A Passive Solar-Thermal Aeration System for Rural Pond Aquaculture

by

Ahmed H. Mahmoud

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Department of Mechanical and Industrial Engineering
University of Toronto

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2016

Abstract

Dissolved oxygen is one of the most critical aspects of water quality in a fish culture system. For small-scale aquaculture farmers in resource-constrained communities, aeration systems – which introduce oxygen to pond water – are out of reach due to their high capital cost and lack of access to electricity. This thesis presents an alternative, passive, affordable, aerator concept to meet the needs of those farmers. Using a solar-thermal collector and heat conductor, the device induces convective circulation in the pond, thereby producing an even dissolved oxygen distribution. In order to evaluate this concept, a tool to predict temperature and dissolved oxygen profiles in a water column was developed, along with CFD simulations of the device. Using results from those simulations, prototypes of the device were designed, constructed and tested in Vietnam and Bangladesh. Field trials of those prototypes showed a dissolved oxygen improvement of 18% near the device.

Thesis Supervisor: Amy M. Bilton
Title: Assistant Professor
Acknowledgements

I would like to extend my sincerest gratitude to all the people who contributed to the work described in this thesis. First and foremost, I thank my academic advisor, Professor Amy M. Bilton, for welcoming me into her lab as her first MASc student and for guiding me through the two years it took to complete thesis. Before I reached out to Professor Bilton, I had suffered from bouts of anxiety brought about by my concerns about my career direction and my future, but after having embarked on this thesis under her auspices, I feel more optimistic about my future prospects than I ever have been. During the course of my thesis, not only did she reward me with the intellectual freedom to explore my research directions, she always provided technical and moral support when progress seemed to grind a halt. Her high standards and expectations pushed me to improve myself both inside and outside of Academia. I am also extremely grateful for her willingness to entrust me to attend the IEEE Global Humanitarian Technology Conference in Seattle to personally present my work to other researchers in the field. It was an opportunity not many graduate students get and one from which I have benefited immensely.

I would also like to thank Tuan Quang and Hai Ta Doan with the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) for their contributions to this project; their diligent effort and cooperation from the data gathering phase to implementation and beyond cannot be overstated. In addition, I received a lot of technical and moral support from Elan Pavlov and Matthew Comstock, for which I am extremely thankful.

Finally, I would like to thank Grand Challenges Canada, the United States Agency for International Development (USAID), and the Powering Agriculture committee of donors for financially supporting this project. Without their backing, this project would not have been possible.
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Nomenclature

\( A \) Air-water interfacial surface area \((m^2)\)
\( D_{O_2-H_2O} \) Diffusivity of oxygen in water \((m^2/s)\)
\( \nabla c_{O_2} \) Concentration gradient of oxygen across the air-water interface \((mol/m^4)\)
\( DO \) Dissolved oxygen at a specified depth \((mg/L)\)
\( DO_d \) Dissolved oxygen deficit \((mg/L)\)
\( C_s \) Dissolved oxygen concentration at saturation \((mg/L)\)
\( C_{s20} \) Measured dissolved oxygen concentration \((mg/L)\)
\( SOTR \) Standard Oxygen Transfer Rate \((kg_{O_2}/h)\)
\( OTR \) Oxygen Transfer Rate \((kg_{O_2}/h)\)
\( K_L \) Equivalent to OTR
\( C_{s20} \) Dissolved oxygen concentration at saturation and 20 °C \((mg/L)\)
\( V \) Pond volume \((L)\)
\( A \) Pond surface area \((m^2)\)
\( SAE \) Standard Aerator Efficiency \((kg_{O_2}/kW/h)\)
\( P \) Brake power of a given aerator \((kW)\)
\( C_p \) Dissolved oxygen concentration of the pond water at the surface \((mg/L)\)
\( T(z,t) \) Water Temperature as a function of depth \(z\) and time \(t\) \((^\circ C)\)
\( K_z \) Turbulent diffusivity coefficient \((m^2/s)\)
\( \rho_w \) Water density \((kg/m^3)\)
\( c_p \) Specific heat of water \((J/kg\cdot ^\circ C)\)
\( \phi(z,t) \) Internal distribution of heat in a water column \((J/m^2.s)\)
\( E_e \) Incident solar irradiance \((J/m^2.s)\)
\( \eta \) Light extinction coefficient \((m^{-1})\)
\( R_s \) Reflectivity of a smooth water surface
\( R \) Reflectivity of a water surface adjusted for surface roughness
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>Solar altitude angle (rad)</td>
</tr>
<tr>
<td>$W_z$</td>
<td>Wind speed as a function of height above the water surface ($m/s$)</td>
</tr>
<tr>
<td>$r$</td>
<td>Water surface reflectance to longwave radiation</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant ($J/m^2 \cdot s \cdot °K^4$)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>Absolute temperature of the air at the water surface ($°K$)</td>
</tr>
<tr>
<td>$\epsilon_a$</td>
<td>Emissivity of air</td>
</tr>
<tr>
<td>$\epsilon_w$</td>
<td>Emissivity of the water surface</td>
</tr>
<tr>
<td>$C_{cloud}$</td>
<td>Cloud cover fraction</td>
</tr>
<tr>
<td>$e_s$</td>
<td>Saturated vapor pressure at the water surface ($Pa$)</td>
</tr>
<tr>
<td>$e_a$</td>
<td>Saturated vapor pressure above the water surface ($Pa$)</td>
</tr>
<tr>
<td>RH</td>
<td>Relative humidity</td>
</tr>
<tr>
<td>$Ri$</td>
<td>Richardson Number</td>
</tr>
<tr>
<td>$\alpha_v$</td>
<td>Volumetric coefficient of expansion of water ($°K^{-1}$)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Equivalent to $\alpha_v$</td>
</tr>
<tr>
<td>$CV$</td>
<td>Control volume</td>
</tr>
<tr>
<td>$P$</td>
<td>Instantaneous rate of photosynthetic oxygen production in the pond ($mg_{O_2}/m^2 \cdot hr$)</td>
</tr>
<tr>
<td>$P_{max}$</td>
<td>Maximum photosynthetic production rate ($mg_{O_2}/mg_{chl-a} \cdot hr$)</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically Active Radiation</td>
</tr>
<tr>
<td>$I$</td>
<td>Instantaneous PAR ($\mu mol/m^2 \cdot s$)</td>
</tr>
<tr>
<td>$I_{sat}$</td>
<td>PAR intensity at which light saturation occurs ($\mu mol/m^2 \cdot s$)</td>
</tr>
<tr>
<td>$k$</td>
<td>Molecular diffusivity of oxygen between air and water ($m/hr$)</td>
</tr>
<tr>
<td>$O_{2,sat}$</td>
<td>Dissolved oxygen concentration at atmospheric equilibrium ($mg/m^3$)</td>
</tr>
<tr>
<td>$z$</td>
<td>Mixed layer depth ($m$)</td>
</tr>
<tr>
<td>$chl - a$</td>
<td>Concentration of chlorophyll-a in the pond ($mg_{chl-a}/m^3$)</td>
</tr>
<tr>
<td>WCR</td>
<td>Water column respiration</td>
</tr>
<tr>
<td>$R_{20}$</td>
<td>Instantaneous rate of WCR in the pond measured at 20 °C ($mg_{O_2}/m^2 \cdot hr$)</td>
</tr>
<tr>
<td>$S_{20}$</td>
<td>Known sediment oxygen demand at 20 °C ($mg/m^2/h$)</td>
</tr>
</tbody>
</table>
Grashof Number

Rayleigh Number

Incident heat flux on a surface ($W/m^2$)

Coefficient of dynamic viscosity ($Pa.s$)

Thermal diffusivity of water ($m^2/s$)

Thermal conductivity of water ($W/m.K$)
Chapter 1

Introduction

1.1 Motivation and Contributions

Aquaculture is the fastest growing food production sector in the world, having expanded at an average annual pace of 8.7% since 1970 (see Figure 1-1). With over 800 million people around the world classified by the United Nations Food and Agriculture Organization (FAO) as chronically malnourished, aquaculture is seen as playing a critical role in providing dietary protein for those millions of people while safeguarding the planet’s natural resources for future generations [1]. This role is further accentuated by the decline in capture fisheries which have become increasingly unsustainable due to overfishing. Today, almost 42% of the world’s fisheries production comes from marine and inland aquaculture, and it is speculated that aquaculture will overtake wild capture as early as 2020. Furthermore, an ecological Life Cycle Analysis (LCA) study comparing the environmental impacts of aquaculture and wild capture found that the former consumes less than half the amount of energy required per unit weight of fish produced and imparts substantially less environmental damage on the land it uses [2].

In the Asia-Pacific region, where the vast majority of aquaculture production originates, over 18 million people engage in fish farming [1] and almost 90% of them are classified by the FAO as small-scale; the vast majority are either individual entrepreneurs or families who manage small, shallow ponds using rudimentary practices and produce a modest amount of fish for their own consumption [3]. Millions more not
recorded in official statistics partake in seasonal or occasional fish farming activities such as pond landscaping and harvesting [4]. Those people typically live in remote rural areas where there are few other sources of alternative income and employment offering significant potential to contribute to their livelihood. As such, aquaculture is recognized by national governments and advocacy organizations as an important component of rural development strategies aimed at improving food security for low-income farming households in the region [5]. Most homestead ponds in those rural areas are typically 1.5 m to 3 m deep, with surface areas ranging from 59 m² to 300 m² [6]. Unfortunately, those ponds typically suffer from poor water quality due to mismanagement and financial constraints, leading to low fish stocking densities and yields. Unless a viable, affordable solution to this issue is found, current growth aquaculture growth rates may become unsustainable and future production targets may not be met.

