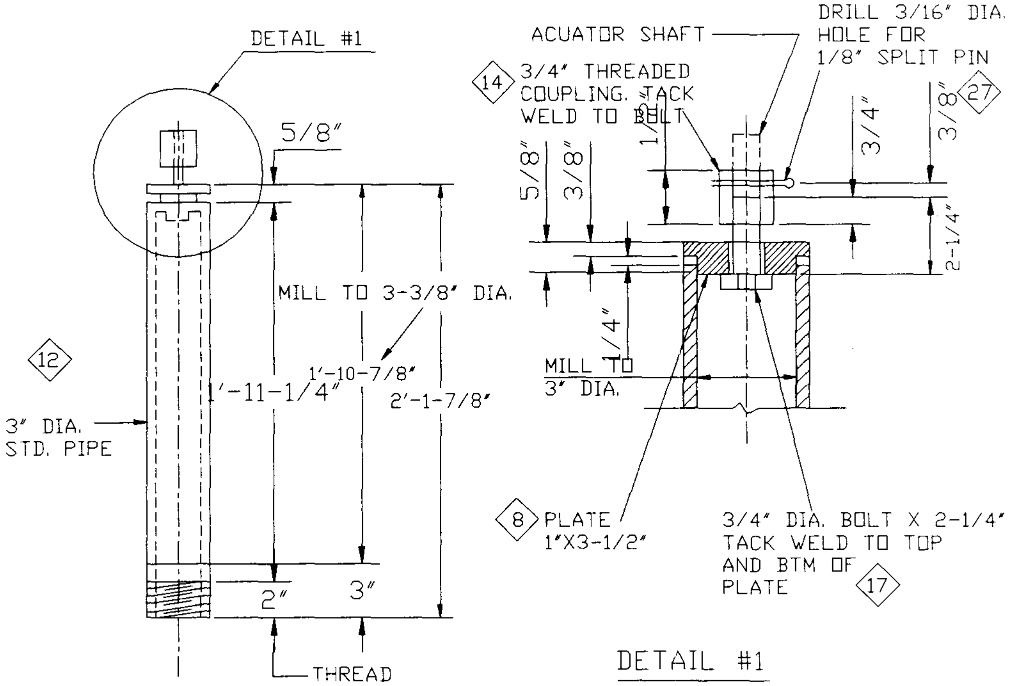
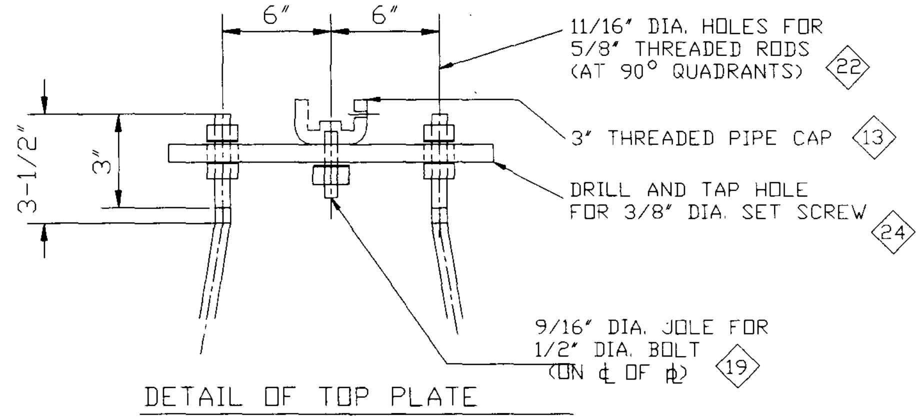

SECTION THROUGH MIXER
INDICATES ITEM NO. ON TABLE 4.1
4'-0"
4'-0"
L2" X 2" X 3/16"
STEEL FRAME
1'-0"
1'-0"
1/4" STEEL PLATE
9
ACTUATOR
28
1'-2.5"
3-1/2" DIA
STD PIPE
MILLED TO
3-3/8" DIA
12
1'-8"
3'-6"
1/8" STEEL
PLATE W/
TEFLON PAD
35
16
2'-1/2"
2" X 6"
WOOD FRAME
1'-0'
2"
1/8" STEEL
PLATE
1'-6"DIA
11
10"
9"
9"
18" X 1/2" X 8'-0"
PLYWOOD
33
6"
6"
10"
10"
1'-8"
3/16"
12"
4'-10"
20" X 0" X 8'-0"
STYROFOAM FLOAT
34
5'-0"
5/8" DIA THREADED ROD
(4 REQ'D)
22
1'-0"
1'-0"
1/8" STEEL PLATE
10
2"
1'-0"
DIA. HOLE
5/8" DIA NUT & WASHER
BOTH SIDES (TYP)
11/16" HOLES
(AT 90° QUADRANTS)
3'-0" DIA. HOLE

FIGURE 4.5



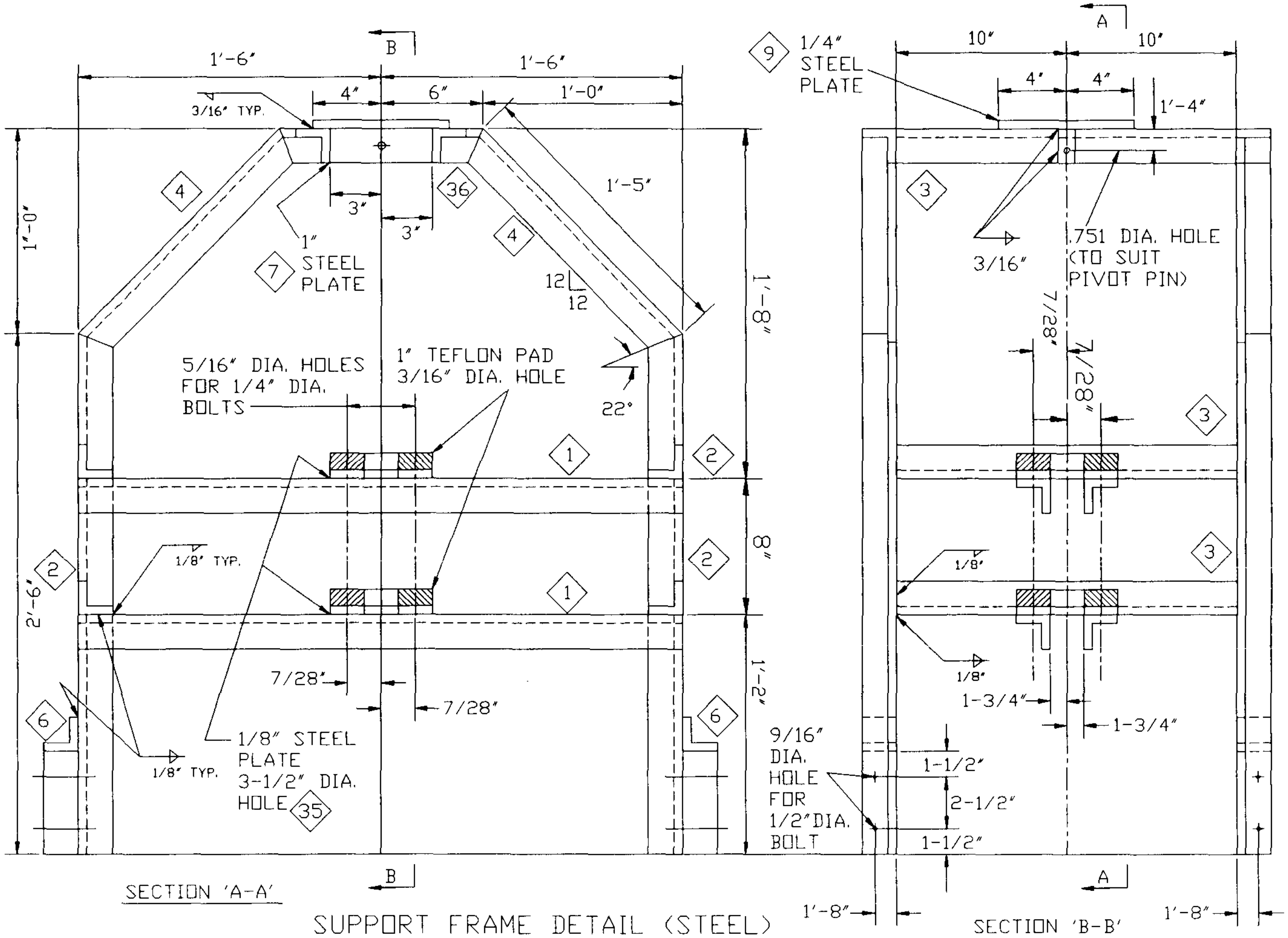
DETAIL OF SHAFT

NOTE: ENSURE THAT BOLT AND COUPLING THREAD MATCH
THREAD ON ACUATOR SHAFT.



DETAIL OF TOP PLATE

11 (18" DIA. X 1/8" THICK)

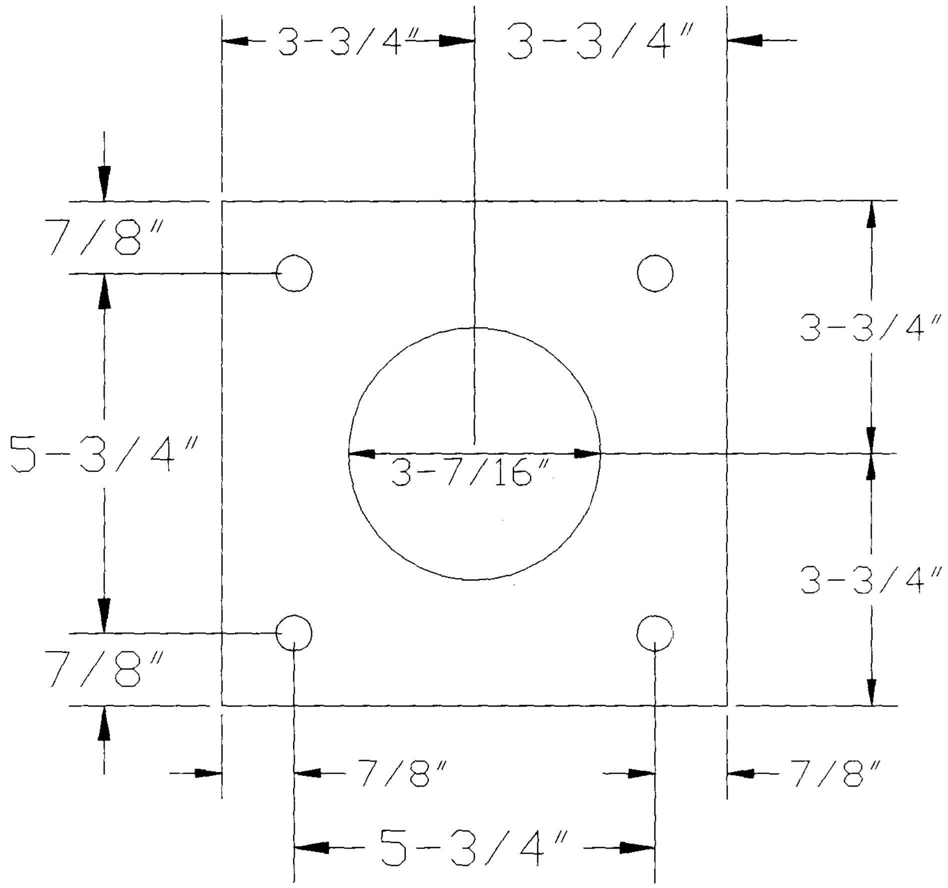


SUPPORT FRAME DETAIL (STEEL)

◇ INDICATES ITEM NO. ON TABLE 4.1

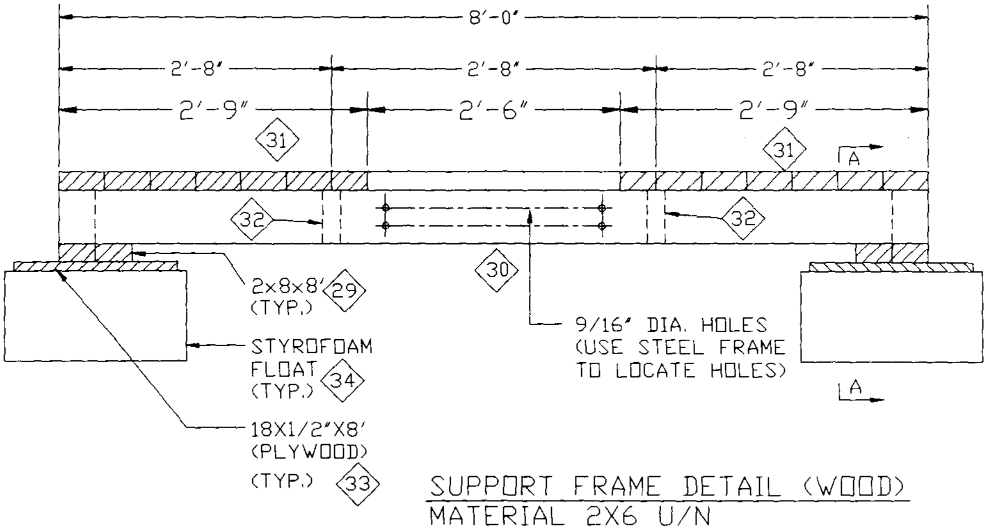
FIGURE 4.6

FIGURE 4.7

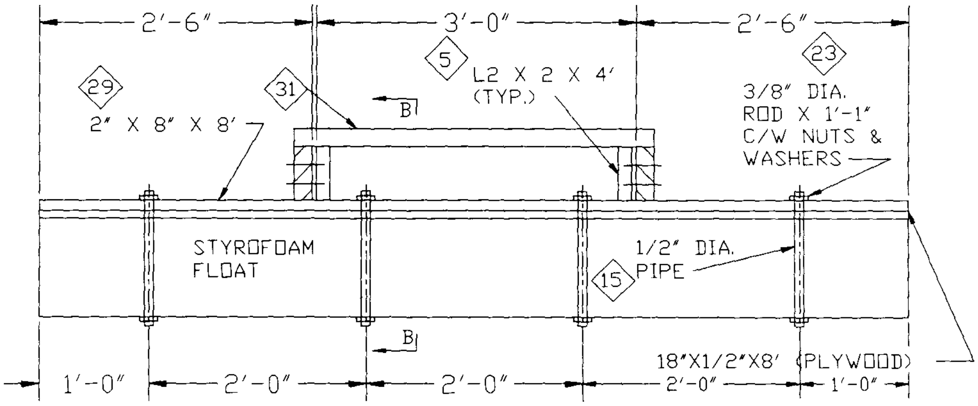


DETAIL OF TEFLON PAD ⟨16⟩

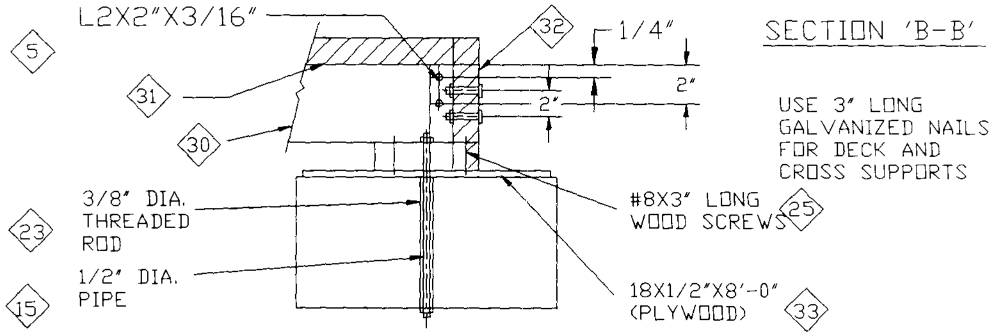
FIGURE 4.8



SUPPORT FRAME DETAIL (WOOD)
MATERIAL 2X6 U/N



SECTION 'A-A'



SECTION 'B-B'

USE 3" LONG GALVANIZED NAILS FOR DECK AND CROSS SUPPORTS

FIGURE 4.9

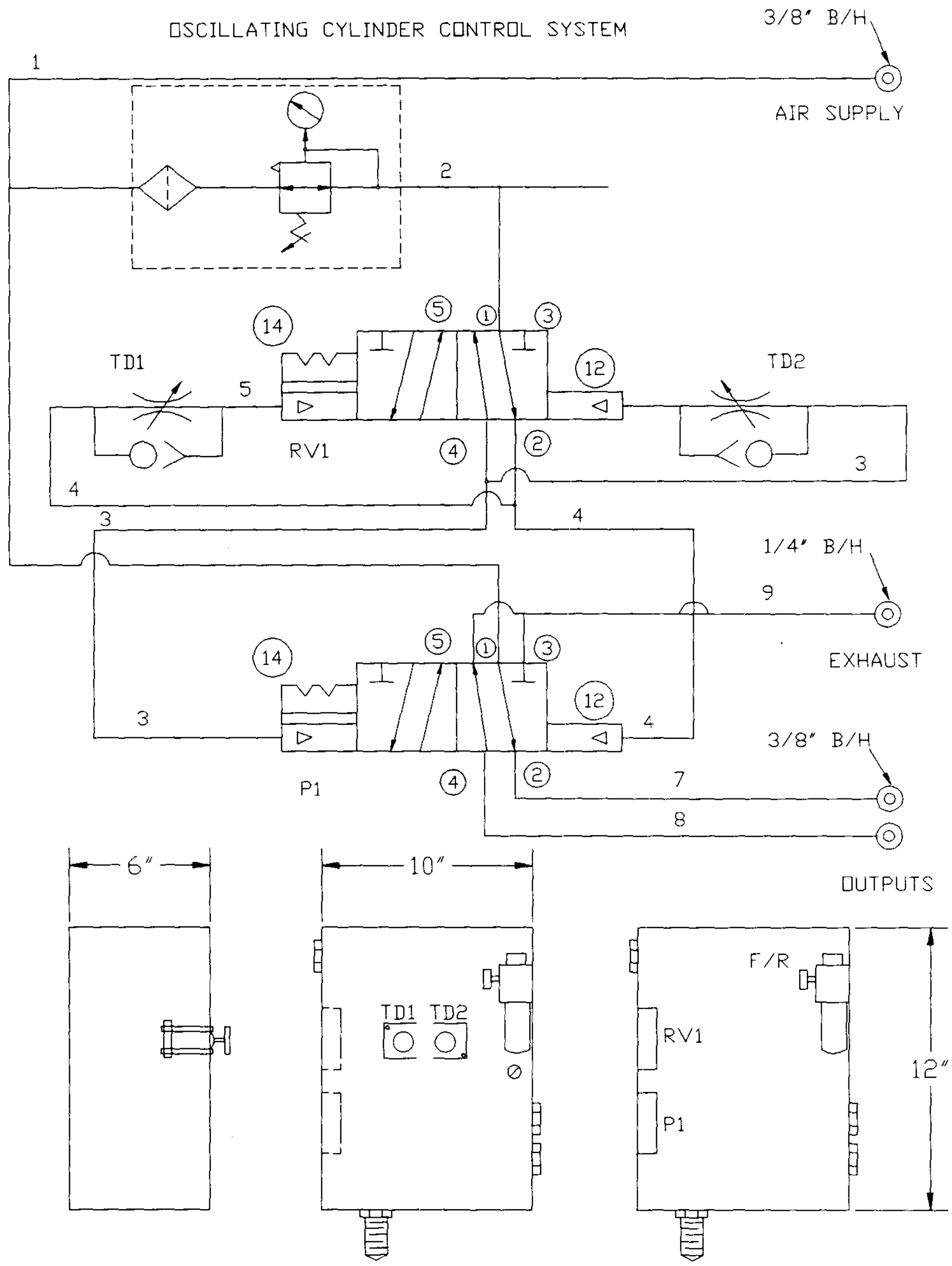

OSCILLATING CYLINDER CONTROL SYSTEM
3/8" B/H
AIR SUPPLY
1
2
14
5
1
3
12
TD1
TD2
5
RV1
4
2
4
3
3
4
1/4" B/H
9
EXHAUST
14
5
1
3
12
3
4
3/8" B/H
P1
4
2
7
8
OUTPUTS
6"
10"
TD1
TD2
F/R
RV1
P1
12"

FIGURE 4.10

OSCILLATION CYLINDER CONTROL SYSTEM

SEQUENCE OF OPERATION:

1. OPERATOR INTRODUCES AIR INTO THE SYSTEM.
   A) TD1 STARTS TIMING.
2. TD1 TIMES OUT.
   A) CYLINDER BEGINS STROKE TRAVEL.
   B) TD2 STARTS TIMING.
3. TD2 TIMES OUT.
   A) CYLINDER STROKE TRAVEL REVERSES.
   B) TD1 STARTS TIMING.
4. STEP #2 REPEATS.

NOTE: CYCLE WILL CONTINUE TO REPEAT UNTIL MAIN AIR IS SHUT OFF.

PARTS LIST

DET. NO.	NO. REQ'D	PART NAME	PART NO.
	1	CONTROL PANEL	136-120
	1	FILTER/REGULATOR	P04B-02G
	1	POWER VALVE	L12PP4520
	1	RELAY VALVE	L12PP4520
	1	DOUBLE TIMER	TMO-2103
	1	SILENCER	B48
	1	EXHAUST BULKHEAD	129B0415
	3	AIR/OUTPUT B/H	129B0621
	LOT	PANEL FITTINGS	-----
	LOT	PANEL TUBING	-----

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1 Introduction

The purpose of the experiments was to investigate the effectiveness of vortex ring generators to mix and aerate a natural body of water and investigate the effect of the depth of location of the mixer impeller on these experiments. All five experiments used the vortex ring generator in a 200,000 US gallon pond in an outdoor natural setting. The desire to mix a natural water body is to improve water quality by destratifying the water in the pond and aerate by turning over the pond water through increased contact with atmospheric air. The vortex ring impeller plate was lowered from a depth of 3 feet, at 2 foot intervals, to depths of 5 and 7 feet to investigate the effect of vortex ring generation on location on mixing and aeration. The pattern and effect of atmospheric air temperature on the surface and bottom pond water temperature as well as the effect on mixing was observed and recorded. Laboratory analysis of water samples were taken periodically during each test to study the effect of mixing on various parameters associated with aeration such as DO, BOD, COD and pH.

Section 5.4 gives a detailed summary of all experiments including laboratory results and detailed calculations for K_La_{20}, SOTR and SAE. Section 5.5 includes several figures used for analysis of the data recorded in Section 5.4.

All the obtained experimental data are presented in these two sections rather than in an appendix at the end of this thesis for reader convenience.

5.2 Experiment Observations

The conditions for the experiments differed due to the changing environmental conditions in which they occurred. Visual observations became important during data collection since interpretation of the data is affected by the natural conditions of the experiment. The observations and mixing results for each experiment will be discussed in this section with discussion of the laboratory results to follow in Section 5.3

5.2.0 Preliminary Experiment

The purpose of the Preliminary Experiment was not to obtain mixing or aeration data but to try out the vortex ring generating apparatus and experiment procedure in the pond. This experiment occurred on May 14, 1994 and a summary of the results appear in section 5.4.0.

The entire vortex ring generating apparatus was fabricated and assembled and floated in the pond as a complete unit. The vortex ring generator was located at a depth of 5 feet in the pond to study the effects of the mixer located at the water mid-depth. An initial trial experiment was conducted using a 1hp air compressor powered by the gasoline generator and operated to deliver the compressed air at 30 psi to drive the mixer. The frequency of oscillation of the impeller was varied over several ranges using the control box in order to determine the best frequency for the mixing/aeration process. This preliminary experiment revealed that the mixer frequency had to be reduced to 1/2 Hertz to obtain good vortex ring generation as observed when the vortex rings broke the surface of the pond. It was also determined after observing the vortex ring formation at the surface of the water and the forcefulness at which the air piston drove the vortex ring plate through its vertical motion that the 1hp air compressor was insufficient. This experiment revealed that even though the calculated power requirement was 1hp as shown in Section 4.1.2, the effect of the small air receiver on the compressor, the mixer equipment configuration and the desire for good vortex ring formation required a greater compressed air capacity. It was therefore decided that a larger capacity air compressor would be used for all subsequent experiments. It was hoped that a larger capacity compressor would provide a large air delivery volume at higher air pressures to permit the frequency to be increased to the desired 1 Hz.

The computer and scanning thermometer were plugged into the power source. It was observed that the generator was capable of supplying power to the air compressor and the peripherals while the mixer was operating. The temperature readings of the scanning thermometer were compared to the handheld thermometer and good agreement within 1/2°F was observed. The scanning thermometer has an automatic calibration mode during start-up and the hand held thermometer provided verification that the scanning thermometer was reading correctly.

The water was initially quite turbid but one was able to view to a depth of 12 inches into the water at the free surface of the pond. This top layer was very clear and was visual indication that the pond was stratified between the top clear layer and the remaining murky water. Temperature readings indicated that there was a 10.5°F temperature difference between the water at the top of the pond and the water at the bottom. When the vortex ring generator was operating, for approximately one hour, it was observed that the bottom was being stirred up indicated by clouds of silt at the pond edge. From this it was concluded that the vortex ring generator was adequately mixing the pond and that a longer mixing duration planned for Experiment #1 would probably produce meaningful results.

The degree of turbidity of the water was relative to the time of year since there was little aquatic plant life growing during the early spring period when the experiments concluded. No animal life appeared to be present other than frogs. The water was very deep at 10 feet 7 inches which was the result of snow and rain run-off. It was observed that the air temperature was slightly cooler than the temperature of the water surface. It was decided that a separate temperature probe would be placed above the equipment storage shed roof during all experiments to measure the effect or air temperature, and possibly, sun, wind and clouds on the surface water temperature.

5.2.1 Experiment #1

Experiment #1 was run on June 4, 1994 and a summary of the data appears in section 5.4.1. The goal of this experiment was to observe how the 3 foot vortex plate suspended 5 feet deep below the pond surface would mix and aerate the pond.

Prior to mixing commencement it was observed that the water appeared to be murkier than during the Preliminary Experiment. One could now only see 6 inches into the water and it was concluded that this was not only due to recent heavy rains but also maturing aquatic plant and animal life. The water was thermally stratified as indicated by the 12°F degree difference between the water surface and bottom of the pond.

Once the test started the frequency was adjusted. The resulting frequency obtained varied between 1/2 to 3/5Hz as measured using a stopwatch. The air pressure needed to achieve the slightly higher frequency than for the preliminary experiment was 40psig. It was attempted to obtain a frequency oscillation of 1Hz but it was observed that the air cylinder was not traveling through its full 3 inch stroke. The control box was not able to supply air to the piston on its downward stroke fast enough while at the same time exhausting the air on the upward stroke and vice-versa. When the frequency was dropped to between 1/2 to 3/5 Hertz the vortex ring development was more pronounced. This was the desired condition since well formed vortex rings travel farther and move more water volume and are thus more effective when mixing. The speed of mixing was not as much a concern as vortex ring formation. To mix the pond, well developed vortex rings must penetrate the stratified water layer in the pond through to the bottom to develop a flow pattern. The formation of vortex rings is therefore more desirable than frequency of generation with the lower frequency maintained to achieve more effective mixing.

A drawback to the tuning of the mixer was that it placed varying loads on the air compressor. This resulted in power fluctuations which affected the scanning thermometer and the temperature readings of the air and water temperature. After adjusting the frequency and air pressure the temperature readings displayed on the video monitor were examined and it was discovered that they fluctuated between 20 and 100°F. This was obviously not correct and therefore the test was halted. The total elapsed time of the first attempt was only one hour at which time only minimal clouding occurred at the edge of the pond indicating that mixing had only just begun. An attempt was made to obtain extension cords to run from a main source to the site to power the computer and the scanning thermometer. This was not successful so rather than halt the experiment, it was started again at 3:00pm and the handheld thermometer used to record temperature. By the time the experiment was started again, 5 hours had elapsed and the pond had once again stratified as indicated by the 6 inch layer of clear water at the surface.

The experiment was recommenced at 3:00pm and ran until 10:30pm. Temperature readings were recorded approximately every hour with the results shown in Figure 5.1. This figure illustrates the effect of atmospheric air temperature on mixing. The ambient air caused the water surface temperature to increase during mixing operations such that rather than having the cooler bottom and warmer surface temperatures converge to a median temperature, the bottom layer warmed up to the surface water temperature. This occurred since the surface water temperature increased initially due to the effect of the warm ambient air temperature, which apparently required the prolongation of the test since it acted as a heat source to the water. The test was therefore continued to try and achieve temperature homogeneity of the water. It was not until the sun set and the air temperature cooled off that the surface water temperature decreased and near the end of the test that the surface and bottom water temperatures became equal.

The vortex rings that broke the surface caused a significant ripple and rollover with little splashing. The downward traveling vortex ring appeared to be the more developed vortex ring than the upward traveling ring because of the observance of the silt clouds at the edge of the pond. This appeared to indicate that the vortex rings were rolling outward across the pond bottom and up the sides of the pond. After approximately 4 hours the pond was completely murky which indicated that destratification and mixing were occurring even though temperature readings revealed that the mixing was not uniform. The experiment was terminated after 7.5 hours with the surface and bottom temperatures homogeneous which was concluded to indicate that the pond was thoroughly mixed.

The results obtained in this first experiment indicated that the vortex ring mixer did mix the pond. The effect of air temperature was to prolong mixing since it increased surface temperature during daylight hours and extended the time to achieve temperature homogeneity. It was not until the hot atmospheric air cooled that it became less of a factor in the destratification process. The problems with the power fluctuation on the scanning thermometer were overcome by taking readings with the handheld thermometer. These were taken at greater time intervals than desired but the mixing trend shown in Figure 5.1 is concluded to be accurate and relevant.

5.2.2 Experiment #2

Experiment #2 was run on July 2, 1994 and a summary of the data appears in section 5.4.2. The goal of the experiment was to observe the effect of locating the generator 5 feet deep into the pond. This set-up was identical to the previous experiment as it was decided that this configuration should be re-run over the desired 12 hour duration with the scanning thermometer working properly.

Prior to this test, the scanning thermometer was re-calibrated by putting all five temperature probes in an ice bath to achieve a reference temperature point. The sensors were re-installed on the copper pipes and placed in the pond the morning of the test according to the procedure outlined in Section 4.4. Prior to test commencement the readings from the scanning thermometer were compared to the handheld thermometer and both were observed to have the same readings within 1/2°F. To prevent another malfunction, adequately sized extension cords were run from the main power source to the computer and scanning thermometer to power these units. The gasoline powered generator was only used to power the 3.3hp air compressor. This eliminated power supply fluctuation for the computer and scanning thermometer such that no further temperature reading inaccuracies occurred during this and all subsequent experiments.

The water prior to Experiment #2 was observed to be clear for 18 inches of depth. This layer was much greater than in the previous tests and could be attributed to little rainfall and runoff during the intervening period between the tests. The water level of the pond was also 2.5 inches less than previously measured and probably due to evaporation from the long and hot sunny summer days experienced during the elapsed time period. It appeared that the pond was beginning to stagnate because of the lack of run-off to replenish the water. Aquatic plant and animal life had grown such that the pond edge was becoming choked with weeds and algae was forming on the mixer floats and securing ropes. Tadpoles, frogs and the occasional turtle were also evident during early morning and late evening. Other life encountered included mosquitoes that made the pond their home. The need for insect repellent and sun block was now clearly apparent which made for unpleasant conditions during testing.

The test began at 10:30am and within 2 hours clouds of silt could be seen at the pond's edge indicating mixing. After approximately four hours the entire pond was murky up to the surface. From this it was concluded that destratification had occurred and that mixing was being achieved. Figure 5.2 in section 5.4.2 shows that the air temperature became very hot during the test as measured by the temperature probes. The air temperature was 78°F when the test began and often reached 90°F during the test. Section 5.4.2 is a summary of the temperature readings recorded during the test. Readings were taken every 5 minutes during the test with only the recordings for every 15 minutes listed in Section 5.4.2 for brevity.

The data and temperature profiles in Figure 5.2 reveal that the hot atmospheric air warmed up the water surface during mixing. This caused the bottom water temperature to rise steadily though out the test. It was not until after the sun set that the air temperature began to decrease which slowly caused the surface water temperature to decrease. While this was occurring the bottom water temperature was still slowly increasing as before. It appeared that the hot atmospheric air was acting as a significant heat source to the pond surface so that during agitation the cool bottom water mixed with the heated surface water and increased in temperature. After the sun set the ambient air temperature decreased and consequently the surface water temperature began to decrease. The test was halted at 10:30pm for convenience. At this time the temperature difference between the water surface and bottom of the pond was within 4°F on average. The trend was such that it was assessed that approximately another two hours would be required to achieve temperature uniformity.