Due to its influence on fish metabolic processes, the amount of dissolved oxygen in pond water is considered to be one of the most important aspects of water quality management in aquaculture, and having poor dissolved oxygen levels in a pond can severely stunt the growth of fish and therefore negatively impact the farmer’s income. This issue may be remedied by using pond aerators which introduce oxygen to the
water either continuously or an emergency basis. According to a survey of carried out by NISTPASS in Bac Ninh, Vietnam on behalf of the University of Toronto, use of aeration is typically prevalent among intensive and semi-intensive fish farmers (See Table 1.1). Nevertheless, for small scale farmers, aerators are out of reach due to their burdensome capital cost, lack of access to reliable electricity, and ongoing maintenance expenses [7]. For those who can afford aerators, however, the investment can be very lucrative. A 1995 study in China found that ponds with aeration systems achieve 47% higher yields than similar ponds without aeration [8].

Table 1.1: Results of a Survey of Intensive and Semi-intensive Fish Farm Operators in Bac Ninh, Vietnam

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Respondents</td>
<td>62</td>
</tr>
<tr>
<td>Average Pond Size (acres)</td>
<td>2.65</td>
</tr>
<tr>
<td>Percentage of ponds which use aeration (%)</td>
<td>76</td>
</tr>
<tr>
<td>Of Which:</td>
<td></td>
</tr>
<tr>
<td>Paddle Wheel (%)</td>
<td>53</td>
</tr>
<tr>
<td>Air Diffuser (%)</td>
<td>20</td>
</tr>
<tr>
<td>Propeller-Aspirator (%)</td>
<td>25</td>
</tr>
<tr>
<td>Other (%)</td>
<td>2</td>
</tr>
</tbody>
</table>

There is a need, then, for an aeration system which impoverished smallholder fish farmers could afford and which can improve their ponds’ productivity. In countries like Vietnam and Bangladesh, where the majority of fish ponds remains small-scale and aquaculture accounts for over 5% of GDP [9], the economic benefits could be very large. This thesis presents a concept for a device to fulfill this need: A novel, simple aeration device which utilizes solar radiation to create convective circulation in the pond, thereby mixing dissolved oxygen across the depth of the water column. The device is inexpensive compared to traditional aeration methods, is easy to maintain, and requires no electricity, making it suitable for millions of subsistence farmers in remote, impoverished areas. A graphical rendering of this propose device is shown in Figure 1-2.
This thesis represents the first evaluation of this new concept. As such, there is a need to develop a framework to assess the impact of the device on dissolved oxygen in aquaculture ponds. The main contributions of this project include the formulation of the conceptual design for the device, creating predictive models for vertical stratification effects in fish ponds, developing a framework for CFD simulations for convective flows in ponds, mechanical design and construction of prototypes for the device, and characterization of the device’s performance after 2 months of operation in Bac Ninh, Vietnam and Srimangal, Bangladesh.

1.2 Thesis Outline

First, Chapter 2 presents a review of topics in the literature that aided in the conceptual development of the device is discussed. This includes a historical and contemporary account of aquaculture in Southeast Asia, an overview of aeration, its prevalence - or lack thereof - among smallholder aquaculture practitioners in remote areas, and
its benefits to fish growth and farmer income. Next, the phenomena of thermal and dissolved oxygen stratification are explained in detail, followed by an examination of existing aeration technologies in the targeted countries of Bangladesh and Vietnam; the goal will be to lay the groundwork for a device that can be competitive with those existing technologies.

Next, a conceptual description of the proposed aeration device is provided in Chapter 3, followed by an overview of the the numerical models developed for this thesis. Those models, which include diel thermal and dissolved oxygen stratification algorithms and CFD simulations, are coupled to provide a tool that can predict the circulation performance of the proposed device.

Finally, fabrication, installation and testing of two prototypes of the system was carried out. An outline of the mechanical design factors and decisions that informed those final designs is provided in Chapter 4, including the rationale for using a glazed solar collector for the absorber and the use of welding to join the absorber to the heat conduction element. Finally, the results from the field trial are discussed, which include the use of a statistical tool to assess the significance of dissolved oxygen improvement imparted by the device.
Chapter 2

Background and Literature Review

2.1 Overview of Aquaculture in Southeast Asia

2.1.1 History

Aquaculture refers to the breeding, rearing and harvesting of aquatic plants or animals in controlled environments such as ponds, tanks or cages. Its widespread practice is relatively modern, having developed in most countries just 30-70 years ago as per-capita availability of wild fish declined [10]. Nevertheless, its roots can be traced as far back as 4,000 B.C.E to China, where inland fish farming developed alongside agriculture as an integral part of its traditional rural-agrarian economy [11]. Historians speculate that the technique of placing fish in ponds was started by fishermen stocking their surplus catch in dammed river beds, and the idea of culturing fish arose from fishermen realizing they could feed and grow the fish in their holding areas [12]. From there, the practice spread to the Red River Delta in Vietnam and Java in Indonesia where limited land for rice cultivation and the lack of wild fish led to early adoption of fish culture. As time passed, aquaculture grew more sophisticated and farmers adopted techniques such as polyculture, whereby different fish species which live at different depths in the water are harmoniously cultivated together, and paddy aquaculture, in which fish are introduced and grown in flooded rice fields to optimize land use and boost productivity. In addition, farmers began integrating aquaculture with
agriculture and husbandry, thereby reducing the incremental costs of maintaining fish ponds.

The combination of these traditional practices are seen today as the cornerstones of modern aquaculture, and they continue to be used by fish farmers across Southeast Asia today, especially by extensive, rural farmers. These traditional practices had been sufficient to satisfy the needs of a simple, rural-agrarian mode of life. However, as governments around the world - particularly in low-income countries in Southeast Asia, where over 75% of aquaculture yields are produced [13] - prioritize further development and intensification of aquaculture as a means of improving food security and alleviating poverty, the need for new, novel, appropriate technology to improve the productivity of fish ponds becomes imperative in order to ensure the sector’s viability and sustainability.

### 2.1.2 Rural Pond Aquaculture in Southeast Asia

Broadly, aquaculture systems may be classified according to their level of intensification, with three categories commonly used by the aquaculture researchers: extensive (also known as traditional or household-scale), semi-intensive, and intensive. Table 2.1 highlights the metrics used to differentiate between each category, with the most important distinguishing factor being stocking density. As shown in the table, extensive aquaculture relies only on the natural nutrients available in the source water to support the aquatic crop being farmed; it is identical to the way natural lakes and reservoirs support a base level of aquatic life. Through different levels of intervention - including methods such as fertilization and supplemental feeding - stocking densities higher than those permitted by natural ecological conditions may be achieved; this constitutes ‘intensification’. Typically, only intensive farmers employ some form of aeration, while semi-intensive and extensive fish farmers are forced to scale back on their stocking density and, as a result, compromise on productivity. This thesis will focus primarily on extensive and semi-intensive small holder farmers who would benefit the most from an appropriate, affordable aeration system that would allow for sustainable intensification of their ponds - that is, greater crop production from
the same pond stocking area. A photograph of a characteristic small-scale extensive pond is shown in Figure 2-1.

![Figure 2-1: Rural Aquaculture in Bangladesh [1]](image)

In rural Southeast Asia, where a handful of countries are responsible for the majority of fish production, a large variety aquatic organisms - including fish, molluscs, crustaceans, and other minor invertebrates - are farmed using a number of diverse methods. Those methods depend largely on geographic location and access to resources, and they include [14]:

- Land-based systems (rainfed ponds and irrigated or flow-through systems)
- Integrated farming systems (livestock-fish, agriculture and fish dual use aquaculture and irrigation ponds)
- Water-based systems (cages and pens, inshore/offshore).
- Recycling systems (high control enclosed systems, more open pond based recirculation).

Of those, the top two methods are the most commonly used by rural, small holder farmers, and since the most common setting for land-based and integrated farming systems is an excavated or naturally-occurring inland pond, the practice is known as
**pond aquaculture.** Due to its low-cost and accessibility for many remote-dwellers, it is the most common form of aquaculture worldwide, comprising over 75% of total farmed fish production [15].