The non-isothermal atmospheric conditions inhibited the thermal destratification process and delayed complete mixing. Uniformity of the pond water had almost been achieved during the 12 hour test. Had the atmospheric air not been so hot, the water temperature would have cooled more quickly at night such that complete mixing would have been obtained by the end of the test. Homogenous mixing should still have occurred but it appeared that the time of year and atmospheric conditions greatly influenced the water temperature and delayed mixing. It was concluded that mixing did occur because of the narrow temperature difference achieved between the bottom and surface despite the effect of hot air on the water surface. A final observation related to the effect of the hot atmospheric air is that the test took much longer than the calculated value of 4.2 hours calculated in section 4.1.2.

5.2.3 Experiment #3

Experiment #3 was run on July 30, 1994 and a summary of the data is presented in Section 5.4.3. The goal of this experiment was to observe the effect of location of the vortex ring generator deeper than before at depth of 7 feet deep. It was anticipated that at this depth it would be a more effective as a mixer than at the 5 foot dept. The drawback to this was that aeration would possibly suffer since the vortex rings would be less energetic when breaking the pond surface.

The warm weather during the period up to this date had affected the pond as the pond depth was reduced to 9 feet 10 inches. It was also observed that there was a 12 inch clear layer at the pond surface below which the water was murky but with a noticeable green hue, as compared with the brown murky hue during the previous experiments. While there was no odour emanating from the pond, it was concluded that the reduced water level and green hue of the water resulted from evaporation and increased photosynthesis activity which accelerated aquatic plant growth and thus oxygen consumption.

The weather again played an important role in this experiment since it was raining heavily when the trial began. This cooled the air to 70°F which was 8.5 degrees less than the initial temperature for experiment #2. The rain did not raise the level of the pond appreciably but it did add fresh, oxygenated water to the pond prior to this test. The rain eventually ceased and by 2:00pm the skies were clear and sunny with the air temperature gradually rising to almost 90°F as in the previous test. Comparing the initial water temperatures for Experiments #2 and #3 as listed in sections 5.4.2.1 and 5.4.3.1 reveals that the difference in water temperature between top and bottom was 4°F less at the time of initiation of Experiment #3. The relative water temperature was also warmer in Experiment #3 as well. The warmer water temperature and slightly cooler air temperature and the vortex ring generator located at 7 feet combined to achieve complete mixing in the 12 hour test period.

Figure 5.3 shows that the atmospheric air temperature increased the surface temperature of the water thereby causing the bottom water to warm up to an intermediate temperature during mixing. It is discernible that at the beginning of the test, the air was cooler than the water temperature and at the end of the test the air cooled off significantly faster that of the water. This is not surprising since the thermal capacity of water is greater than the thermal capacity of air.

The effect on mixing is that the water surface temperature begins to fall after the air temperature is below the water surface temperature and when mixing occurs, the temperature of the bottom of the pond experiences an increase.

Prior to the test the air compressor was adjusted to supply air at 50psig to the vortex ring generator. This permitted an increase in operating frequency to 4/5Hz during mixing while still enabling the air cylinder to energetically travel its full 3 inch stroke. The resulting vortex rings were sufficiently formed such that the surface agitation caused by the vortex ring generator located 7 feet deep was only slightly less pronounced than that generated by the one located at a depth of 5 feet. The achievement of complete mixing in 12 hours reveals that the increased air pressure and frequency increased mixer effectiveness. The effect on aeration will be discussed in a later section with the laboratory results of all experiments are summarized.

5.2.4 Experiment #4

Experiment #4 was run on August 27, 1994 and a summary of the data is presented in section 5.4.4. In this experiment the vortex ring plate was raised to 3 feet below the pond surface. This depth was selected in order to complete a series of depth effects on aeration by the mixer. The 3 foot depth was chosen since it was anticipated that it would produce more energetic vortex rings breaking the pond surface and thus better aerate the pond than the 5 or 7 foot depth mixer. The potential drawback to this was that mixing would possibly suffer since the vortex rings would be more pronounced at the surface than at the bottom of the pond.

The water depth of the pond was a few inches less than the previous test indicating that there appeared to be insufficient run off to replenish the pond. The murky green hue was still present below a clear top layer approximately 12 inches deep. Aquatic plants had also grown significantly such that algae of 2 to 3 inches in length had grown on the mixer floats. The mosquitoes were still present and the tadpoles had grown into young frogs. The presence of plant and animal life revealed that while the pond may be stratified and oxygen poor, the ecology of the pond was vibrant.

The experiment was similar to the previous experiments. At the 3' depth it was not expected that the vortex ring generator would mix the pond completely within the 12 hour test period. During mixer operation vortex rings were observed to break the pond surface and were very pronounced as shown in Photograph P-1. The vortex ring rose 2 to 3 inches above the surface and caused splashing as it rolled outwards once it broke the surface of the water. The silt clouds along the sides of the pond were still visible but it took 3 hours instead of the usual 2 to make themselves apparent.

One problem encountered during this experiment was that one temperature sensor malfunctioned early in the test. It was discovered that there was incomplete contact at the plug connecting the extension lead wire to the sensor plug on the copper pipe. The connection was repaired and it worked for approximately 1 hour after which it malfunctioned once again. Previous experiments revealed that the two sets of temperature sensors were redundant so the experiment continued with one sensor reading surface temperature and two measuring the bottom temperature.

Mixing was achieved with the mixer impeller at a 3' depth in the 12 hour test period. An important factor was the initial temperature difference between the surface and bottom was only 8°F as compared with the 14 to 17°F difference in the previous tests. The air temperature again appeared to again have played an important role in the mixing time. Figure 5.4 shows that the air temperature was quite warm at test commencement and once the sun set, the air temperature cooled such that the bottom water temperature and surface temperatures eventually met to achieve complete temperature homogeneity. Had the temperature difference between the surface and bottom not been as narrow it was surmised that complete mixing may have taken longer. The aeration effectiveness of this location could not be evaluated at the time of mixing, since the water samples had to be laboratory tested to measure DO. The results of this laboratory testing will be discussed in Section 5.3.

5.2.5 Experiment #5

Experiment #5 was run on October 2, 1994 and a summary of the collected data is presented in section 5.4.5. The goal of this experiment was to observe the performance of the dual plate mixer operating in the field. This mixer has been described in detail in section 4.2.3. Briefly, the mixer consists of two 21 inch diameter plates with 7 inch holes in the centre. Both plates were 14 inches apart and were driven by two air cylinders with a 2 inch stroke.

The 1hp compressor was used instead of the 3.3hp compressor since the dual plate mixer is significantly smaller. The mixer operated using compressed air at 40psig and at a frequency of 4/5Hz to produce well formed vortex rings. The test began at 8:00am and the most significant feature of this test was that the air temperature was significantly less than the water temperature and that the water appeared to be isothermal at the start of the test. The temperatures at first glance indicated that the pond was mixed but visual observation of the pond revealed that there was a clear 6 inch layer of water above a murky layer. This indicated that the pond was stratified even though the temperature of the surface and bottom was identical. Possibly, the fluid velocities were insufficient to keep particulate matter in suspension. However, the fluid circulation may have been sufficient to destratify the thermal layers.

The data in Section 5.4.5 and Figure 5.5 show that the air temperature increased appreciably during the test. The morning air temperature was close to freezing but as the sun broke over the trees the air temperature above the pond increased greatly. The surface and bottom water temperatures remained almost identical until the air temperature warmed up the surface. The temperature of the water at the bottom of the pond did not increase appreciably during mixing which indicated that the pond was not being mixed. Throughout the test no silt clouds were observed at the sides of the pond. The clear top layer of water remained clear with the only cloudiness appearing in the immediate vicinity of the dual plate vortex ring mixer. The conclusion was that the mixer was too small to mix the pond. The temperature trends shown in Figure 5.5 and the lack of uniformity of colour of the pond based on visual observation formed the basis of this conclusion. The test was therefore halted at 6:00pm after 10 hours of test time.

The apparatus did not mix the pond but it did show that both temperature and visual observations are needed to verify if mixing occurred. Air temperature not only prevents and prolongs confirmation of mixing via temperature observation, but it may also give the illusion that the pond is mixed by cooling the water surface to the same temperature as the bottom. Visual observation of particulate suspension also gives an indication as to whether mixing and destratification are occurring. It is surmised that both of these factors must be considered to conclude if an apparatus is providing adequate agitation.

5.3 Experimental Results

The results of all experiments appear in section 5.4 including plots of temperature trends during mixing. Section 5.5 contains additional graphs of DO, BOD, COD and pH.

5.3.1 Mixing

Figures 5.1 through 5.5 illustrate the mixing trends for all five experiments. One of the main objectives of this research was to observe the effectiveness of the vortex ring generator when mixing a natural water body. Detailed observations have been discussed in the previous section but additional comments are necessary to describe the mixing action of the vortex ring generator.

The figures all show that the temperature probes measuring the bottom water temperature experience a moderate temperature rise within the first 1 to 2 hours of mixing. Figure 5.3 reveals that Experiment #3 experienced the most pronounced rise in water temperature at the bottom of the pond. This rise occurs approximately at the same time as the first silt clouds were observed at the edge of the pond. This indicated that destratification commenced as the oxygen poor and stagnant water at the bottom of the pond was stirred up as the vortex rings transported surface water to the bottom thereby setting up a flow pattern.

The initial increase in bottom water temperature is not matched by a similar decrease in the surface temperature. The surface temperature was observed to be greatly affected by the temperature of the atmospheric air in contact with the water. During daylight hours the surface water temperature increased and the bottom water increased in temperature towards the surface temperature during mixing. When the atmospheric air cooled the heat source to the water was reduced such that the surface water cooled slightly while the bottom continued to warm to equilibrium with the surface.

The results of Experiment #5 showed that the dual impeller mixer did not mix the pond but it did illustrate that a volume of water can have uniform temperature but still have particulate stratification. This observation is important since homogenous distribution is vital for complete mixing. The visual observation of the destratifying action and the uniform water colour, in addition to uniform temperature readings, are concluded to be necessary elements to determine that a natural water body is mixed.

5.3.2 DO & BOD

The dissolved oxygen, DO, and biological oxygen demand, BOD, of the pond water was determined by taking water samples every two hours during each experiment. The laboratory results for each experiment appear in Section 5.4. The aeration created by the mixing action of the vortex ring generator was determined by the DO and BOD results of each experiment.

It was difficult to determine the time effects of mixing on DO and BOD because to some extent the rate of bacterial action will affect the results. Figures 5.6 through 5.10 in Section 5.5 illustrate the net results. As the vortex ring generator mixes it forces the top and bottom stratified water layers of the pond to become mixed. The oxygen poor bottom layer therefore becomes introduced to the top water layer which is richer in oxygen. As the pond is mixed the activity of biological organisms increase since they are exposed to water with higher levels of oxygen due to the effects of mixing. The organisms consume this oxygen and their activity increases to levels greater than the long term equilibrium levels in the pond. As their activity increases the DO level in the water decreases since the organisms consume oxygen. As the organisms satisfy their demand for oxygen, their oxygen requirements decrease such that BOD decreases. The dissolved oxygen level therefore increases since oxygen is being added during contact with the atmospheric air during mixing.

The mixing action and rollover of the pond water increases contact with the atmospheric air thereby increasing oxygen transfer. Figures 5.6, 5.8 and 5,9 for Experiments #1, #3 and #4 show the oxygenation patterns in the pond. These figures illustrate the increased BOD due to biological organisms consuming more oxygen. Figures 5.8 and 5.9 clearly show the dip in dissolved oxygen and the corresponding rise in BOD representing biological activity of the pond. The DO levels of the pond appear to fall further after the rise in BOD. Longer test duration may be required to prove that, as mixing occurs, more contact is made between the atmospheric air and water surface such that more oxygen is transferred to the water. Such an occurrence would be evidence of the oxygen deficit that occurs in biological systems as discussed in the literature references found in Chapter 3. According to the references, steady flow of oxygen to the water through mixing would eventually satisfy all biological organism activity requirements such that the oxygen deficit would be eliminated and equilibrium attained.

Figure 5.6 for Experiment #1 does not show the deficit as clearly as Figures 5.8 and 5.9 but it does show that the pond was initially low in dissolved oxygen. This was perhaps unusual since cold water absorbs more oxygen than warm water and natural water bodies are expected to have higher levels of dissolved oxygen during winter than summer. The mixing action of the vortex ring generator as illustrated by this figure shows that dissolved oxygen has satisfied the BOD of the pond and has started to increase once the BOD was satisfied. It is also interesting to note that a DO value of 6.82 mg/l and a BOD value of 2.13 mg/l of oxygen at the end of the test is lower than that experienced during Experiments #3 and #4. This observation reinforces the observation that the time of year when testing occurs must be taken into consideration when testing natural water bodies.

Figure #5.7 illustrates the results from Experiment #2. It can be seen that the DO and BOD trends were very erratic. The DO and BOD levels were also low compared to Experiments # 1 and #3. After much study and discussion with Walker laboratory personnel it was determined that the water samples for Experiment #2 may have been insufficiently refrigerated for a period of time after the samples were collected The net result was that the biological organisms in the samples continued to consume the dissolved oxygen in the liquid. The test results for DO and BOD for Experiment #2 are most likely to be invalid and meaningless for this discussion.

The DO and BOD results for Experiments #3 and #4 show the increase and decrease in BOD as DO is consumed. Experiment #3 was for the 7 foot deep vortex ring location and figure 5.8 reveals that BOD increased greater than any other of the experiments. It is concluded that the deeper mixer location caused greater mixing of the bottom water where biological organisms and sedimented bottom material normally see less oxygen than surface organisms. By stirring up the bottom it appears these organisms saw more oxygen rich water than normal and their activity therefore increased to a greater degree than in the other experiments. Experiment #4 with the vortex ring at the 3 foot level and Figure 5.9 illustrates a higher final DO level after mixing than other experiments. The greater mixing, splash and rollover of the vortex ring at the water surface appeared to increase contact with the atmospheric air and thus oxygen transfer. The higher DO and lower BOD levels for Experiment #4 as compared to Experiment #3 seems to confirm this observation.

In Experiment #5 the mixer did not mix the pond but figure 5.10 shows some DO activity. It is interesting to observe that when this experiment occurred that the atmospheric air temperature became quite cool at night which could be one explanation for the BOD level which is the lowest of all experiments. The DO levels appear to be higher than Experiment #1 and it appears that the biological organisms' activity were slowing due to lower atmospheric and water temperatures thereby lowering the demand for oxygen. The fact that the pond was aerated 5 times in a 5 month period may explain the higher levels of DO as compared with Experiment #1.

The last observation from the figures is that Experiments #3 and #4 occurred during the hot summer months when there is little rainfall. The green hue of the lower stratified water layer in the pond appears to indicate increased BOD activity but the high DO levels in the pond, especially in August during

Experiment #3, seem to indicate that there is residual oxygen being left in the pond from each previous test. The mixing action of the vortex ring generator appears however to increase BOD and thus DO levels such that no matter how much DO may be in the pond, the biological organisms present could always consume more oxygen if it was available.

5.3.3 COD and pH

The Chemical Oxygen Demand (COD) and pH values obtained from the water samples do not vary significantly from experiment to experiment. Compared to BOD, the chemical oxygen demand or COD does not appear to be significantly affected by the mixing action of the vortex ring generator. COD levels for Experiments #1 through #4 varied between 39 and 59 mg/l oxygen as illustrated in figure 5.11. All experiments have similar trends and the rise and fall of COD appears to coincide somewhat with BOD even though COD and BOD are not proportional to each other. The final values of COD for most experiments seem close to the values at the beginning of each experiment. The unusual result observed form Figure 5.11 is that Experiment #5 has low COD levels indicating a slowdown in biological activity due to the time of year. Another interesting feature is that even with the known problems with the samples for Experiment #2, the COD results did not seem to be affected. It was mentioned during the literature search that the COD was a more reliable test than the BOD and it appears that this is an example of this, since the results do not seem to be affected by the unrefrigerated water samples.

The acidity level of the pond was never too extreme for a natural water body. Figure 5.12 shows that pH levels were relatively alkaline and varied between 8.7 and 7.9 for Experiments #1, #3 and #4. The literature search mentioned that aeration does not affect pH and this appears to be illustrated by the results. The problems with Experiment #2 water samples do seem to have affected the pH results for this test. The pH levels for Experiment #5 appear lower than the other experiments. This may be related to the decreased biological activity observed in the pond due to the time of year.

5.3.4 Exponential Decay

The temperature difference between the water surface and bottom were plotted on a semi-log scale over time as shown in Figures 5.13 to 5.17. For Experiments 1,2,3 and 4 the slope of the plots reveal that the effect of destratification through the action of the vortex ring mixer was significant. The slope of each plot was relatively smooth during each test. This smooth slope on the semi-log plots reveal that destratification was accelerated by the vortex ring mixer.

The effect of temperature greatly influenced destratification as the slope of each plot increased towards the end of each test. Once the sun set and the heat source was removed, the surface and bottom water temperatures were able to converge relatively quickly. Each test has a slightly different slope revealing that in a test outside of the laboratory external factors greatly effect the ability to achieve destratification of a body of water. Figure 5.17 for Experiment #5 has a slope that increased over time. Figure 5.17 corresponds to Figure 5.5 showing that as the test proceeded the surface and bottom water temperatures diverged indicating that destratification did not occur because the dual plate mixer was undersized for the application.

5.3.5 Summary of Calculated Results

The detailed calculations for K_La_{20}, SOTR and SAE for all five experiments appear in section 5.4. The logarithmic equation represented by Equation 2.8 in Chapter 2 was used to determine the volumetric transfer coefficient for each test. The exponential form of the equation to determine K_La was not used since the ANSI/ASCE standard requires an increased amount of oxygen samples taken at shorter time intervals. This was not possible with the apparatus and procedure available for the experiments in this thesis. The K_La coefficient was corrected to standard conditions at 20 °C using a standard θ value of 1.024. Oxygen saturation and waste water correction factors were not used to adjust K_La_{20} since their purpose is to correct for waste water characteristics during municipal waste water testing which was not applicable to the experimental results from mixing and aerating the pond. Depth correction was also not done because the atmospheric pressure during each test was very close to standard atmospheric conditions. The summary of the calculated results for all five experiments is as follows:

		(1/hr)	(kgO_2/hr)	(kgO_2/kWh)
Table 5.1	Mixer Type	K_La_{20}	SOTR	SAE
EX #1	5 Feet Deep	0.0098	0.0674	0.0274
EX #2	5 Feet Deep	-0.0022	-0.151	-0.0062
EX #3	7 Feet Deep	0.0114	0.0784	0.0319
EX #4	3 Feet Deep	0.012	0.0826	0.0336
EX #5	Dual Plate	0.0014	0.0099	0.004

The first observation to be made from the above table is that the results for Experiment #2 are invalid as indicated from the negative calculated values. The other immediate observation is that all other experiments increased the amount of oxygen to the pond as indicated by the standardized volumetric transfer rate K_La_{20}.

Experiment #1 has a low K_La_{20}, SOTR and SAE value. This is related to the low initial DO level of the pond in early June when the test occurred. The mixer located at a depth of 5 feet was a compromise between mixing and aeration and while the mixing was effective the aeration capability is not as great as the other vortex ring generator configurations.

Experiments #3 and #4 are interesting in that the vortex ring generator located 3 feet deep in the pond had the highest transfer coefficient, K_La, and oxygen transfer rate, yet the mixer at a depth of 7 feet had a similar transfer coefficient and oxygen transfer rate. The shallow mixer aerated the pond the best of all vortex ring locations due to the splashing and rollover of the vortex ring as it broke the water surface. The vortex rings generated were very energetic which was necessary to have sufficient upward velocity and buoyancy to break the surface of the water. The deep mixer did not aerate as well but its performance is reasonable and appears to have the most effective mixing. The deep vortex ring had the greatest transfer coefficient and oxygen transfer rate and may be perhaps linked to the better mixing at this location. The intermediate depth vortex ring, located at 5 feet, neither mixes nor aerates well and appears to be a compromise with substandard performance. From these results it can be concluded that the vortex ring located at 7 feet provides good mixing while adequately aerating the pond, and that the vortex ring at 3 feet provides good aeration while providing adequate mixing.

The dual plate vortex ring generator in Experiment #5 did not mix the pond but the small amount of water movement it did generate transferred a small amount of oxygen. This seemingly small transfer may best illustrate that mixing a natural water body will aerate by causing surface turbulence that changes water contact with atmospheric air.

5.4.0 Preliminary Experiment - May 14, 1994

Weather:	Sunny with light winds all day.
Air Temperature:	63°F at 11:00am
Pond Depth:	10 feet 7 inches
Preliminary Readings:	At 2 feet below the surface the water temperature was 65.5°F with a pH of 8.3. At 7 inches off of the bottom of the pond the water temperature was 55°F with a pH of 7.9.
Compressor:	1hp operating at 30 psig.
Vortex Mixer Frequency:	1/2Hz
Water Colour:	Murky, could only see approximately 12 inches below the surface of the water.
Vortex Mixer Configuration:	The mixer had a 3 foot diameter vortex ring plate with a 12 inch diameter hole in the middle. The plate was located 5 feet below the surface of the water.
Experiment Purpose:	The purpose of the preliminary experiment was to test the experiment apparatus and see how well the mixer generated vortex rings and the suitability of the compressor, mixer stroke, frequency and parameter recording during an experiment.

5.4.1 Experiment #1 - June 4, 1994

Weather: Sunny with light winds all day.

Air Temperature: 78°F at 3:00pm

Pond Depth at Mixer: 10 feet 7 inches

Temperature Probe Location: TO was located above the shed roof.
T1 was located 1 foot below the water surface.
T2 was located 1 foot 7 inches off the bottom of the pond.

Test Duration: The test started at 3:00pm and finished at 10:30pm.

Compressor: 3.3hp operating at 40psig.

Vortex Mixer Frequency: 1/2 to 3/5Hz

Vortex Mixer Stroke: 3 inches

Water Colour: Very murky, could not see deeper than 6 inches.

Vortex Mixer Configuration: The mixer had a 3 foot diameter vortex ring plate with a 12 inch diameter hole in the middle. The plate was located 5 feet below the surface of the water.

Experiment Purpose: First experiment run of the vortex ring mixer to determine the time necessary to mix the pond while taking water samples to determine the effect of mixing on DO, BOD, COD and pH.

5.4.1.1 Experiment #1 Results

Experiment #1 Time and Temperature Readings

Time - Hours	TO - °F	T1 - °F	T2 - °F
0	78	67	59
1.5	78	66.5	58.5
2.5	75	68	60.5
3.5	70	65.5	60.5
5.5	65	62	60.5
6.5	60	58	58
7.5	60	58	58

Experiment #1 Laboratory Results

Time - Hours	DO - mg/lO_2	BOD - mg/lO_2	COD - mg/lO_2	pH
1.5	4.25	2.61	48	8.0
5.5	4.71	2.76	55	7.9
7.5	6.82	2.13	54	8.0

The following are the detailed calculations used to determine the K_La of Experiment #1:

From the above tables:

Time (Hours)	DO mg/l O_2	Surface Temperature
0	4.25	66.5
5.5	4.71	62
7.5	6.82	58

Average Surface Temperature = 62.1°F or 16.7°C

Interpolating From Table F-1 in ASCE Standard No. 2-91 using the average temperature of 16.7C gives C_∞*= 9.73mg/l of O_2.

Using Equation 2.9 to determine K_La:

Logarithmic Form: $\ln(C_\infty^* - C)/(C_\infty^* - C_0) = -K_Lat$

$T = 5.5$: $\ln(9.73-4.71)/(9.73-4.25) = -K_La_{5.5}$ $K_La_{5.5} = 0.0275/\text{hr}$

$T = 7.5$: $\ln(9.73-6.82)/(9.73-4.25) = -K_La_{7.5}$ $K_La_{7.5} = 0.0844/\text{hr}$

From the above equations the volumetric transfer coefficients calculated were used in a linear least squares regression analysis with the results as follows:

Time - Hours	K_La
0	0
5.5	0.04987
7.5	0.07699

From the regression, m = 0.00907 which gives the overall volumetric transfer coefficient of Experiment #1 as $K_La = 0.00907/\text{hr}$.

To correct for temperature influences and to convert to standard conditions as required by the ASCE standard, K_La is transformed by Equation 2.11 as follows:

$K_La_{20} = K_Lat\theta^{(20-T)}$ where $\theta = 1.024$

$K_La_{20} = 0.00907(1.024^{(20-16.7)})$

$K_La_{20} = 0.0098/\text{hr}$

The value of K_La_{20} for Experiment #1 is used in to determine the standard oxygen transfer rate, SOTR, and the standard aeration efficiency, SAE, as represented by Equations 2.17 and 2.18.

$$\mathrm{SOTR} = K_La_{20}C_{\infty}{}^*{}_{20}V$$

$$\mathrm{SOTR} = (0.0098/\mathrm{hr})(9.09\mathrm{mg/l})(200{,}000\mathrm{USgal}) \\ \times (3.784\mathrm{gal/l})(1\mathrm{kg}/1\mathrm{x}10^6\mathrm{mg})$$

$$\mathrm{SOTR} = 0.0674\mathrm{kgO_2/hr}$$

$$\mathrm{SAE} = \mathrm{SOTR/Power}$$

$$\mathrm{SAE} = (0.0674\mathrm{kgO_2/hr})(1/3.3\mathrm{hp})(1.342\mathrm{hp}/1\mathrm{kW})$$

$$\mathrm{SAE} = 0.0274\mathrm{kgO_2/kWh}$$

Where $C_{\infty}{}^*{}_{20} = 9.09$mg/l is the tabular value for dissolved oxygen at the standard condition of 20°C.

5.4.2 Experiment #2 - July 2, 1994

Weather:	Sunny with light winds initially. Winds later increased to 10 to 20mph.
Air Temperature:	78.5°F at 10:45am
Pond Depth at Mixer:	10 feet 4.5 inches
Temperature Probe Location:	TO was located above the shed roof. T1 and T3 were located 5.5 inches below the water surface. T2 and T4 were located 1 foot and 1/2 inch off the bottom of the pond.
Test Duration:	The test started at 10:30am and finished at 10:30pm.
Compressor:	3.3hp operating at 40psig.
Vortex Mixer Frequency:	3/5 to 4/5Hz
Vortex Mixer Stroke:	3 inches
Water Colour:	Relatively clear, could see 18 inches below the water surface.
Vortex Mixer Configuration:	The mixer had a 3 foot diameter vortex ring plate with a 12 inch diameter hole in the middle. The plate was located 5 feet below the surface of the water.
Experiment Purpose:	This experiment was identical to the previous experiment in that the 5 foot deep vortex plate was used.

5.4.2.1 Experiment #2 Results

Experiment #2 Time and Temperature Readings

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
0.00	78.5	69.2	51.3	69.6	51.9
0.25	77.5	69.9	52.8	70.0	53.8
0.50	79.8	70.3	52.5	70.3	53.7
0.75	79.8	70.5	53.3	71.3	55.1
1.00	79.7	71.1	53.7	73.2	55.3
1.25	81.5	72.6	53.9	71.4	55.4
1.50	81.7	71.6	54.4	72.5	55.9
1.75	84.1	72.8	54.6	72.5	56.8
2.00	85.5	72.7	55.5	72.8	56.9
2.25	82.4	74.1	56.0	72.6	57.2
2.50	83.7	73.0	56.6	73.1	58.7
2.75	84.0	73.4	57.1	73.8	58.4
3.00	85.0	73.5	57.6	76.6	58.9
3.25	84.3	75.1	57.9	74.9	59.0
3.50	85.1	72.3	58.1	73.1	59.3
3.75	87.6	76.0	58.4	73.7	59.5
4.00	88.8	75.6	58.7	75.0	60.1
4.25	89.9	77.0	58.9	73.6	60.1
4.50	87.5	75.6	59.1	74.1	60.3
4.75	89.6	76.1	59.4	74.2	60.4
5.00	88.7	75.9	59.5	75.5	60.6
5.25	90.6	73.3	59.8	77.2	61.0
5.50	91.1	72.8	59.8	76.2	61.2
5.75	90.5	73.6	60.1	74.1	61.1
6.00	87.5	72.9	60.3	71.5	61.4
6.25	87.9	75.6	60.4	74.6	61.5
6.50	87.5	75.4	60.5	72.2	61.6
6.75	88.9	74.9	60.7	73.6	62.1
7.00	89.3	75.1	61.0	74.8	62.0

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
7.25	87.9	71.9	61.0	74.5	62.2
7.50	84.4	74.9	61.2	72.4	62.3
7.75	85.2	74.9	61.4	74.7	62.6
8.00	84.5	74.3	61.5	72.1	62.6
8.25	79.3	71.4	61.7	73.2	62.9
8.50	79.1	71.7	61.7	73.6	63.1
8.75	78.8	71.7	61.9	72.1	63.2
9.00	77.6	73.0	62.1	72.6	63.4
9.25	75.7	72.2	62.2	72.2	63.4
9.50	76.3	69.4	62.3	72.5	63.4
9.75	75.0	69.5	62.5	72.5	63.5
10.00	73.6	70.0	62.5	69.3	63.7
10.25	72.4	69.2	62.5	70.5	63.8
10.50	68.8	69.3	62.7	69.3	64.0
10.75	67.4	68.8	62.7	69.4	64.0
11.00	66.6	68.8	62.8	69.0	64.2
11.25	65.7	68.5	62.8	69.0	64.2
11.50	64.4	68.1	63.0	68.8	64.2
11.75	64.2	68.0	63.0	68.3	64.3
12.00	64.0	67.8	63.1	68.0	64.5

Experiment #2 Laboratory Results

Time -Hours	DO - mg/lO_2	BOD - mg/lO_2	COD - mg/lO_2	pH
0	4.95	1.17	39	7.54
2	4.32	1.86	56	7.47
4	4.56	1.50	39	7.45
6	3.70	1.74	44	7.45
8	4.78	1.47	47	7.47
10	3.91	1.50	50	7.49
12	4.84	3.69	59	7.52

The calculations to determine K_La, K_La_{20}, SOTR and SAE are identical to that used in the section 5.4.1.1. The final results are summarized below.

Average Surface Temperature = 71.5°F

Interpolating From Table F-1 in ASCE standard 2-91 using an average temperature of 21.94°C gives $C_\infty^* = 8.75$mg/l of O_2.

Equation 2.9 was used to determine the K_La values at the time of each water sample. These K_La values were then used in a linear least squares regression analysis with the results given as follows:

Time - Hours	K_La
0	0
2	-0.00467
4	-0.00934
6	-0.01401
8	-0.01869
10	-0.02336
12	-0.02803

From the regression, m = -0.00234 which gives the overall volumetric transfer of Experiment #2 as $K_La = -0.00234$.

Equations 2.11, 2.17 and 2.18 were used to determine K_La_{20}, SOTR and SAE given as follows:

K_La_{20} = -0.0022/hr,

SOTR = -0.0151kgO_2/hr,

SAE = -0.0062kgO_2/kWh

5.4.3 Experiment #3 - July 30, 1994

Weather: Overcast with occasional heavy rain initially. The skies were clear by 2:00pm. Winds were 20mph.

Air Temperature: 70°F at 10:30am

Pond Depth at Mixer: 9 feet 10 inches

Temperature Probe Location: TO was located above the shed roof.
T1 and T3 were located 4.5 inches below the water surface.
T2 and T4 were located 5.5 inches off the bottom of the pond.

Test Duration: The test started at 10:45am and finished at 10:45pm.

Compressor: 3.3hp operating at 50psig.

Vortex Mixer Frequency: 4/5Hz

Vortex Mixer Stroke: 3 inches

Water Colour: Slightly murky, could see 12 inches below the water surface.

Vortex Mixer Configuration: The mixer had a 3 foot diameter vortex ring plate with a 12 inch diameter hole in the middle. The plate was located 7 feet below the surface of the water.

Experiment Purpose: This experiment determined if mixing would be better obtained by using a vortex ring plate that was placed deeper in the pond.