Table 2.1: Classification of Aquaculture Systems by Farming Intensiveness [16] [15]

<table>
<thead>
<tr>
<th>Type</th>
<th>Water Quality Management</th>
<th>Stocking Density (kg/ha)</th>
<th>Yield (t/ha/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extensive</td>
<td>Low quality manure or macrophytes</td>
<td>&lt;1,000</td>
<td>0 - 1</td>
</tr>
<tr>
<td>Semi-Intensive</td>
<td>High quality manure and/or pellets</td>
<td>1,000 - 5,000</td>
<td>1 - 15</td>
</tr>
<tr>
<td>Intensive</td>
<td>Pellets, aeration and recirculation</td>
<td>&gt;5,000</td>
<td>15 - 50</td>
</tr>
</tbody>
</table>

When considering a pond to be used for fish culture, a farmer must ensure that the pond has access to good quality water and a non-porous clay soil bottom so as to avoid leaching of nutrients or leakage to the water table; in cases where the ground is extremely porous, a polyethylene or nylon liner may be used to achieve the same goal [15]. In reality, however, most small holder farmers do not have control over the type or quality of soil bottom and do not intervene to change its properties. Those that do understand the need for minimizing soil porosity carry out soil compaction by draining the pond at the end of the season and allowing livestock to walk about on the foundation of the pond [17]. The pond bottom should be tilted at a 4:1 slope to facilitate draining of the pond at the end of the harvesting season; this is necessary to rid the pond of any containments that built up during the grow-out period. For small scale farmers, pond drainage is not common practice, even at the end of the season. Rather, the pond is rain- or river- fed and is allowed to overflow or evaporate. This results in deterioration of pond water quality with time. Finally, ponds are typically 1-2 meters deep and are square or rectangular in shape, though the latter is often preferred by farmers since it reduces the width of the seine needed to harvest the pond. Sizes vary widely depending on the level of intensification, species being cultured, and
geographical considerations. In Vietnam, extensive ponds are on average 0.5 ha, and in Bangladesh where population density is among the highest in the world, it is only 0.12 ha [17]. A diagram of a typical pond with good water management is shown in Figure 2-2.

![Figure 2-2: Water Management System in a Typical Fish Pond](image)

In semi-intensive or intensive hatcheries, several types of ponds are used for different stages of the cultured species' life cycle. For commonly farmed fish species such as pangas, carp and tilapia, breeding starts in small spawning ponds or net cages where brood fish are allowed to mate. Eggs are then collected from the pond and seeded into a nursery or rearing pond, where they are grown to a predetermined size then transferred to a large grow-out pond where they live for the rest of the harvest period. Fish collection is most often carried out using seine nets dragged across the length of the pond [14].

The conditions in each pond require meticulous attention by the farmer, and the sortation and handling of the fish during each transfer stage and are very labour intensive. Since many small scale farmers lack the resources and technical knowledge to undertake and manage such a complex operation, most purchase broodstock or fingerlings from more sophisticated hatcheries and grow their fish in a single pond. Alternatively, they catch small fish from nearby natural water bodies and use those fish as their crop.

Regardless of what method is used to stock fish ponds, one of the most important determinants of fish pond productivity for any type of farmer is an assured water supply of sufficient quantity and adequate quality. For most rural fish farms in South-
east Asia, the source of water is an irrigation canal, river, creek, reservoir or rainfall runoff. Where irrigation canals are used as the source, water is usually gravity-fed to the pond using feeder channels. These sources of water are typically very nutrient-rich and therefore promote the growth of algae in the pond. In most cases, that is a benefit for the pond since it increases the amount of oxygen available for the fish during the day as there is a greater number of photosynthesizing phytoplankton in the pond, but in thermodynamically stable, stagnant ponds, it causes steep stratification across the water column which limits the dissolved oxygen in the pond to the first foot (or less) of water, thereby reducing the area fish can occupy (See Section 2.4). In addition, during nighttime, as phytoplankton switch to respiration, oxygen levels can drop to critically low levels in highly eutrophic ponds, causing oxygen distress for the fish. In those cases, having an aeration system would be vital to fish farmers who cannot control their water quality due to restrictions on their water source or their inability to afford an aeration system.

2.1.3 Aquaculture in Vietnam and Bangladesh

The experiments carried out for this thesis targeted two countries in Southeast Asia where small-scale aquaculture plays a prominent role in food security and income for rural households, Vietnam and Bangladesh. Within both countries, aquaculture comprises more than 5% of national GDP [9] [18], aeration is not widely used among small-scale fish farmers, and the governments of both countries are committed to promoting and improving the quality of aquaculture among the rural poor.

Bangladesh

Bangladesh is one of the poorest and most densely-populated countries in the world. At least 47 million Bangladeshis live in poverty, and of those, 26 million are in extreme poverty, defined as subsisting on an average of US $1.25 or less a day [19]. While the country has made large strides in improving livelihoods in urban centers - having lifted 16 million out of poverty from 2000 to 2010 - people living in rural
areas continue to suffer from pervasive and extreme hardship. In trying to address rural poverty, governments and NGOs in Bangladesh have turned to aquaculture as a means of meeting the nutritional needs of the rural poor, a fifth of whom are understood to suffer from chronic food insecurity and malnutrition [20]. Those efforts sought to promote small-scale forms of aquaculture, and have been largely successful at improving the nutritional diets of the families they targeted. Today, fish is a natural complement in the diet of most Bangladeshis, supplying almost 60% of each individual’s protein intake [20].

Low-intensity, small-scale fish farming is historically the most common form of aquaculture in Bangladesh, and while semi-intensive and intensive systems have emerged in the past 15 years, the aquaculture landscape is dominated by homestead and small-scale ponds [21]. During the period between 1985 and 2013, aquaculture grew faster than the population and at a rate that was more than twice that of marine and capture fisheries, which now contribute only 45% of Bangladesh’s total annual fish production [22]. Overall, aquaculture constitutes almost 5% of the country’s GDP and assures the livelihoods of over 13 million people. Fish farming is particularly vital to rural families, among whom 73% are involved in the practice [23].

Inland pond culture in Bangladesh may be classified into three subsets: ‘homestead pond culture’, ‘entrepreneurial pond culture’, and ‘commercial semi-intensive carp culture’. It is estimated that each type accounts for approximately 30% of total aquaculture production, with the majority of farming taking place in rural areas. WorldFish estimates that about 4.27 million households (20% of rural inhabitants) operate a homestead pond, covering a combined area of 265,000 ha [21]. A large number of these ponds are *ghers*, dike ponds which are used for prawn farming and are integrated with vegetable farming carried out on the soil dug out to excavate the pond. Those ponds are typically small (0.08 - 0.1 ha), are used for multiples purposes, and very little attention is given to their water quality. Accordingly, they have very low stocking densities and yields. Most interventions to improve the productivity of homestead and entrepreneurial small holder ponds have focused on feed and stocking logistics, but none address aeration. For families practicing aquaculture, the contri-
bution of the practice to household income varies, but it never exceeds 15% [20]. Use of aeration could potentially increase this income ceiling.

Among the barriers to widespread aeration use is social inertia, exhibited by suspicion among fish farmers that aerators are worth their steep investment. Understanding the concerns and social structures in the fish farming community is key to the dissemination of a technology such as aeration, and therefore interfacing with farmers is key to the introduction of an alternative aeration system. Through a number of conversations with farmers in a hatchery in Srimangal, Bangladesh, the following insights were offered as potential reasons for the absence of widespread aeration in Bangladesh:

- **Prohibitive costs** – A small, 1 hp paddle wheel aerator costs approximately 50,000 BDT (630 USD), which is equivalent to over a year and half’s salary of the average Bangladeshi [24]. Among semi-intensive and intensive farmers, oxygen tablets may be used, but those also incur high costs, with each two-week treatment costing 800 BDT (10 USD) for a small pond.

- **Access to electricity** – A 2004 survey study of energy poverty in Bangladesh found that less than a third of 2,388 sampled households in rural Bangladesh have access to grid electricity [25], and those that do have access typically experience multiple outages and rolling blackouts every month, rendering electricity unreliable for time-critical applications such as pond aeration; statistics from the World Bank, displayed in Figure 2-3, found that Bangladeshis expect on average 65 outages per month, five times higher than the average of low income countries. So unreliable is the access to electricity that over half of Small and Medium Enterprises (SMEs) in Bangladesh, including farmers, have been found to own a diesel generator to mitigate the effect of outages on their daily operations [26]. As purchasing those generators incurs a high cost to the farmers, and since running costs are high for the average farmer, little incentive is left to putting aside money to buy a reliable aeration system.

- **Maintenance** – Typically, 6 kW of aeration are required per hectare of pond
being cultured, and while maintenance costs vary, on average, they would be around 5,000 BDT/kW (63 USD/kW). Amortized over its 10 year service life, an aerator would cost about 10,000 BDT/kW/year (127 USD/kW/year), a prohibitive cost for most small-scale farmers [28]. Additionally, since mechanical aeration is virtually absent in Bangladesh, few technicians possess the skills needed to service them, especially in rural areas. Lack of reliability and difficult maintainability are dissuasive for many farmers since aerator failure can result in catastrophic fish kill and a severe drop in productivity. In a survey of shrimp farmers in 20 developing countries, 22% of respondents cited aerators failure as the top cause of mortality in their ponds [29].

**Vietnam**

Aquaculture in Vietnam started on the banks of the Red River delta, where almost 20% of the country’s population lives today. As is the case with Bangladesh, fish culture in Vietnam is a cultural tradition dominated by subsistence-oriented, small-scale freshwater ponds, and the fish it produces constitutes the majority of protein consumed by the country’s population, 80% of whom live in rural areas [30] [17].
The difference is that pond culture systems in Vietnam tend to be integrated with other traditional activities such as rice farming and husbandry. Those ponds are commonly known as VACs, an acronym derived from the Vietnamese words for garden (vuon), pond (ao), and livestock (chuong) [17], and they are typically stocked with carps and fed with low-quality inputs such as farm by-products and human waste. Accordingly, yields from those ponds tend to be poor, and this has adversely affected nutritional standards in those rural areas. While multiple government interventions have been undertaken to increase farmer access to higher-quality pond inputs and technologies, inflation-adjusted fish prices continue to rise in large part due to insufficient supply [31]. This is in spite of a consistent 5-7% annual increase in aquaculture production over the past decade in Vietnam.