5.4.3.1 Experiment #3 Results

Experiment #3 Time and Temperature Readings

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
0.00	70.0	72.5	58.2	73.5	57.6
0.25	71.5	72.8	58.3	73.7	57.8
0.50	76.5	73.0	58.5	73.8	58.0
0.75	74.1	73.2	60.2	73.8	58.8
1.00	76.3	73.4	61.1	74.0	62.0
1.25	82.5	73.6	62.3	74.1	62.6
1.50	83.6	73.9	62.7	74.2	63.6
1.75	75.3	74.1	63.4	74.2	64.4
2.00	81.9	74.2	63.9	73.6	64.7
2.25	82.4	74.3	64.6	73.2	65.3
2.50	77.1	74.3	65.1	73.0	65.8
2.75	83.5	74.4	65.4	72.7	66.2
3.00	83.6	74.6	65.7	72.4	66.4
3.25	89.0	74.5	66.0	72.3	66.8
3.50	81.2	74.1	66.3	72.1	67.1
3.75	80.7	74.6	66.6	72.0	67.4
4.00	81.6	74.2	66.5	72.0	67.5
4.25	85.0	74.8	66.8	72.0	67.7
4.50	83.3	74.6	67.1	71.9	67.9
4.75	92.2	76.2	67.4	72.3	68.2
5.00	80.8	75.4	67.3	72.2	68.1
5.25	88.0	75.2	67.6	72.9	68.4
5.50	85.3	75.6	67.7	73.0	68.7
5.75	84.2	75.0	67.8	73.0	68.7
6.00	86.0	75.2	67.7	73.0	68.8
6.25	82.8	75.4	68.0	73.3	69.1
6.50	77.0	76.0	68.1	74.3	69.2
6.75	79.9	75.4	68.3	73.7	69.4
7.00	77.2	75.3	68.4	73.7	69.4

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
7.25	78.2	75.2	68.4	73.3	69.5
7.50	79.9	75.2	68.5	73.0	69.5
7.75	81.3	74.6	68.7	72.9	69.6
8.00	79.9	73.8	68.8	72.8	69.6
8.25	80.0	74.3	68.8	72.6	70.0
8.50	76.9	73.8	69.0	72.5	70.1
8.75	74.1	73.8	69.2	72.5	70.2
9.00	75.0	73.5	69.3	72.5	70.4
9.25	73.5	73.5	69.4	72.6	70.4
9.50	71.3	73.4	69.5	72.6	70.4
9.75	69.5	73.2	69.5	72.6	70.5
10.00	69.5	73.0	69.9	72.6	70.7
10.25	68.3	72.9	70.0	72.4	70.8
10.50	67.1	72.7	70.0	72.4	70.9
10.75	66.2	72.5	70.2	72.3	70.8
11.00	65.2	72.4	70.3	72.4	71.0
11.25	65.2	72.3	70.2	72.2	71.1
11.50	65.1	72.3	70.5	72.2	71.3
11.75	64.5	72.1	70.7	72.1	71.4
12.00	63.6	71.9	70.6	71.9	71.1

Experiment #3 Laboratory Results

Time -Hours	DO - mg/lO_2	BOD - mg/lO_2	COD - mg/lO_2	pH
0	10.51	3.39	41	8.54
2	10.06	3.18	49	8.52
4	9.39	3.57	41	8.33
6	9.02	5.07	43	8.24
8	9.57	4.95	53	8.33
10	9.94	3.57	43	8.22
12	9.63	3.48	42	8.08

The calculations to determine K_La, K_La_{20}, SOTR and SAE are identical to that used in the section 5.5.1.1. The final results are summarized below.

Average Surface Temperature = 73.14°F

Interpolating From Table F-1 in ASCE standard 2-91 using an average temperature of 22.86°C gives $C_\infty^* = 8.59$mg/l of O_2.

Equation 2.9 was used to determine the K_La values at the time of each water sample. These K_La values were then used in a least squares regression analysis with the results given as follows:

Time - Hours	K_La
0	0
2	0.0235
4	0.047
6	0.0705
8	0.094
10	0.1175
12	0.141

From the regression, m = 0.01175 which gives the overall volumetric transfer of Experiment #3 as $K_La = 0.01175$.

Equations 2.11, 2.17 and 2.18 were used to determine K_La_{20}, SOTR and SAE given as follows:

K_La_{20} = 0.0114/hr,

SOTR = 0.0784kgO_2/hr,

SAE = 0.0319kgO_2/kWh

5.4.4 Experiment #4 - August 27, 1994

Weather:	Hot and humid with clear and sunny skies. Winds were very light.
Air Temperature:	85.2°F at 10:15am
Pond Depth at Mixer:	9 feet 6 inches
Temperature Probe Location:	TO was located above the shed roof. T1 and T3 were located 5 inches below the water surface.(T1 malfunctioned during test) T2 and T4 were located 1 inch off the bottom of the pond.
Test Duration:	The test started at 10:15am and finished at 10:15pm.
Compressor:	3.3hp operating at 50psig.
Vortex Mixer Frequency:	4/5Hz
Vortex Mixer Stroke:	3 inches
Water Colour:	Slightly murky, could see 12 inches below the water surface.
Vortex Mixer Configuration:	The mixer had a 3 foot diameter vortex ring plate with a 12 inch diameter hole in the middle. The plate was located 3 feet below the surface of the water.

Experiment Purpose: This experiment determined if aeration would be more effective by using a vortex ring plate that was placed closer to the water surface

5.4.4.1 Experiment #4 Results

Experiment #4 Time and Temperature Readings

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
0.00	85.2		63.6	71.7	63.2
0.25	86.2		63.7	71.8	63.6
0.50	85.2		65.9	71.9	65.2
0.75	86.9		66.3	72.2	65.6
1.00	87.4		66.6	72.6	67.2
1.25	90.4		66.9	73.0	67.3
1.50	89.3		67.5	73.3	67.8
1.75	86.5		67.9	73.8	68.3
2.00	84.1		68.1	73.9	68.7
2.25	82.1		68.1	73.6	68.9
2.50	80.6		68.1	74.0	69.1
2.75	83.8		68.5	74.5	69.4
3.00	87.2		68.7	74.2	69.6
3.25	87.8		68.8	74.4	69.7
3.50	87.7		68.9	74.3	69.8
3.75	84.9		68.9	74.8	69.7
4.00	84.1		69.1	74.8	70.1
4.25	84.8		69.3	75.1	70.2
4.50	82.9		69.4	74.4	70.3
4.75	86.5		69.5	74.8	70.3
5.00	93.1		69.6	75.4	70.3
5.25	85.0		69.6	74.3	70.5
5.50	83.3		69.7	74.7	70.5
5.75	84.7		69.9	75.8	70.6
6.00	84.7		70.0	75.1	70.7
6.25	84.9		70.0	75.2	70.8
6.50	86.4		70.2	75.1	71.0
6.75	87.5		70.3	75.0	71.1
7.00	84.3		70.4	74.8	71.3

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
7.25	81.8		70.4	75.0	71.3
7.50	81.7		70.5	74.7	71.4
7.75	79.2		70.5	75.1	71.6
8.00	79.5		70.5	74.7	71.6
8.25	76.7		70.6	75.5	71.7
8.50	76.4		70.6	74.9	71.6
8.75	74.1		70.9	74.7	71.9
9.00	73.3		71.0	74.8	72.0
9.25	72.3		71.0	73.7	72.1
9.50	71.4		71.1	73.8	72.1
9.75	71.3		71.2	73.6	72.1
10.00	70.9		71.2	73.7	72.3
10.25	70.6		71.1	73.5	72.3
10.50	70.2		71.3	73.3	72.3
10.75	70.0		71.2	73.1	72.2
11.00	69.6		71.3	73.0	72.3
11.25	69.4		71.2	72.7	72.3
11.50	69.4		71.2	72.6	72.3
11.75	69.4		71.1	72.4	72.1
12.00	69.1		71.1	72.2	72.1

Experiment #4 Laboratory Results

Time -Hours	DO - mg/lO$_2$	BOD - mg/lO$_2$	COD - mg/lO$_2$	pH
0	11.2	2.79	51	8.69
2	11.0	2.31	51	8.64
4	10.4	2.70	53	8.64
6	10.6	3.72	45	8.39
8	9.5	4.44	53	8.32
10	9.77	2.28	55	8.23
12	8.34	2.25	43	8.11

The calculations to determine K_La, K_La_{20}, SOTR and SAE are identical to that used in the section 5.4.1.1. The final results are summarized below.

Average Surface Temperature = 73.8°F

Interpolating From Table F-1 in ASCE standard 2-91 using an average temperature of 23.2°C gives $C_\infty^* = 8.55$mg/l of O_2.

Equation 2.9 was used to determine the K_La values at the time of each water sample. These K_La values were then used in a least squares regression analysis with the results given as follows:

Time - Hours	K_La
0	0
2	0.02587
4	0.05175
6	0.07762
8	0.10349
10	0.12936
12	0.15535

From the regression, m = 0.01294 which gives the overall volumetric transfer of Experiment #4 as $K_La = 0.01294$.

Equations 2.11, 2.17 and 2.18 were used to determine K_La_{20}, SOTR and SAE given as follows:

K_La_{20} = 0.012/hr,

SOTR = 0.0826kgO_2/hr,

SAE = 0.0336kgO_2/kWh

5.4.5 Experiment #5 - October 2, 1994

Weather: Cool with clear and sunny skies. Winds were very light.

Air Temperature: 36.6°F at 8:00am

Pond Depth at Mixer: 10 feet 9 inches

Temperature Probe Location: TO was located above the shed roof.
T1 and T3 were located 12 inches below the water surface.
T2 and T4 were located 6 inches off the bottom of the pond.

Test Duration: The test started at 8:00am and finished at 6:00pm.

Compressor: 1.0 horsepower operating at 40psig.

Vortex Mixer Frequency: 4/5Hz

Vortex Mixer Stroke: 2 inches

Water Colour: Murky, could only see 6 inches below the water surface.

Vortex Mixer Configuration: The mixer was a dual plate mixer with two 21 inch vortex ring plates with a 7 inch diameter hole in each plate. The plates were placed 14 inches apart and placed 3 feet deep in the pond.

Experiment Purpose: This experiment was to determine the effectiveness of the dual plate vortex ring mixer in a natural pond setting.

5.4.5.1 Experiment #5 Results

Experiment #5 Time and Temperature Readings

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
0.00	36.6	53.8	53.2	55.3	55.7
0.25	43.4	53.7	53.5	54.9	55.3
0.50	46.9	53.6	53.4	54.5	54.8
0.75	44.7	53.4	53.4	54.3	54.5
1.00	45.3	53.5	53.3	54.1	54.5
1.25	47.2	53.6	53.2	54.1	54.4
1.50	47.5	53.5	53.2	54.1	54.3
1.75	48.6	53.7	53.3	54.2	54.2
2.00	50.2	53.8	53.4	54.0	54.3
2.25	48.0	53.8	53.4	54.0	54.2
2.50	58.6	53.9	53.0	53.3	53.7
2.75	61.6	54.0	53.2	53.7	53.9
3.00	68.4	54.2	53.5	54.2	54.3
3.25	74.3	54.2	53.5	54.3	54.2
3.50	73.8	54.4	53.6	54.4	54.1
3.75	75.4	54.6	53.8	54.6	54.2
4.00	78.9	55.0	54.2	55.1	54.5
4.25	81.4	55.3	54.4	55.2	54.4
4.50	76.9	56.0	54.8	58.0	56.0
4.75	70.1	56.3	55.2	58.6	56.6
5.00	65.8	56.5	55.1	58.4	56.5
5.25	64.9	56.6	54.8	58.6	56.0
5.50	65.1	56.5	54.5	58.9	55.8
5.75	64.4	56.5	54.3	58.8	55.5
6.00	66.6	56.6	54.2	59.2	55.4
6.25	66.6	56.9	54.2	59.2	55.2
6.50	65.2	57.1	54.1	59.0	55.4
6.75	66.0	57.1	54.1	58.9	55.4
7.00	68.5	57.1	54.1	60.0	55.3

Time - Hours	TO - °F	T1 - °F	T2 - °F	T3 - °F	T4 - °F
7.25	66.5	57.4	54.1	59.9	55.4
7.50	65.8	57.5	54.1	60.3	55.4
7.75	68.5	57.5	54.2	60.5	55.3
8.00	65.8	58.0	54.1	59.7	55.4
8.25	68.5	57.9	54.2	60.3	55.4
8.50	69.6	58.0	54.2	60.0	55.5
8.75	67.1	58.0	54.1	59.8	55.5
9.00	67.5	58.1	54.1	60.4	55.4
9.25	58.8	57.9	54.1	60.1	55.4
9.50	64.4	57.8	54.1	59.8	55.6
9.75	63.1	57.7	54.1	59.6	55.5
10.00	61.3	57.5	54.1	59.4	55.3

Experiment #5 Laboratory Results

Time -Hours	DO - mg/lO$_2$	BOD - mg/lO$_2$	COD - mg/lO$_2$	pH
0	7.42	1.44	34	7.38
2	7.69	1.47	31	7.42
4	8.24	1.44	28	7.47
6	7.23	1.50	32	7.42
8	7.56	1.65	36	7.43
10	7.21	1.53	26	7.46

The calculations to determine K_La, K_La_{20}, SOTR and SAE are identical to that used in the section 5.5.1.1. The final results are summarized below.

Average Surface Temperature = 55.6°F

Interpolating From Table F-1 in ASCE standard 2-91 using an average temperature of 13.6°C gives $C_\infty^* = 10.4$mg/l of O_2.

Equation 2.9 was used to determine the K_La values at the time of each water sample. These K_La values were then used in a least squares regression analysis with the results given as follows:

Time - Hours	K_La
0	0
2	0.00249
4	0.00497
6	0.00746
8	0.00994
10	0.01243

From the regression, m = 0.00124 which gives the overall volumetric transfer of Experiment #5 as $K_La = 0.00124$.

Equations 2.11, 2.17 and 2.18 were used to determine K_La_{20}, SOTR and SAE given as follows:

K_La_{20} = 0.0014/hr,
SOTR = 0.0099kgO_2/hr,
SAE = 0.004kgO_2/kWh

FIGURE 5.1 - EXPERIMENT #1 MIXING RESULTS

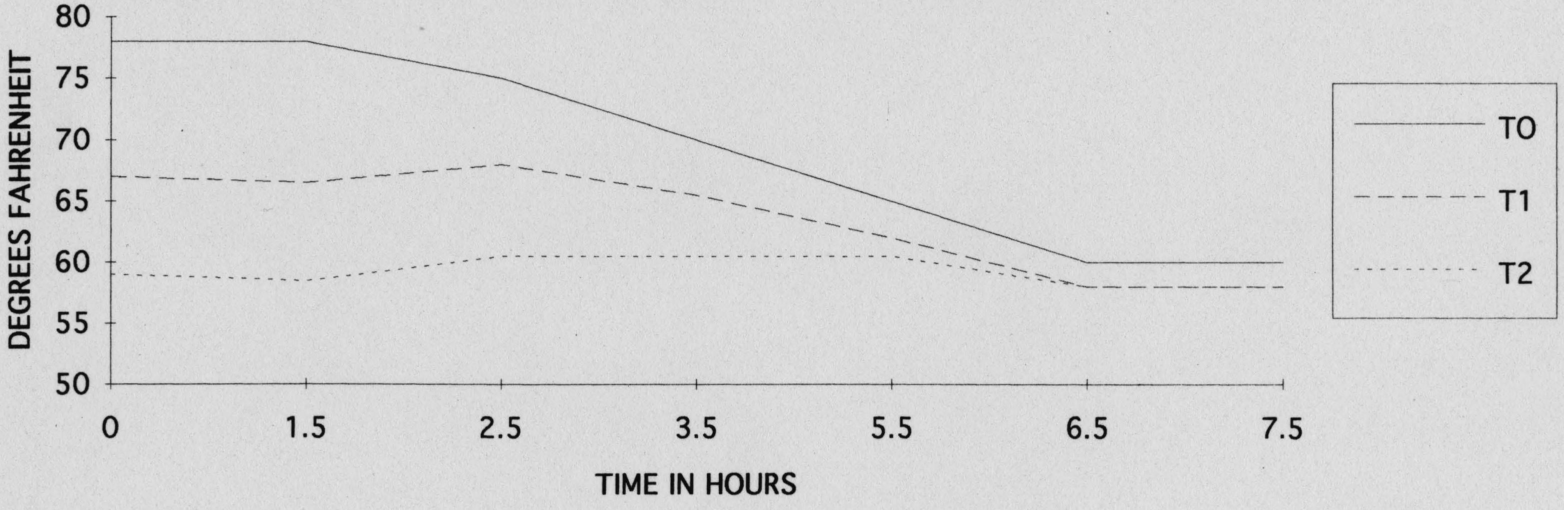


FIGURE 5.2 - EXPERIMENT #2 MIXING RESULTS

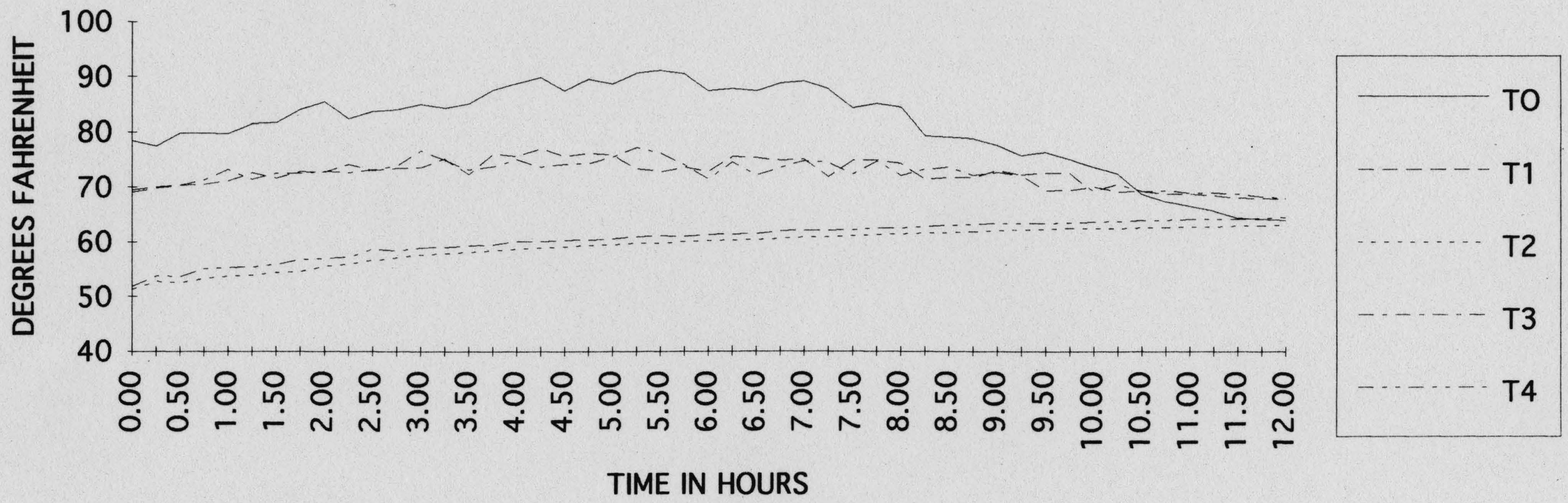


FIGURE 5.3 - EXPERIMENT #3 MIXING RESULTS

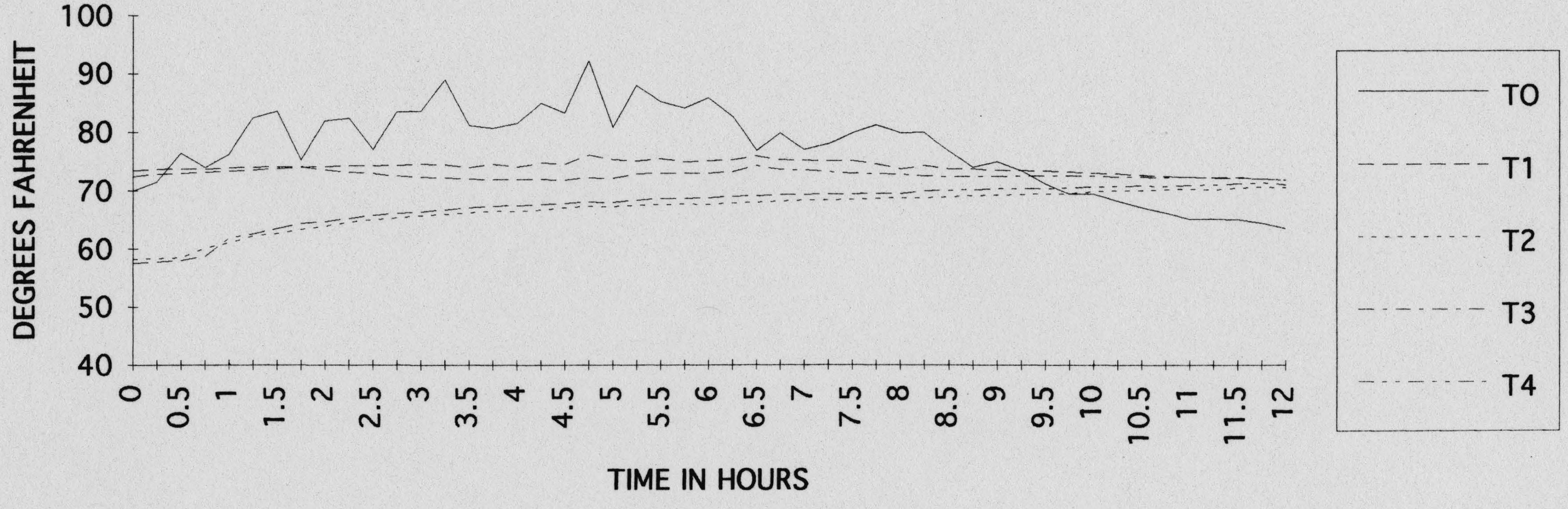


FIGURE 5.4 - EXPERIMENT #4 MIXING RESULTS

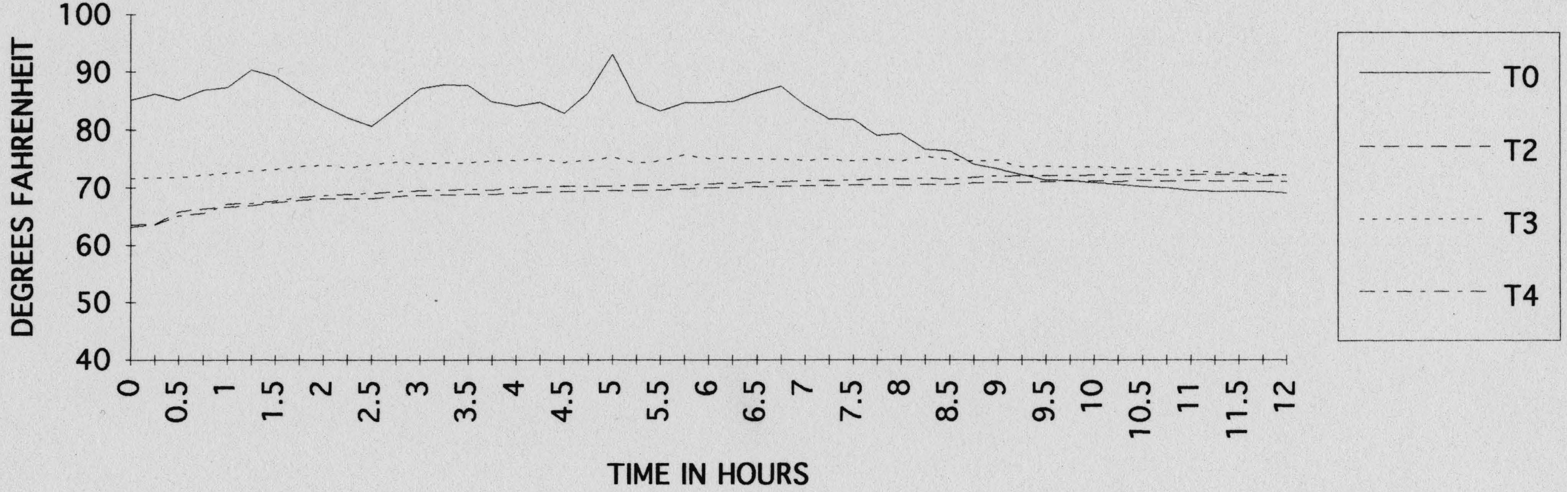


FIGURE 5.5 - EXPERIMENT #5 MIXING RESULTS

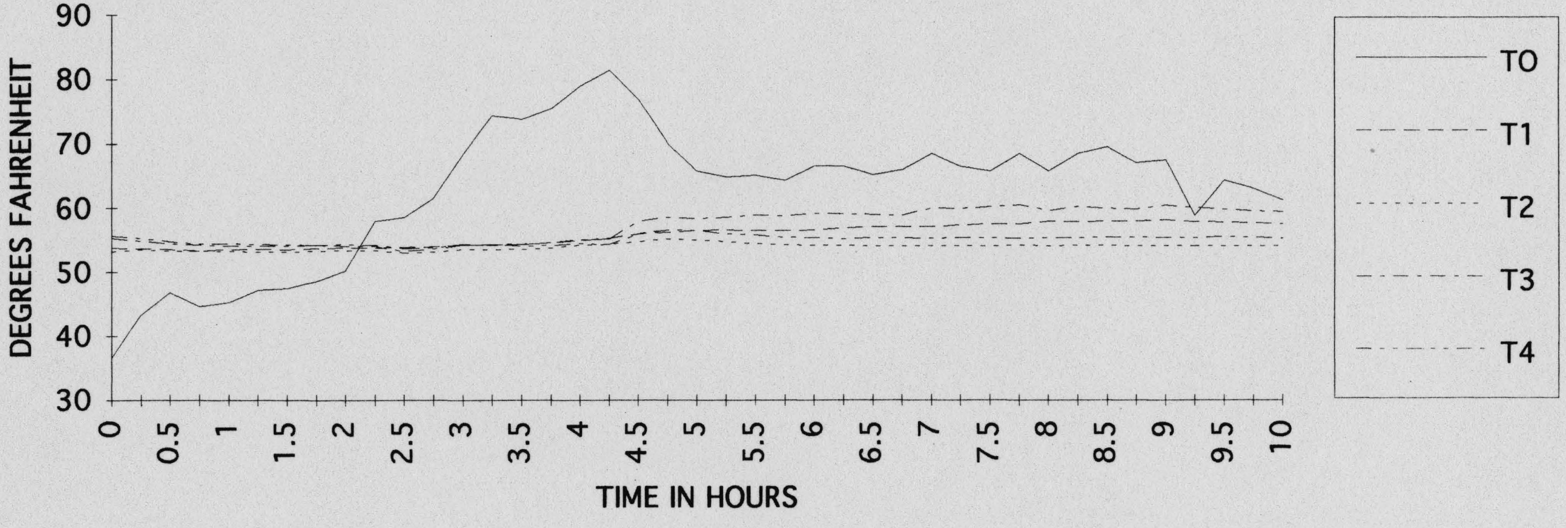


FIGURE 5.6 - EXPERIMENT #1 DO & BOD

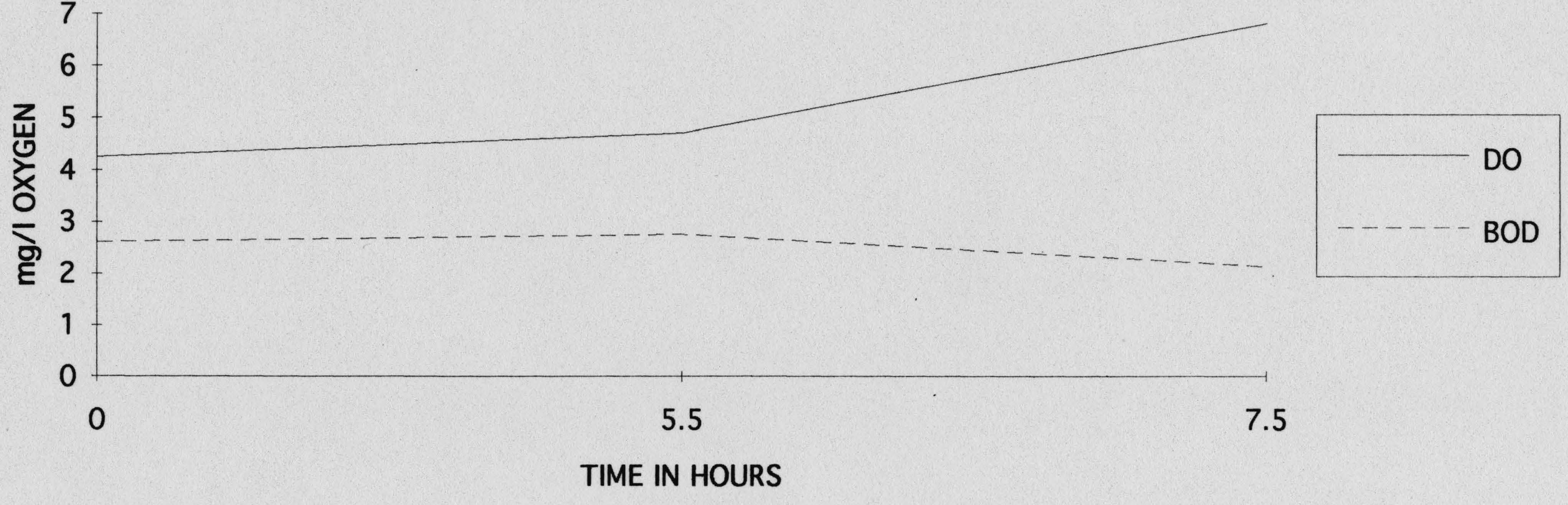


FIGURE 5.8 - EXPERIMENT #3 DO & BOD

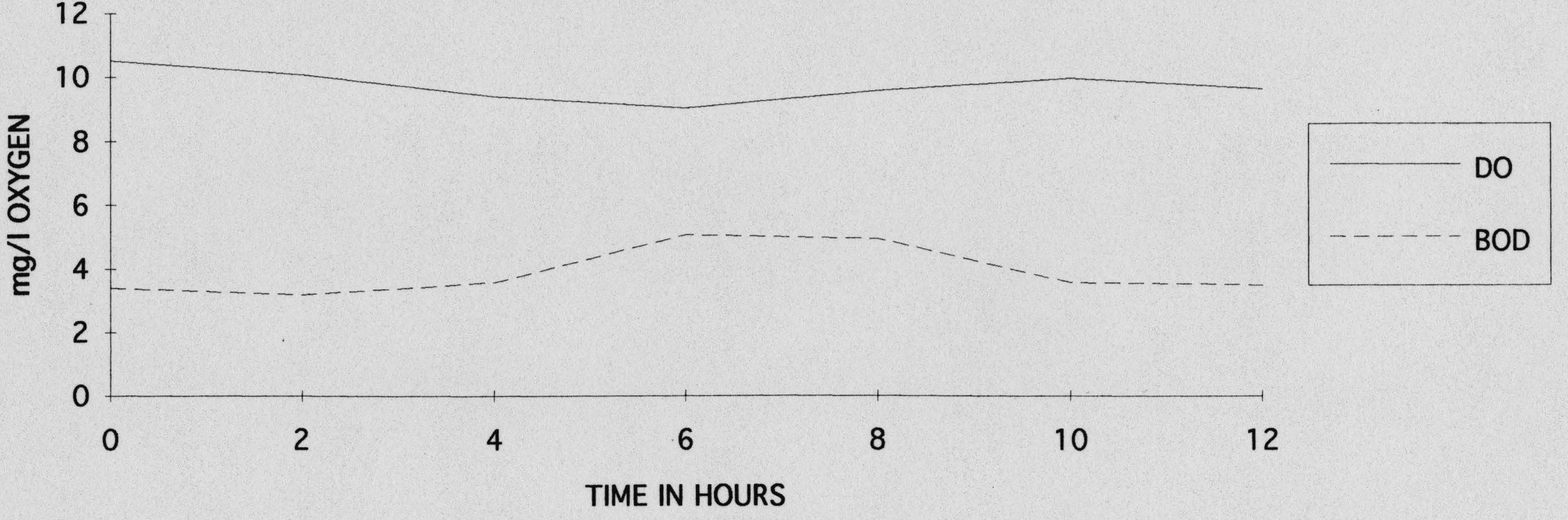


FIGURE 5.7 - EXPERIMENT #2 DO & BOD

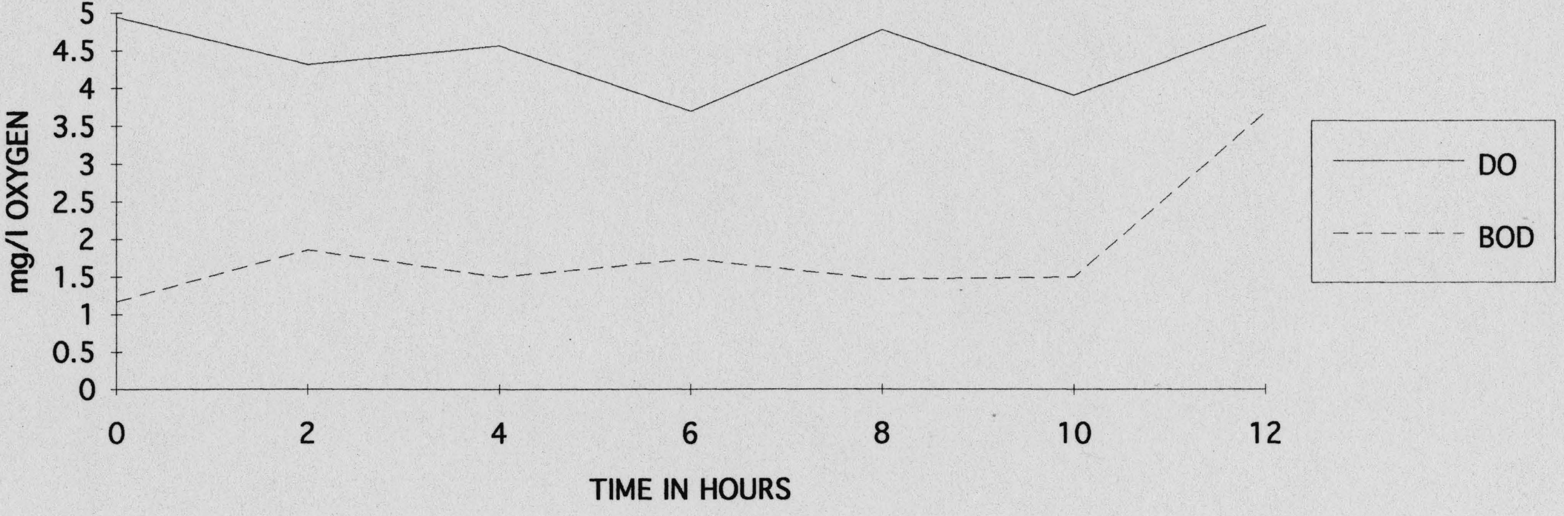


FIGURE 5.9 - EXPERIMENT #4 DO & BOD

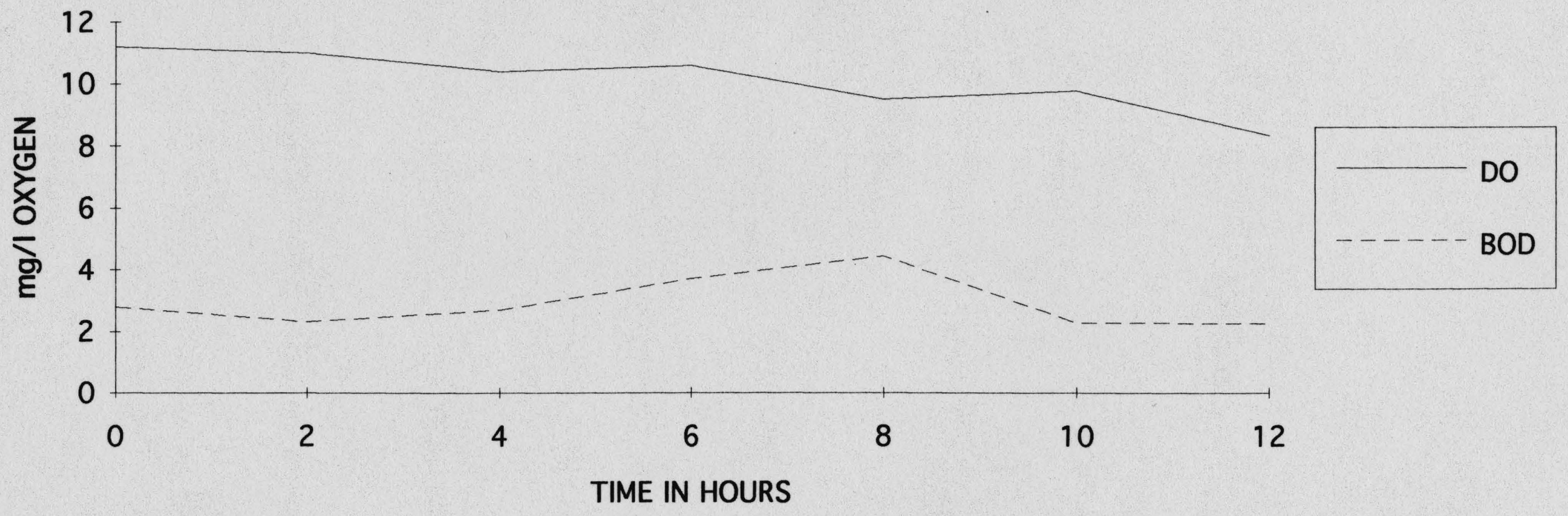


FIGURE 5.10 - EXPERIMENT #5 DO & BOD

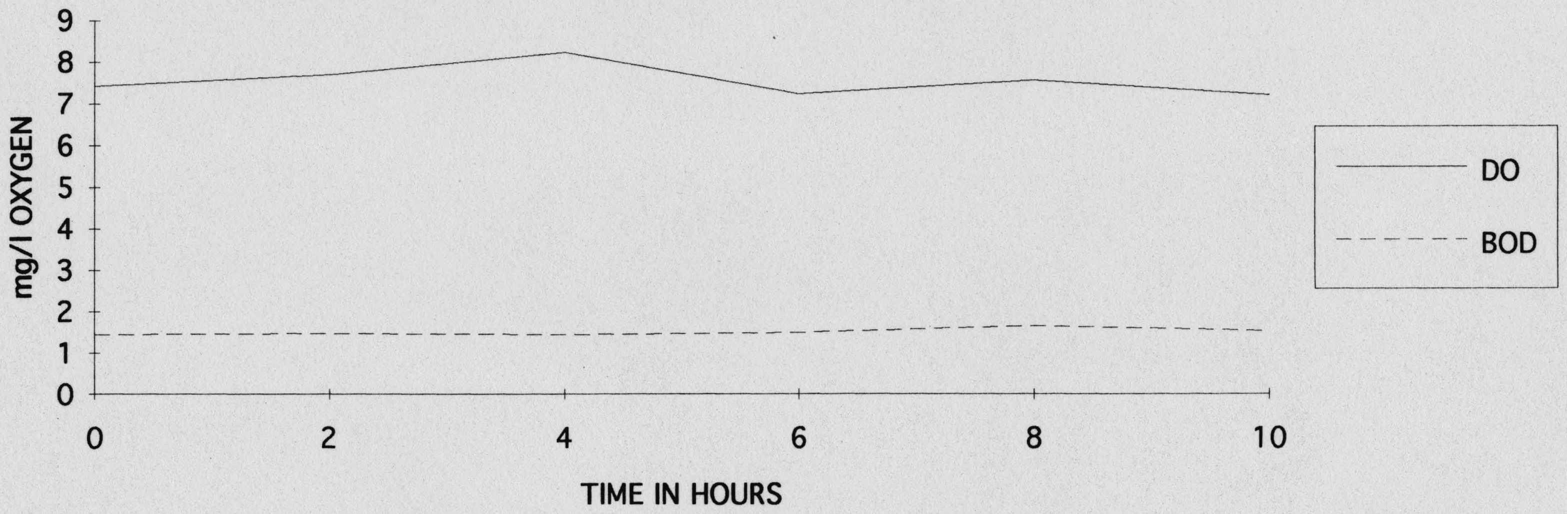


FIGURE 5.11 - EXPERIMENT COD COMPARISONS

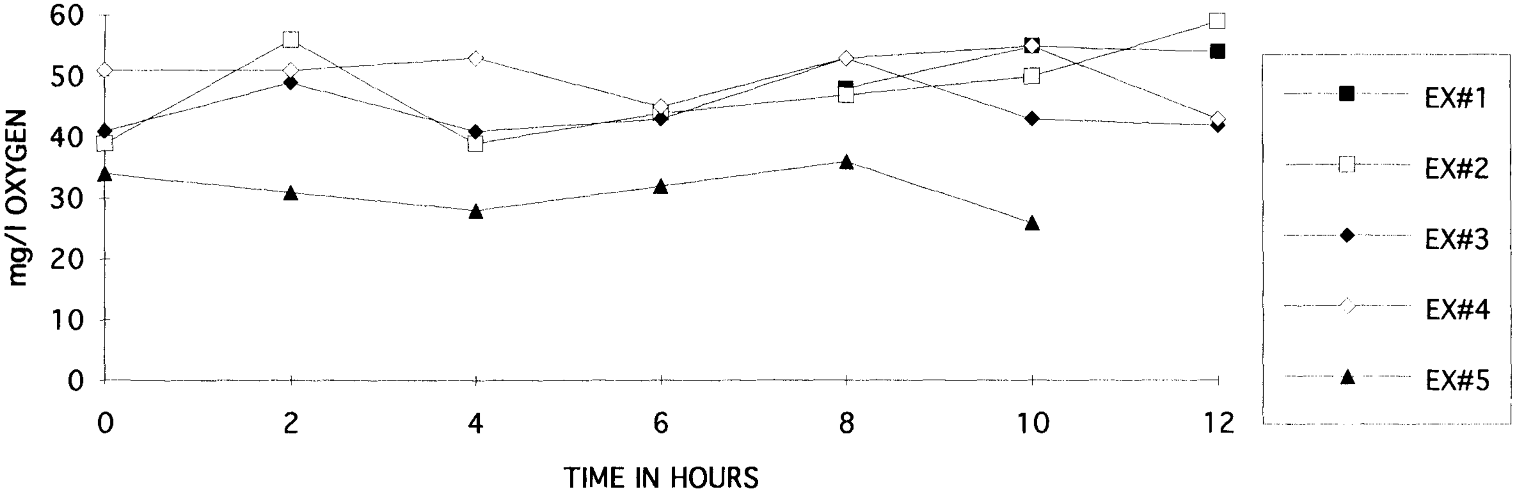


FIGURE 5.12 - EXPERIMENT pH COMPARISONS

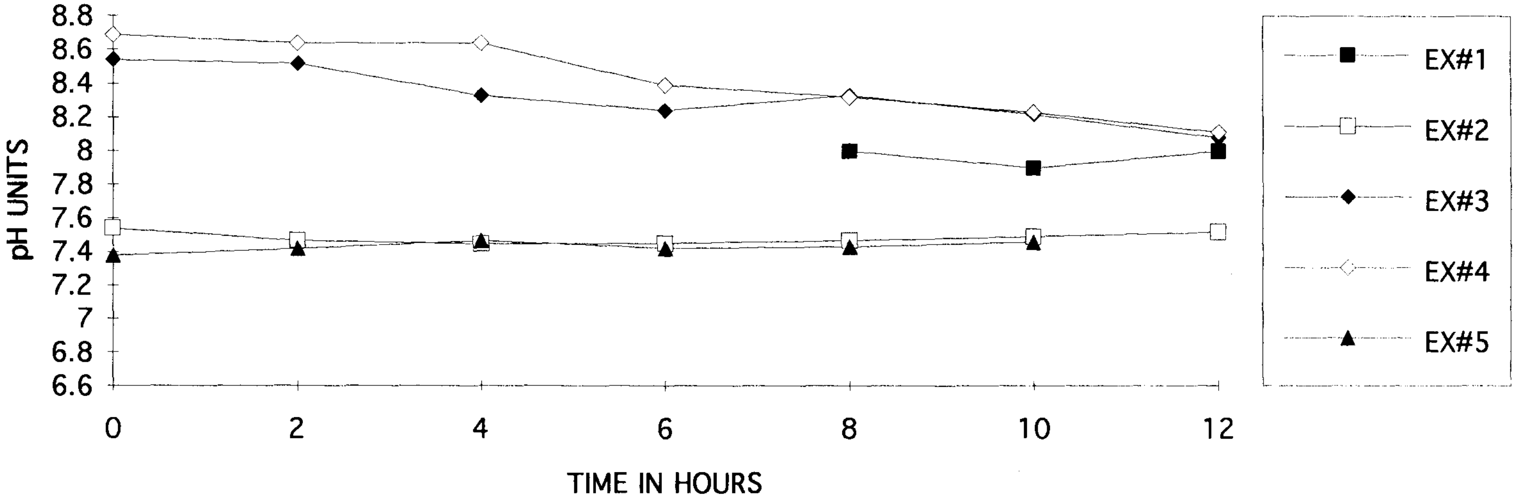


FIGURE 5.13 - EXPERIMENT #1 LOG(TS-TB) & TIME

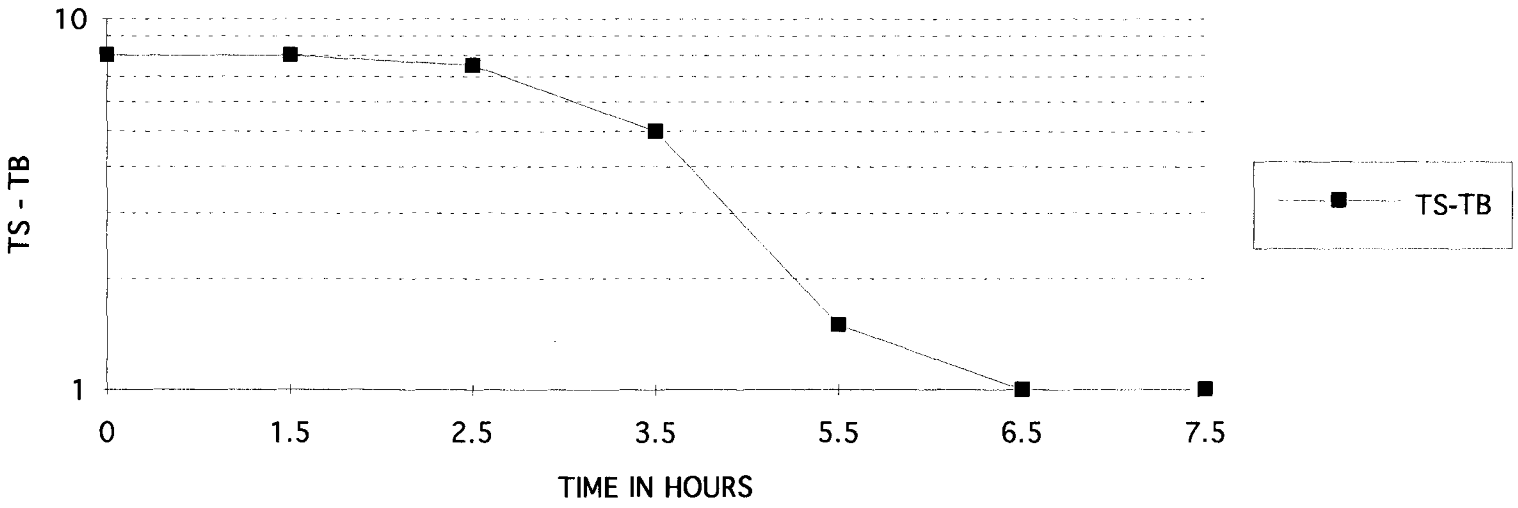


FIGURE 5.14 - EXPERIMENT #2 LOG(TS-TB) & TIME

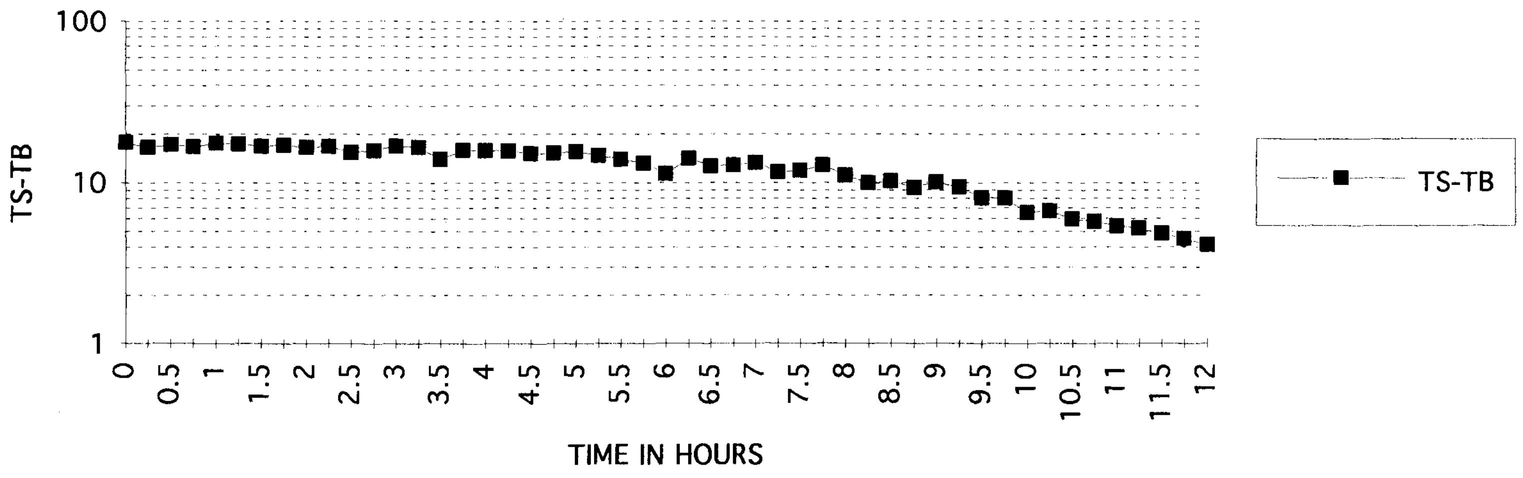


FIGURE 5.15 - EXPERIMENT #3 LOG(TS-TB) & TIME

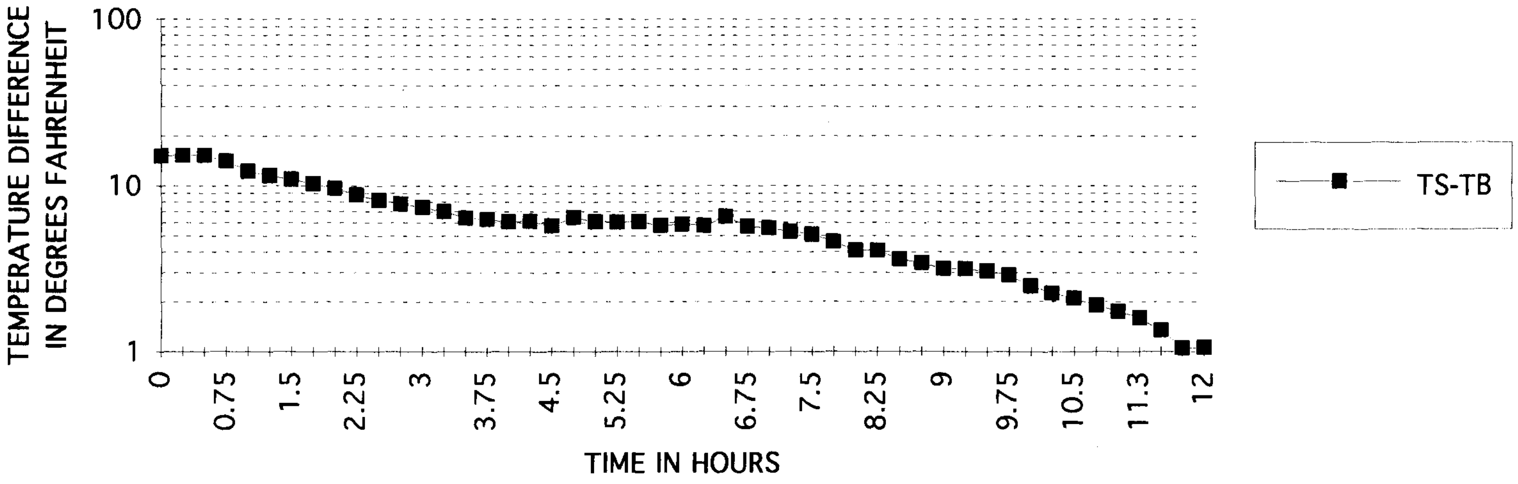


FIGURE 5.16 - EXPERIMENT #4 LOG(TS-TB) & TIME

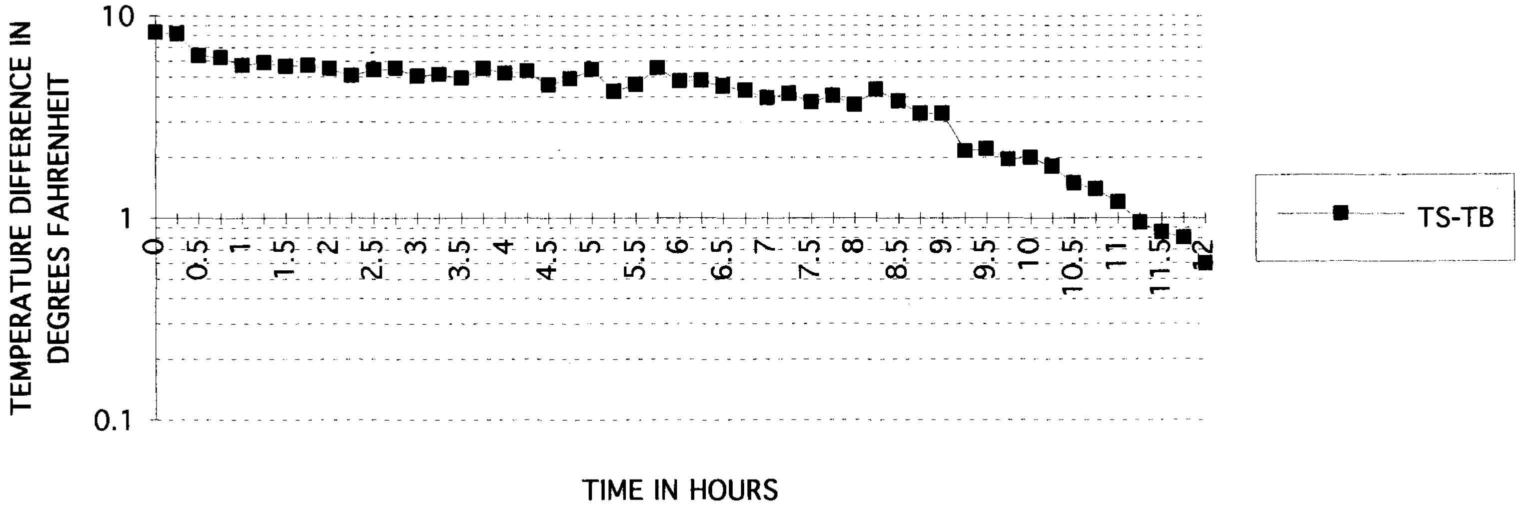
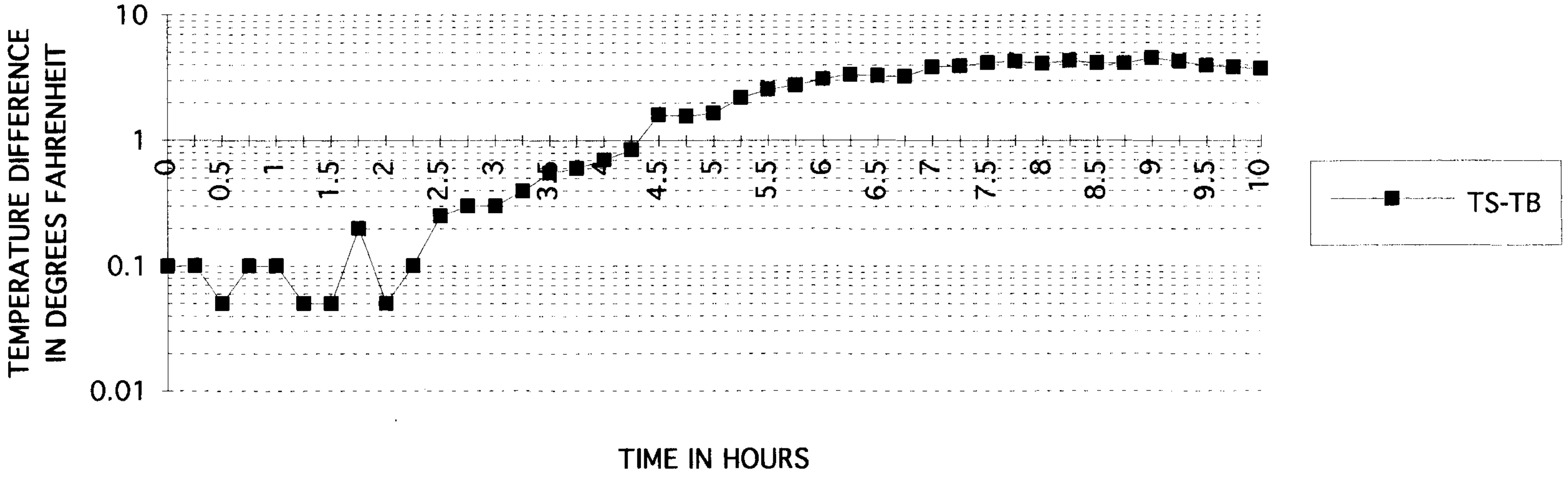
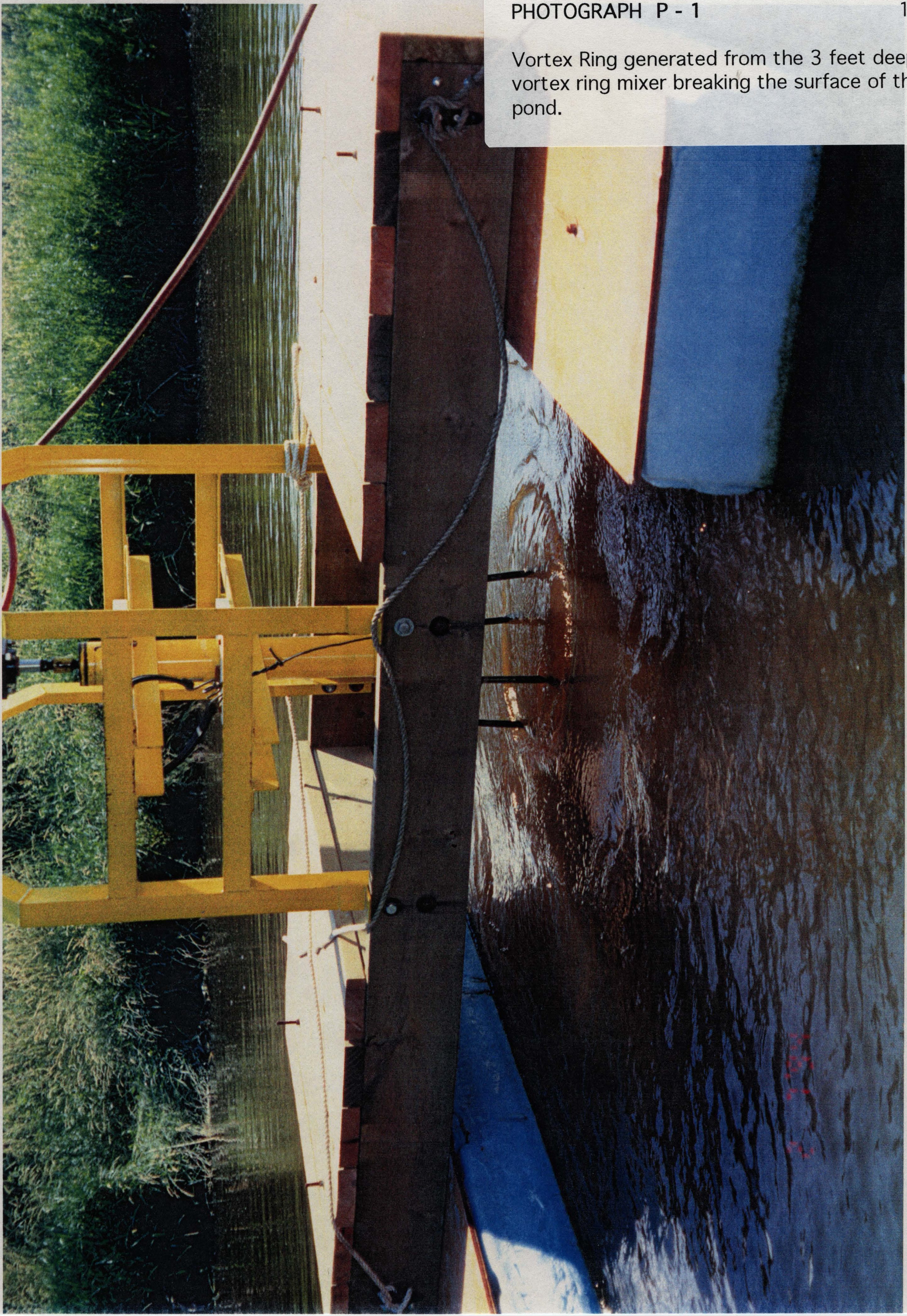


FIGURE 5.17 - EXPERIMENT #5 LOG(TS-TB) & TIME



PHOTOGRAPH P - 1

Vortex Ring generated from the 3 feet deep vortex ring mixer breaking the surface of the pond.



CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions:

The data obtained during experiments with these plate type vortex ring mixers showed that they performed well for mixing a natural water body. The configuration that allows the vortex ring generator to float in the centre of a water body is advantageous because it allows the mixer to be positioned in the best location for mixing and aeration. The position of the vortex plate also important. It can be concluded from these experiments that the 7 foot deep placement of the vortex ring generator plate provided the best mixing while aerating the pond. The location of the generator at 3 feet aerated the pond the best of the three locations while adequately mixing the water. The 5 foot deep placement of the vortex ring plate was a compromise between mixing and aerating that appears not well suited for either mixing or aeration. The desired application of a floating vortex ring generator in a pond should therefore be selected based on the need for mixing or aerating with a compromise being avoided if possible, since neither goal is adequately satisfied.