In many cases, VACs are operated with a high water flow-through, with inlet trenches connected to up-land ponds or river tributaries. This negates or reduces the need for aeration. Nevertheless, it results in transportation of eroded particles into the pond, increasing its turbidity, or possibly diseases from other ponds which have been observed to result in mass mortalities of grass carp [32]. Additionally, nutrients and feed could be leached out from the pond, resulting in further reduction in productivity. The overall impact is that fish production for many VACs is very low, with yields as low as 1,904 kg/ha, less than half those achieved by slightly better-managed ponds [33] [30]. Nevertheless, they still play a very large role in food and income security for a large number of rural poor communities, and any effort to improve yields for such farmers can have a large ameliorating impact on poverty in those rural communities. Since certain kinds of fish culture can provide per-unit-area incomes up to twice as high as those possible from rice cultivation [34], technological contributions to aquaculture that improve water quality and pond productivity can divert farmer resources toward fish farming as it becomes sustainable and more profitable.

As is the case in Bangladesh, aeration - mechanical or otherwise - is rarely used [18], to the detriment of productivity. While there in no published literature to delineate reasons for their lack of use, a survey carried out by NISTPASS on behalf of the University of Toronto indicates that those reasons are identical to the ones
offered by Bangladeshi farmers. They include: prohibitively high capital costs, lack of access to reliable electricity, the costs of running the aerators for several hours every night, and maintenance concerns. Regarding access to electricity, one farmer complained that it takes several months to register for a grid connection before getting power, and even then, extralegal expenses may have to be arranged to facilitate the transaction. Further, the use of aeration may require hiring additional staff to run and maintain the devices. Therefore, a passive aeration system which requires little operating and maintenance costs could potentially persuade many of the farmers who continue to hold out on investing in a proper aeration system for their pond.

2.2 Water Quality Management in Fish Ponds

2.3 Importance of Water Quality

In the context of aquaculture systems, water quality refers to the various pond attributes that affect the survival, reproduction, growth, and management of cultured aquatic species. As a consequence, it requires a careful understanding by aquaculture practitioners. Knowledge of which factors affect water quality the most, as well as being able to intervene to influence those factors, permits aquaculturalists to improve environmental conditions for fish, avoid stress and parasite related diseases, and ultimately produce larger, healthier crops of fish. Any water body can support a certain amount of aquatic life to some extent, however, for stagnant inland ponds, extreme care must be exercised to ensure water quality does not deviate far from favorable conditions. Further, to overcome the pond’s natural limitations on production, farmers need to understand how they can manipulate water quality by processes such as water exchange and aeration which combat the detriments caused by pond water stagnation.

In aquaculture literature, stocking density, nutrients, salinity, pH, plankton population and, most importantly, dissolved oxygen are often singled out as the most important water quality variables that farmers can directly influence [15]. As this
thesis is concerned primarily with the effects of dissolved oxygen on fish health and growth, the following discussion will focus on the dynamics of dissolved oxygen in aquaculture ponds, as well as aspects of water quality that directly influence pond oxygen levels.

Dissolved oxygen supports all organisms in a fish pond, including phytoplankton, zooplankton, and fish in the water column, as well as benthic bacteria on the pond bed. Among fish, oxygen uptake varies from one species to the next. For example, bottom feeders, crabs, oysters and worms need minimal amounts of oxygen (1-3 mg/L), while shallow water fish need higher levels (4-15 mg/L) [35]. Whichever species are cultured, it is still beneficial for fish farmers to maximize their dissolved oxygen levels since there is a wealth of experimental literature which has shown a positive correlation between dissolved oxygen concentration and fish survival and growth [36] [37] [38].

On a daily basis, the amount of dissolved oxygen in a pond is highest during the day when photosynthesis by phytoplankton is underway - oftentimes far exceeding the saturation limit of the water - and lowest at night when respiration depletes it. This daily variation in dissolved oxygen is known as the diurnal cycle and is discussed in greater length in Sections 2.4 and 2.6. In natural water bodies, the supply of oxygen produced by photosynthesis or diffused from the atmosphere is most often at an ecological equilibrium with the biological oxygen demand in the pond. On the other hand, in an aquaculture pond, the biomass of plants, animals, and microbes is usually much higher than in natural waters, so oxygen is sometimes consumed faster than it is produced. This necessitates the use of aerators, the types and effectiveness of which are explained in Section 2.5.

Water is said to be saturated with dissolved oxygen when the partial pressure of oxygen ($P_{O_2}$) in the water is equal to that in the surrounding air. The concentration of oxygen, typically reported in units of $mg/L$, under saturation conditions is denoted by $C_S$. For freshwater, there are multiple factors that affect this saturation level. Among those, the most important factors are:
**Temperature**

Warm water holds less dissolved oxygen than cool water since the solubility of oxygen decreases with increasing temperature. Many attempts have been made to find a mathematical correlation between temperature and dissolved oxygen concentration at saturation. One of the most widely-used formulations is that of Benson and Krause, which is given by [39]:

\[
C_S = 1.43 \exp \left( -173.43 + 249.63 \left( \frac{100}{T} \right) + 143.35 \ln \left( \frac{T}{100} \right) - 21.85 \left( \frac{T}{100} \right) \right)
\]  

(2.1)

where \( T \) is the water temperature (°C).

In addition to reducing the thermodynamic capacity for dissolved oxygen uptake by the water, increasing temperature accelerates respiration rates of fish and other organisms, which removes oxygen from the water column. This makes oxygen management in tropical areas, where many small-scale fish farmers reside, particularly challenging.

**Plankton**

Phytoplankton have a very large impact on water quality in any pond. Many fish culture manuals stress that an algal bloom must be maintained to improve oxygen levels, to prevent macrophyte growth, and to provide natural foods, either directly or indirectly, for fish in the pond [15]. At the same time, however, uncontrolled algal growth due to eutrophication or other phenomena can result in blooms which can consume almost all the oxygen in the pond at nighttime, resulting in metabolic distress for the fish, stunted growth or mass fish kills.

The influence of phytoplankton can be seen in the daily fluctuations of dissolved oxygen in pond water. During the day, dissolved oxygen levels rise as phytoplankton undergo photosynthesis in the presence of sunlight, and at night, dissolved oxygen levels decline as they switch to respiration. The bigger the algal bloom, the more pronounced the dissolved oxygen fluctuations will be (See Section 2.4 for more detail.
on diel patterns governing dissolved oxygen dynamics in shallow fish ponds).

Most phytoplankton are single-celled plants that contain chlorophyll-a which they use to capture sunlight. This sunlight is then photosynthesized, along with nutrients and carbon dioxide in the water, to produce oxygen. There are multiple ways to measure the concentration of phytoplankton in pond water. The most accurate method involves centrifugation of a water sample, followed by analysis in a spectrophotometer. The concentration is subsequently reported in units of $\mu$g/L. Another less precise method to qualitatively gauge the density of phytoplankton is by using the Secchi disk, a round 8” half-white, half-black disk which is lowered in the water until it can no longer be seen by the observer; the depth at which the disk disappears is known as the Secchi Disk Depth (SDD). This depth depends in varying amounts on both turbidity and algal density, and no concrete method exists to quantitatively distinguish their effects on the SDD, making it difficult to find a direct correlations between phytoplankton and the SDD. Nevertheless, this measurement may be used to estimate phytoplankton concentration using a number of regression models developed over the years, however the mathematical rigor and versatility of those models are yet to be proven [15] [40] [41].

**Rainfall**

Rainfall plays an important role in rural aquaculture, especially in places such as Bangladesh where it is the only mechanism available to fill ponds. With regards to dissolved oxygen, rain has the effect of cooling the surface of the pond, thereby promoting convective circulation which results in a more even oxygen distribution across the water column. In cases where rainfall is accompanied by high wind speeds, a sudden turnover of pond water may occur. If this takes place on a day when the pond is vertically stratified and average dissolved oxygen levels are low, it may cause severe oxygen distress for the fish.
2.3.1 Benefits of Aeration and Farming Intensification

Among aquaculturists, it is commonly accepted that 1 kW of mechanical aeration with floating, electric paddlewheel aerators will allow 700-800 kg of fish production above that possible in unaerated ponds. This is equivalent to 18-21% of the value of extra production from the pond [28]. It is also understood that fish farming in remote, rural areas without aeration and low rates of water exchange typically produces very low yields (<1,000 kg/ha/yr) [34]. Indeed, there exists extensive literature that supports this common wisdom. One of the most direct studies on the benefits of aeration was one carried out by Teichert-Coddington and Green, in which Nile Tilapia were grown in aerated and non-aerated ponds for a full season with periodic fish weigh-ins. Growth was found to be linear and faster in the aerated treatments but was asymptotic in the non-aerated ponds, showing that lower dissolved oxygen levels due to the lack of aeration dampened growth (Figure 2-4).

![Graph of Nile Tilapia growth](image)

Figure 2-4: Graphic Representation of the Growth of Nile Tilapia [42]. Redrawn from source.

Another study carried out in 1995 in China showed that aerated ponds achieve 47% higher yields than similar ponds without aeration. Moreover, under the same pond management system and ecological circumstances, it was found those ponds
with aeration could be stocked on average 64% more than ponds without aeration [43].

In addition to higher yields, aeration has been found to vastly improve fish survival and general water quality in fish ponds. For example, in one study in Louisiana in 1993, channel catfish were stocked in 14 identical ponds. The effect of five aeration treatments on fish growth, survival, and pond water quality were evaluated. The aeration treatments were: no aeration, short nighttime aeration, long nighttime aeration, twice-daily aeration, and continual aeration. Over a period of three months, various different water quality measurements were taken, including temperature, dissolved oxygen, alkalinity, and chemical oxygen demand, as well as fish weigh-ins. At the end of the study, the average final weight of fish was found to have been significantly affected by aeration; Survival was very low (67%) in unaerated pond compared to the average of the aerated ponds (90%). Furthermore, fish growth in unaerated ponds was 54% lower than the average of the aerated ponds, and algal blooms were inhibited due to the continuous water movement near the water surface [44].

A confirmation study of the Louisiana results was carried out by Qayyum, Ayub, and Tabinda in 2005, wherein fingerlings of Rohu, Mrigal Carp, Silver Carp and Grass Carp were cultured in six brick lined ponds for a period of six months. Three of the six ponds served as aerated ponds and other three as non-aerated ponds. Fish in each pond were fed a 20% protein diet, and the ponds were fertilized with cattle manure and chemical fertilizers in equal amounts. Significantly higher growth rates, dissolved oxygen, and fish survival was observed for every cultured species in aerated ponds as compared to the non-aerated ponds. Indeed, pond aeration resulted in 2095 kg/acre more fish production with a substantially higher economic benefit [45].

Another way to look at the benefits of aeration, especially in the context of the countries under focus for this study - Vietnam and Bangladesh - is to investigate the positive impacts of aquaculture intensification, a phenomenon with which aeration is always associated, as was highlighted in Section 2.1.2. Table 2.2 highlights the results of a study in the Asia-Pacific which compared extensive (homestead) and intensive farming on the measures of stocking density, yield and employment. It was found that,
in both countries, higher yields, stocking densities, and protein output per hectare of cultured area were obtained from intensively farmed ponds as compared to extensive ponds. At the same time, despite the high pond productivity, less labor per hectare was required with intensive ponds than extensive ponds. In Vietnam specifically, extensive pond stocking densities were found to be almost half than those for intensive ponds, with output yields 95% lower and protein yields 86% lower.

A case cannot be made that these differences are solely due to aeration since there extensive ponds suffer from many other water quality deficiency issues unrelated to dissolved oxygen levels. However, offering small scale farmers an affordable option to aerate their ponds can enable them to elevate their ponds to a higher level of intensification, which would have a large impact on their food security and income generation as outlined in the above results.

Table 2.2: Input-Output Variables for Farmed Carp in Vietnam and Bangladesh [46]

<table>
<thead>
<tr>
<th></th>
<th>Vietnam</th>
<th>Bangladesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Intensive</td>
<td>Intensive</td>
</tr>
<tr>
<td>Farm size (ha)</td>
<td>0.59</td>
<td>0.182</td>
</tr>
<tr>
<td></td>
<td>2.01</td>
<td>0.065</td>
</tr>
<tr>
<td>Yield (kg/hr)</td>
<td>406</td>
<td>8,606</td>
</tr>
<tr>
<td></td>
<td>8,606</td>
<td>3,580</td>
</tr>
<tr>
<td>Stocking Density (fingerlings/ha)</td>
<td>5,557</td>
<td>10,833</td>
</tr>
<tr>
<td></td>
<td>11,521</td>
<td>11,684</td>
</tr>
<tr>
<td>Protein (kg/ha)</td>
<td>43</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Labor (person-days/ha)</td>
<td>370</td>
<td>357</td>
</tr>
<tr>
<td></td>
<td>364</td>
<td>303</td>
</tr>
</tbody>
</table>

2.4 Thermal and Oxygen Stratification in Water Bodies

Foremost among the ecological conditions that affect cumulative levels - and spatial distribution - of dissolved oxygen across shallow fish ponds is water column stratification, visually represented in Figure 2-5. This phenomenon is most pronounced in
warm climates - such as in Vietnam and Bangladesh - and manifests itself as a de-
cline in both water temperature and dissolved oxygen with depth in the pond. During
thermal stratification, the water column is divided into three semi-discrete layers:

- The epilimnion, a warm layer near the surface where temperature is very nearly
  constant due to wind-induced convection

- The thermocline, a layer where the declining temperature gradient is most pro-
nounced and whose thickness varies by the time of day; it is thickest at solar
  noon and non-existence at nighttime

- The hypolimnion, a layer of cool, dense water near the bottom of the pond
  which is typically devoid of aquatic life, except for anaerobic benthos. Most fish
  cannot survive in this layer for extended periods of time since it is stagnant and
  suffers from persistently low dissolved oxygen levels throughout the day

The magnitude of difference between surface and bottom levels of dissolved oxygen
is not constant throughout the day; rather, it varies diurnally with solar irradiance.
During the day, shallow waters become warmer, and therefore less dense, than deeper
waters that receive less solar heating due to sunlight extinction. As a result, a de-
clining temperature gradient forms across the depth of the pond, with the largest
temperature drop taking place over the thermocline. In the absence of heavy rain or
strong winds, turbulent heat diffusion and convection are minimized, and the pond
will become vertically-stagnant and thermally-stable during the majority of daytime
hours [47].

As a consequence of this stagnation, limited water mixing takes place across the
depth of the pond. Water in the epilimnion - where the vast majority of oxygen-
producing phytoplankton live, and where light needed for photosynthesis is least at-
tenuated - becomes supersaturated with oxygen during the day. Consequently, some
of this oxygen is lost to the atmosphere by diffusion if conditions are windy. Mean-
while, water in the hypolimnion is starved of oxygen due to benthic respiration and
a lack of photosynthetic activity [48]. This nonuniformity of oxygen distribution in
Figure 2-5: Daytime Thermal and DO Stratification in a Typical Fish Pond 2.5 m Deep

Fish ponds create a situation where oxygen can reach anoxic conditions in the hypolimnion, and may result in high rates of fish mortality or poor growth if the pond is overstocked or suddenly turned over [49]. Therefore, most fish are constrained to living near the surface of the pond. This, however, has two downsides: First, sustained levels of supersaturated dissolved oxygen near the water surface can result in gas bubble disease in most species of fish, and this could result in significant death rates in the crop [50]. Second, the absence of fish in deeper water leaves a large portion of the pond uninhabited, thereby limiting its stocking density [51]. In cases where surface waters are too warm for a particular species, fish may swim near the oxygen-deficient bottom most of the time, surfacing occasionally to breathe, and in so doing, exerting energy which adversely affects their growth. It is therefore evident
that the combined effects of stratification - that is, extremely high oxygen levels near the surface which are lost to the surrounding air, uninhabitable, anoxic water near the bottom of the pond, and little vertical mixing - are a detriment to pond productivity and fish survival.

Only at night, as surface waters cool down in the absence of sunlight, do convective cells begin forming across the pond and the water column begins to destratify. However, by that point, cumulative dissolved oxygen will have declined across the water column as phytoplankton switch from photosynthesis to respiration. This is shown in Figure 2-6, which displays water temperature and dissolved oxygen measurements at 4 different depths for a 1 m deep fish pond in Srimangal, Bangladesh over a period of 4 days. Marked stratification was observed on those days, with a steep difference in temperature and dissolved oxygen between the top and bottom sensors during sunlight hours. As the sun sets, however, temperatures between adjacent layers equalize due to differential cooling, and convective mixing begins to take place, resulting in equalization of dissolved oxygen levels. At the same time, due to the termination of photosynthesis, dissolved oxygen levels drop in all layers, and continue dropping in tandem due to fish and plankton respiration until they reach critically-low levels around dawn. External interventions by means of aerators or circulators are therefore necessary to overcome the limitations brought about by stratification and create a greater and more even distribution of oxygen across a pond’s water column.

2.5 Current State of the Art in Aquaculture Aeration

As outlined in the previous sections, it is crucial to address oxygen losses and thermal stratification in fish ponds if productivity is to be prioritized. To that end, water mixing is carried out. Mixing disturbs the water surface, thereby increasing its roughness, enlarging the interfacial surface area between air and water and facilitating oxygen diffusion across the water surface. This may be better understood using Fick’s First
Figure 2-6: Graphs Showing (a) Thermal and (b) Dissolved Oxygen Stratification in a 1 m deep Fish Pond in Bangladesh for the Period Between 11/25 and 11/29.
Law of diffusion, which is given by:

$$\left( \frac{dm}{dt} \right)_{O_2} = -D_{O_2-H_2O} \nabla c_{O_2} A$$ (2.2)

where:

$$\left( \frac{dm}{dt} \right)_{O_2} \quad \text{molar flow rate of dissolved oxygen across the water surface (mol/s)}$$

$$D_{O_2-H_2O} \quad \text{diffusivity of oxygen in water (m}^2/{s})$$

$$\nabla c_{O_2} \quad \text{concentration gradient of oxygen across the interface (mol/m}^4)$$

$$A \quad \text{Air-Water interfacial surface area (m}^2)$$

Of the variables upon which the oxygen diffusion rate is directly proportional, only the air-water interfacial surface area may be meaningfully influenced. As explained above, in the case of fish ponds and other water bodies, this is accomplished by mixing the water. Not only does mixing enhance diffusion into the water surface, it also causes mass transfer of water and dissolved oxygen from the surface to other places within the water body, primarily by cooling surface waters and therefore creating conditions suitable for convection. This is especially beneficial during the day when the pond is stratified and the surface is supersaturated with oxygen.