The dual plate vortex ring generator has potential even though the mixer used was too small to adequately mix the pond. There is great potential for the dual plate mixer to shoot a vortex ring to the bottom of the pond to mix the water while at the same time directing a vortex ring upward to break the surface of the water and increase contact with the atmospheric air to aerate the pond. It would appear that the unit used, although exhibiting a desirable pattern of fluid movement, was inadequate for the size of test pond used. Obviously, a larger unit should be constructed and tested in the pond.

The simplicity of operation and the low power consumption per unit of oxygen transferred should be appealing for future applications. Data in the literature indicates that air powered propeller type mixers have power densities in excess of $1000 W/m^3$. The single plate vortex ring mixers used in the experiments had a power consumption of $0.26 W/m^3$ which is several orders of magnitude less than comparable propeller mixers. The overall oxygen transfer rate for the vortex ring mixer set-up was poor compared with aerators specifically designed to transfer oxygen into waste water. These aerators typically transfer 1 to 3 kgO_2/kWh compared to $0.0336 kgO_2/kWh$ for the single plate vortex ring mixer located at a depth of 3 feet. This is not surprising since the vortex ring mixers are specifically mixers and not aerators. The long term desire was to keep substandard natural water bodies destratified. When this is achieved the renewed water contact with the atmospheric air will transfer oxygen thus aerating the entire water body.

The aeration of a natural water body has been shown to be realized through mixing and should open up new applications for the vortex ring generator. The formation of defined vortex rings that travel great distances in a natural water body is a desirable method to mix a water body as well as maintain the degree of mixing required over time. Mixing the natural water body increases water contact with the atmospheric air and therefore oxygen transfer to the water. The vortex ring generator appears ideally suited to mixing large natural water bodies which will destratify and thereby aerate. The low power consumption of the vortex ring mixers allows long term operation to destratify low quality bodies of water. By keeping the water destratified the oxygen content of the water will increase allowing for improved aquatic life and thus rejuvenation.

6.2 Recommendation

It is important that a more efficient drive cylinder and controller be used. A more responsive drive cylinder during the up and down stroke would provide more energetic vortex rings. Aeration could be improved by perhaps using two vortex ring generators or a suitably sized dual plate vortex ring generator. One plate could fire a strong vortex ring that would cause significant splashing such that bubbles would form in air and collect oxygen before falling back into the water. This would allow for faster aeration while maintaining mixing and thus destratification of the pond. However, long term tests over a year or so would even out the effects of air temperature and other factors. A slow speed vortex ring mixer operated continuously may be sufficient for this type of pond.