Water mixing does not need to be carried out artificially; it occurs naturally by simple diffusion and is influenced in very large part by wind which shears and disturbs the water surface and, in doing so, increases the air-water interfacial surface area. One numerical study attempted to quantify the impact of wind on mixing and found a strong correlation between wind speed and the thickness of the epilimnion - the column of water within which temperature and other ecological variables are constant. Using convective turbulence calculations, the authors simulated the mixing depths at three wind speeds and for three different water column temperature gradients. The results, shown in Figure 2-7, uncovered a positive proportional relationship between wind speed and destratification. They also show that, when the pond is less stratified, the effect of wind on water mixing is even more pronounced [52].

Nevertheless, most rural inland fish ponds are typically small (<1 ha) and are sur-
rounded by tall dikes, resulting in very limited wind fetch and mixing. Additionally, during most of the day, the surface of the water is supersaturated with oxygen, and is therefore more likely to lose than gain oxygen. This prompts the need for water mixing using artificial means, typically by use of aeration or circulation.

Aeration not only improves water quality by increasing dissolved oxygen. It can minimize organic matter accumulation that may increase oxygen demand in the pond, reduce the density of algal blooms that can lead to oxygen depletion and fish health issues, and shift the composition of algae blooms that may lead to flavor issues in fish. In deciding what type of aeration to install in a pond, several factors need to be considered, including [14]:

- Pond size
- Pond depth
- Pond shape
- Energy availability
- Capital and running costs

Figure 2-7: Effect of Wind Speed on Mixing Depths in Fish Ponds [53]
• Aerator efficiency
• seasonal changes (e.g. ice cover)

While there is a large variety of aerators in use by fish farmers, the most commonly used types can be broadly classified into two categories: Surface Aerators and Destratification Circulators.

2.5.1 Surface Aeration Systems

As the name implies, surface aerators are mechanical devices which improve water quality by acting on the water surface. Their influence is similar to the effect of wind, but their impact on dissolved oxygen levels is much larger. The two most prominent and widely-used surface aerators are paddle wheels and propeller-aspirator pumps.

Due to their versatility, effectiveness and simplicity, paddle wheels are considered by most to be the most effective type of aerator (see Figure 2-8). They consist of a motor and a shaft connected to a circular arrangement of paddles which agitate and splash the water as they make contact with the surface. The pattern, length, and shape of the paddles affect the aeration efficiency of the unit. Paddle wheel aerator designs range from farm-manufactured units consisting of an automotive axle and differential with paddles welded to a wheel, to precisely machined and manufactured paddles attached in a spiral pattern around a drum. They can be powered by electricity, fuel, or can be driven to a tractor. They could be stationary or powered by propellers to sweep the pond, however, most fall under the former category.

Propeller-aspirator aerator units are less common and consist of a rotating, hollow shaft attached to a motor shaft (see Figure 3-2). The submerged end of the rotating, hollow shaft is fitted with an impeller which agitates the water at a velocity high enough to cause a drop in pressure over the diffusing surface. This pulls air down the hollow shaft, which then passes through a diffuser and enters the water as fine bubbles. Those bubbles are then mixed into the pond water by the turbulence created by the propeller.
2.5.2 Destratification Systems

Destratification circulation systems are not used to the same extent as surface mechanical aerators, but they have some application-specific advantages. For example, they are effective with deeper ponds, as well as highly turbid ones. The two most widely-used destratification systems are diffused-air aerators (commonly known as bubblers) and air lift pumps.

Diffused-air systems (see Figure 2-10) use a low pressure, high volume air blower to provide air to spargers placed at the bottom of the pond. The minimum permissible system pressure becomes greater with increasing depth of water above diffusers, because enough pressure must be available to force air through the piping system and cause the air to exit from the diffuser against the hydrostatic pressure at the discharge point. Diffused-air systems that release fine bubbles usually are more efficient than those that discharge coarse bubbles. This results because fine bubbles present a greater surface area to the surrounding water than larger bubbles. Oxygen diffuses into water at the surface, so a large surface area facilitates greater oxygen absorption. Beside injecting oxygen directly into the pond water, the pressure drop caused by the velocity of the bubble stream pulls the oxygen-deficient surrounding water near the bottom upward, whereupon it is re-oxygenated on contact with the air. As water reaches the surface, it spreads outward, sinks back, and forms creates a circulation loop. This action breaks down stratification in the pond and creates an even dissolved-oxygen environment across the pond depth. Efforts to make such
a system sustainable and off-grid include using solar photovoltaic modules or wind turbines to run the compressors needed for the system. However, at present, those systems are far too expensive for the average rural fish farmer.

The other method to achieve the same outcome as air diffusers is by using a vertical air lift pump (see Figure 2-11), which comprises a motor and impeller similar to a propeller-aspirator. The difference is that, with an air lift pump, the motor and impeller are fully submerged, and the water is channeled upward through a draft tube. As anoxic, hypolimnetic water is pumped upward, it is exposed to an oxygen-rich water/air interface. At the same time, oxygen-rich epilimnetic water sinks to the bottom of the pond, thereby oxygenating the deeper strata of the pond making them habitable for fish and increasing the cultivatable volume of the pond.
2.5.3 Assessment of Current Systems

In trying to assess the effectiveness of the various types of aerators described in the section above, researchers have developed techniques for evaluating their capabilities. Boyd highlights two types of recommended techniques for testing: steady state and non-steady state [52]. In the steady state test, the aerator is mounted in a stream of water with a known volumetric flowrate. Dissolved oxygen concentrations are then measured upstream and downstream of the aerator. The increase represents the mass of oxygen transferred into the water by the aerator [56]. This type of test is suitable for applications involving small water basins and is too costly to carry out for larger ponds since the volumetric flowrates required to measure a meaningful difference in dissolved oxygen are too large. Therefore, the non-steady state test is preferred.

Non-steady state tests are conducted by deoxygenating a basin of clean water of known volume with sodium sulfite and cobalt and measuring the change in oxygen concentration as the water is reoxygenated by an aerator. This is done by taking dissolved oxygen measurements at regular intervals as oxygen levels rise in the water from 0% to 80% saturation. At each point, the dissolved oxygen deficit is calculated as:

\[ DO_d = C_s - C_m \]  

where:

- \( DO_d \) Dissolved oxygen deficit (mg/L)
- \( C_s \) dissolved oxygen concentration at saturation (mg/L)
- \( C_{s20} \) Measured dissolved oxygen concentration (mg/L)

Next, the natural logarithms of dissolved oxygen deficits are plotted versus the time of aeration; the line of best fit is then drawn using regression analysis and the slope of this graph represents the Oxygen Transfer Coefficient (OTC) at ambient temperature, denoted by \( K_L a_T \). Using a temperature correction for oxygen diffusivity, this figure is corrected to calculated the Standard Oxygen Transfer Coefficient.
(SOTC), denoted by $K_{L}a_{20}$. This figure is then used to estimate the oxygen transfer efficiency of the aerator using:

$$SOTR = K_{L}a_{20} \ C_{s20} \ V$$  \hspace{1cm} (2.4)

where $SOTR$ is the Standard Oxygen Transfer Rate ($kgO_2/h$). $C_{s20}$ is the dissolved oxygen concentration at saturation and 20 $^\circ$C ($mg/L$), and $V$ is the Pond volume ($L$). By definition, then, the SOTR is the amount of oxygen that an aerator will transfer to water per hour under standard conditions, which in this case is defined as 20 $^\circ$C.

Finally, the SOTR value may be divided by the power applied at the aerator shaft to obtain the standard aeration efficiency (SAE), given simply as:

$$SAE = \frac{SOTR}{P}$$ \hspace{1cm} (2.5)

where:

$SAE$ Standard Aerator Efficiency ($kgO_2/kW/h$)

$P$ Brake power of the aerator ($kW$)

Additionally, the actual oxygen transfer rate for an aerator operating in a fish pond may be estimated with the following equation [57]:

$$OTR = SOTR \ \frac{C_{s} - C_{p}}{9.09} \ 1.024^{T-20} \ \alpha$$ \hspace{1cm} (2.6)

where:

$C_{p}$ Dissolved oxygen concentration of the pond water at the surface ($mg/L$)

$T$ Pond water temperature at the surface ($^\circ C$)

$\alpha$ Correction factor for water quality

Boyd et al. tested a large number of electric aerators for oxygen transfer efficiency. Values for SOTR and SAE are summarized in Table 2.3 [58]. While there is a wide variability in the reported results, these data demonstrate that paddle wheel aerators
are the most efficient. In fact, surface aerators in general performed significantly better than destratification circulators, however, the latter conferred benefits to water quality besides an improvement in dissolved oxygen content. In reporting the results, the authors concede that it would be inaccurate to infer that paddle wheel aerators are objectively better than any other type of aerator for any type of pond. Rather, they explain that choice of aeration should be looked at in the context of cost and pond conditions, pointing out that under certain circumstances such as small or deep ponds, even the lowest-scoring aerators in their experiment - diffused-air circulators - could be better than mechanical surface aerators.

Table 2.3: Summary of SOTR \((kgO_2/h)\) and SAE \((kgO_2/kW/h)\) values for electric aerators used in aquaculture [58]

<table>
<thead>
<tr>
<th>Aerator Type</th>
<th>SOTR Range</th>
<th>SAE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
</tr>
<tr>
<td>Paddle Wheel</td>
<td>2.5 – 23.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Propeller-Aspirator Pump</td>
<td>0.1 – 24.4</td>
<td>1.6</td>
</tr>
<tr>
<td>Vertical Air Lift Pump</td>
<td>0.3 – 10.9</td>
<td>1.4</td>
</tr>
<tr>
<td>Diffused Air</td>
<td>0.6 – 3.9</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Indeed, while the figures in Table 2.3 are valuable, they do not take into account the additional improvements to water quality of destratification circulators which are not necessarily accomplished by surface mechanical aerators. To that end, a different type of experiment may be used, albeit its result is neither standardized nor reported by manufacturers and there is a lack of literature on this subject. In the experiment, a large concentration of sodium chloride is dissolved in a large container and poured around a circulator in a pond. Specific conductance is measured at intervals at several places and depths in the pond until all specific conductance values are essentially equal. The mixing rate may be estimated as:

\[ MR = \frac{AD}{PT} \]  

(2.7)
where:

\[ MR \quad \text{Mixing rate (m}^3/kW \cdot hr) \]
\[ A \quad \text{Pond area (m}^2) \]
\[ D \quad \text{Pond depth (m)} \]
\[ P \quad \text{Brake power of the aerator (kW)} \]
\[ T \quad \text{Time for complete mixing (hr)} \]

One large downside of this type of test is it does not produce consistent results, requires a very long time to carry out, and no methodology exists to interpret the results or extrapolate circulator performance from test conditions to a full-scale fish pond. Therefore, it is overlooked by both researchers and manufacturers in favour of the SOTR tests.

## 2.6 Aquaculture Modeling

Since temperature and dissolved oxygen play a large role in the health and survival of fish, accurate characterization of those parameters is of critical importance in understanding how the proposed aeration system should be designed. Additionally, having tools which can predict those parameters would reduce the number of inputs required to predict the performance of the device. A review of some studies which attempted to model temperature and dissolved oxygen stratification is discussed in this section, and a detailed explanation of the models developed for this thesis is covered in Chapter 3.

### 2.6.1 Thermal Stratification

Aquaculture pond stratification is a poorly documented phenomenon and the processes causing stratification are not well understood. Attempts to characterize temperature patterns in aquaculture ponds are not common in the literature, and where they exist, most tend to be limited in applicability due to their narrow scope. For
example, one the earliest attempts at computer modeling of pond temperatures was the Maintenance of Aquaculture Pond Temperatures (MAPT) model developed by Klemetson and Rogers. It relied primarily on thermodynamic relations and daily weather station measurements in order to produce a graph which predicts pond temperatures throughout the year [59]. A similar attempt was carried out by Fritz et al. for wastewater stabilization ponds. It used the same thermodynamic relations, albeit it reduced the number of inputs by providing a tool to estimate theoretical shortwave irradiance for a particular time and location, and it adjusted the longwave component of radiation using empirical findings from Ryan and Stolzenbach [60]. Those models, however, do not provide information on hourly temperature fluctuations throughout a single day, which is the focus of this research.

A smaller subset of temperature modeling studies have focused on those diurnal fluctuations, however, most assume the water temperature is vertically uniformly distributed and do not account for stratification. The Pond Heat and Temperature Regulation (PHATR) model by Lamoureux et al. presented one of the more robust attempts at simulating those hourly temperature fluctuations; using detailed meteorological measurements at 15 minute intervals at a test aquaculture pond, a model was constructed which agreed closely with measured temperatures at the water surface. However, due to the high cut-in speed of the anemometer used in the study, evaporative and convective surface losses were understated, resulting in largely overestimated water temperatures. [61]. Other models, such as one developed by Caldwell et al., sought to find statistical correlations between historical climatic conditions and water temperatures. While those models showed good accuracy on most simulated days, they had to be calibrated for the particular site and did not posses global applicability [62].

The only model found in literature which accurately characterizes thermal stratification in aquaculture ponds was that of Losordo and Piedrahita, which accounts for both temperature fluctuations throughout the day and vertical heat transport using a limited set of input parameters [63]. It is a one-dimensional heat transfer model in which the pond is divided into a number of discrete, horizontally-homogeneous layers.
Vertical transport of heat is described by a diffusion equation in which the diffusivity coefficient, $K_z$ is incorporated in a conservation equation of the form:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left( K_z A \frac{\partial T}{\partial z} \right) + \frac{\phi(z,t)}{\rho_w c_p}$$  \hspace{1cm} (2.8)

where:

- $T(z,t)$ Water Temperature as a function of depth and time (°C)
- $A(z)$ Horizontal surface area of the pond at depth $z$
- $\phi(z,t)$ Internal distribution of heat sources due to radiation absorption inside the water column ($J/m^2.s$)
- $K_z$ Diffusivity coefficient ($m^2/s$)
- $\rho_w$ Water density ($kg/m^3$)
- $c_p$ Specific heat of water ($J/kg.°C$)

In the model, $\phi(z,t)$ was broken down into individual equations representing the sources and sinks of energy for each control volume and Equation 2.8 was integrated in time to calculate the temperature change throughout the day, thereby producing a diurnal temperature profile for each control volume in the pond.

In characterizing the turbulent diffusion of thermal energy and mass between the horizontally layers (that is, in order to calculate $K_z$), the authors used the eddy diffusion model, which relates turbulent heat transport in the water column to the Richardson number. This method was validated by Henderson-Sellers as the most appropriate for shallow ponds [64]. During periods of heating of the water body, turbulent diffusion is the dominant source of vertical mixing, and vertical advective/-convective transport are minimal under stratified conditions. However, during periods of net cooling of the pond, convective transport due to buoyant instabilities in the water column becomes a dominant source of vertical mixing. In the turbulent eddy diffusion model, several methods may be used to account for convective heat transfer. For their model, the authors cited research by Sundaram and Rehm in which good
characterization of convective flow was accomplished by setting $K_z$ to a maximum value $K_{z,\text{max}}$, which must be calibrated for each site [65].

While this model provides a good basis for this thesis, it relied on a wealth of meteorological data which was not easily available, therefore adjustments to the model had to be carried out; most notably, an alternative formulation for evaporative heat losses, using research from Crow et al., was necessary [66].

2.6.2 Dissolved Oxygen Stratification

As with thermal stratification, few established dissolved oxygen stratification models exist in the literature, and where attempts were made, most focused primarily on predictions of nighttime dissolved oxygen decline or to gauge its seasonal variations [67].

Of the earliest empirical models developed to characterize dissolved oxygen dynamics was published by Boyd et al. It sought to estimate early morning dissolved oxygen concentrations in a pond stocked with channel catfish using curve-fitted estimates for plankton community respiration, wind diffusion, and fish and benthic respiration [68]. While the model produced simulations which agreed with measurements within $\pm$ 10% and its underlying equations remain valid today, it is inappropriate for systems in which plankton respiration is not the major DO sink or in which nighttime dissolved oxygen declines are curvilinear, as they typically are for most ponds.

To address this issue, Madenjian et al. developed the Whole Pond Respiration-Diffusion (WPRD) model, which used a modified form of the Boyd et al. equations, along with rigorously measured community respiration rates, to predict nighttime dissolved oxygen profiles in marine shrimp ponds [69]. The model performed well under most conditions and for a variety of environments, however, it required a large number of inputs that are difficult to acquire, did not track dissolved oxygen during the day, and did not offer any formulation for dissolved oxygen production by phytoplankton.

Building on those studies, Culberson and Piedrahita developed one of the few mechanistic, diurnal dissolved oxygen models which characterized oxygen profiles at different depths. Using the same methodology carried out by Losordo and Piedrahita
to model thermal stratification, the authors divided ponds into control volumes and applied to them equations which account for oxygen production and consumption [67]. Diffusion and convection were accounted for using the eddy diffusivity method, and the model was integrated in time to arrive at dissolved oxygen profiles for each control volume. The authors validated their model using three ponds in three disparate locations in order to test for its global applicability, and while the simulations did not fit perfectly with the measured values, the overall pattern, as well as the predicted destratification time were well-characterized. The authors speculate that the model lacked accuracy due to poor-resolution water temperature measurements in two of the three ponds, which necessitated interpolations that may have produced incorrect temperature profiles. This validates the need for a thermal stratification model which can accurately predict temperatures using a set of basic inputs without the need for direct pond measurements.