Larger or irregular water bodies could be mixed and aerated by several floating vortex ring generators strategically located through out the water body. Computer control could also increase or decrease mixing depending on the need to aerate or destratify the water. The computer would continuously monitor temperature to measure mixing as well as monitor a dedicated oxygen meter allowing constant monitoring of DO levels. The low power consumption requirements of the mixers would allow several mixers to be placed in a water body to initially destratify and aerate after which some could be removed or turned down to economically maintain mixing over long periods of time. This would allow for short term water remediation and also long term water quality maintenance. Considering the increased demands placed on natural water courses as population increases, the vortex ring mixer is well suited to reverse the inevitable water quality deterioration that accompanies the increased waste water and water pollution with human habitation.

The mixing and destratification of a natural water body is complex because of heat flows at the contact between water and earth and water and atmospheric air. The heat flows due to sunlight reflecting off the water surface and wind effects also play a significant role. A suggestion may be to construct a scale model for laboratory tests to see what can be achieved under ideal conditions such as constant temperature, no wind, no sunshine, etc. Other recommendations include conducting tests without any agitation or aeration to determine a base case for the water body so that after agitation it may be easier to see what effect, if any, occurred.

Obviously, any further experiments of this nature would require a very careful analysis of this data and the actual pond conditions. Many factors affect the results of this investigation such as residual BOD and COD, and the biological activity in both the sediment and the water. These conditions will affect the environmental conditions of the pond and impact any further investigation. It is recommended that further research be conducted with emphasis on improved observation of water body destratification and homogeneity through measurement of turbidity and an increased number of temperature probes. Longer duration trials are also recommended and should include numerous sampling for DO, BOD and COD measurement.

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