2.7 Summary

In this chapter, a background on the factors that drove the motivation behind this project was discussed. This included a historical overview of aquaculture in the Asia-Pacific region, followed by the status and deficiencies of current fish farming practices, specifically in Vietnam and Bangladesh which were identified as the target countries for this research. This was followed by a primer on water quality management in fish ponds, focusing on the importance of dissolved oxygen on the survivability and health of the fish, and by extension, the income of fish farmers. The dynamics of dissolved oxygen in water bodies are related to a phenomenon known as thermal stratification, which results in diurnal sinusoidal oscillations in temperature and dissolved oxygen. In addition, it causes a declining vertical gradient of dissolved oxygen which reduces the overall habitable volume of any given pond. To overcome its impact, aeration systems are typically used in more intensive aquaculture operations. However, for most farmers in Bangladesh and almost all small holder farmers in Vietnam, aeration is out of reach due to capital cost, unreliable electricity and maintenance concerns.
An overview of commonly-used aerators and circulators highlighted the advantages and disadvantages of those systems, as well as the methods used to gauge their performance. There is an opportunity, then, to offer a sustainable, affordable aeration system for small holder farmers.
Chapter 3

Ecological and System Modeling

The overall purpose of this research program is to devise a sustainable, appropriate method to tackle stratification in rural aquaculture ponds whose owners could otherwise not afford a circulation system. Specifically, the goal is to overcome the natural imbalances in temperature and dissolved oxygen in the pond to vertically mix water evenly across the water column to create a higher cumulative dissolved oxygen content in the pond. Ultimately, this would minimize oxygen losses at the surface, since supersaturated water would oxygenate lower strata of the pond, and may help increase the volume of pond within which fish can live.

This thesis contributes to the development of this technology by developing an approach to model the temperature and dissolved oxygen dynamics in a typical pond. As explained in Section 2.4, shallow aquaculture ponds frequently undergo diurnal cycles of thermal and dissolved oxygen vertical stratification during periods of hot, windless weather. This is characteristic of many rural ponds in Southeast Asia. Vertical temperature gradients of up to 12.0 °C/m have been documented in catfish production ponds in China [53].

In stratified ponds, heat and oxygen near the surface of the pond are effectively segregated from the lower pond water by the density gradient in the water column. Convective vertical mixing occurs only after the density gradient in the water column breaks down, usually due to surface cooling after sunset. Of these parameters, dissolved oxygen stratification leads to the most serious problems as oxygen depletion...
may cause crop mortalities during periods of stratification. Thermal and oxygen stratification in aquaculture production ponds can also have more subtle, chronic effects on pond production. Pond stratification can result in zones of poor environmental quality that can effectively limit the usable culture volume.

In this chapter, a methodology to model the temperature and dissolved oxygen in aquaculture ponds is developed and validated using data from two test environments in Southeast Asia. In addition, a 2D CFD model is constructed and used to size the proposed aeration device using Design of Experiments Methodology. The results of the final CFD model are then used to predict the dissolved oxygen profiles in the pond as a result of the device’s convective circulation.

3.1 Test Environment

For this project, two sites have been chosen for data collecting and testing:

Vietnam

![Satellite Image of the Aquaculture Research Center](image1.png)
![Close-up of Pond 1 to be used for prototype testing](image2.png)

Figure 3-1: Satellite Image of the Aquaculture Research Center [70]
Figure 3-2: Close-up of Pond 1 to be used for prototype testing

Through a partnership with the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) and the Bac Ninh Department of Science and Technology (DOST), two fish ponds on the outskirts of Hanoi, Vietnam were secured as pilot ponds for the project, however, only one was used for the project.
Photographs of the test site are shown in Figure 3-1 and Figure 3-2, and basic information about the site and the two ponds is provided in Table 3.1.

Table 3.1: Pond Characteristics in Bac Ninh, Vietnam

<table>
<thead>
<tr>
<th>Site Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinates</td>
<td>21°06’ 20.6&quot;N 106°02’ 32.2&quot;E</td>
</tr>
<tr>
<td>Site Elevation</td>
<td>6 m above sea level</td>
</tr>
<tr>
<td>Average Air Temperature</td>
<td>23.5 °C</td>
</tr>
<tr>
<td>Average Annual Rainfall</td>
<td>1,680 mm</td>
</tr>
<tr>
<td>Average Insolation</td>
<td>4.97 kWh/m²/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pond Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pond Dimensions</td>
<td>85 m x 30 m</td>
</tr>
<tr>
<td>Pond Depth</td>
<td>2 - 3 m</td>
</tr>
<tr>
<td>Species Cultivated</td>
<td></td>
</tr>
<tr>
<td>Carp</td>
<td>200 kg total - 150 g/fish</td>
</tr>
<tr>
<td>Tilapia</td>
<td>500 kg total - 400 g/fish</td>
</tr>
<tr>
<td>Black Carp</td>
<td>50 kg total - 700 g/fish</td>
</tr>
<tr>
<td>Butterfish</td>
<td>700 kg total - 600 g/fish</td>
</tr>
<tr>
<td>Average Stocking Density</td>
<td>230 g/m³</td>
</tr>
</tbody>
</table>

In contrast to the rural, modest ponds being targeted by this project, the two ponds used for this study are large and better managed, with an intricate water exchange system and a limed, compacted soil bed. In addition, stocking density was kept to a minimum during the experiments.

Meteorological sensors were installed at site to gather data on wind speed, solar irradiance and ambient temperature. This was done using an Inspeed101 cup anemometer, a custom-made LMZ35 analog temperature sensor probe, and an Apogee SP-215 silicon-cell photodiode pyranometer connected to an Arduino fitted with a datalogger shield (See Figure 3-3). However, due to pervasive overheating problems with the datalogger real-time clock, the Arduino was substituted with a Monarch TrackIt dual-channel voltage logger after three months after installation. In addition to meteorological data, dissolved oxygen and water temperature were measured using an Onset HOBO U-26 dissolved oxygen logger (See Figure 3-4). All measurements were
taken at 10-30 minute intervals. Data collection for the site ran from April 9, 2015 to March 17, 2016 with some intermittencies due to technical issues with the loggers.

**Bangladesh**

In Bangladesh, two rainfed ponds – each approximately 0.11 ha in surface area and 1.5 m deep – were secured for pilot testing in a hatchery in Srimangal, a small rural town in western Bangladesh. The ponds belong to the international development NGO BRAC, which was a partner on this project and assisted in sensor placement, as well as prototype construction and installation.

As with Vietnam, a weather station and a series of Onset HOBO U-26 dissolved
Figure 3-5: Weather Station Setup in Bangladesh

Figure 3-6: Temperature and Humidity Logger

oxygen loggers were used to monitor the pond. However, rather than placing the weather station land-side, it was mounted on a floating, water-resistant platform to collect localized data (see Figure 3-5). An RM Young 85000 ultrasonic anemometer was substituted for the cup anemometer in order to acquire better quality wind data for the temperature model. Further, since the only regional meteorological weather station in the vicinity of the pond did not provide reliable hourly data on ambient conditions, a standalone Monarch Track-It temperature/relative humidity sensor was installed close to the ponds (see Figure 3-6). Finally, a Maxim DS18B20 digital waterproof temperature sensor was placed into the bottom soil of one of the ponds and its data was logged using an Arduino datalogger. This was done to aid in heat transfer calculations between the bottom water layers and the sediment. Data collection for the site started on December 13, 2015 and is ongoing.

3.2 Temperature Modeling

While the main focus of this research is to establish a robust dissolved oxygen model to help predict the performance of the proposed aeration device, it was important to develop a numerical model which predicts pond water temperature at various depths throughout the day since temperature and thermal stratification have a significant effect on dissolved oxygen distribution. With this model, it is possible to estimate the
dissolved oxygen distribution in a given pond and quantify the impact of the proposed aeration device using only basic pond characteristics and climatic data.

The pond temperature model described herein is one-dimensional heat transfer model based entirely on thermodynamics (as opposed to site-specific Bayesian models), and it uses input parameters from readily-available ecological field data, as well as empirical relationships commonly applied to heat balance calculations for larger and deeper bodies of water. It is valid for any shallow water body given that all site characteristics are known.

### 3.2.1 Model Setup

![Diagram of Thermal Stratification Model Setup](image)

Using the Losordo and Piedrahita method outlined in Section 2.6, the pond is sub-divided into a number of discrete, horizontally-homogeneous layers (See Figure 3-7). Heat additions and losses in each control volume are accounted for using source and sink terms, and vertical transport of heat is described by an eddy diffusion term, $K_z$ which estimates both diffusive and convective heat transport between the different control volumes of the pond. For the present model, the pond was divided into two control volumes, although more may be added if information about the middle strata of the pond is required. For each control volume, the energy balance is given by:
\[
\left( \frac{dE}{dt} \right)_{CV} = (\phi_{sw} - \phi_{swr}) + (\phi_{lw} - \phi_{lwr}) - \phi_{c} \pm \phi_{c} \pm \phi_{sed} - \phi_{gw} \pm \phi_{wx} \pm \phi_{d} \pm \phi_{conv} \quad (3.1)
\]

where:

- \( (\frac{dE}{dt})_{CV} \) Net rate of heat exchange in the control volume
- \( \phi_{sw} \) Attenuated shortwave solar radiation
- \( \phi_{swr} \) Reflected shortwave radiation
- \( \phi_{lw} \) Longwave radiation
- \( \phi_{lwr} \) Reflected longwave radiation
- \( \phi_{c} \) Evaporative heat loss
- \( \phi_{c} \) Sensible heat transfer
- \( \phi_{sed} \) Heat exchange with pond sediment
- \( \phi_{gw} \) Heat exchange with groundwater table
- \( \phi_{d} \) Diffusive heat transport across the control volume
- \( \phi_{conv} \) Convective heat transport across the control volume

Note: All the terms in Equation 3.1 above are in units of \( J/m^2 \cdot s \)

Each term in the this heat budget is governed by a set of thermodynamic equations. Most are theoretical in nature, however, in some cases - such as with evaporation - empirical relations from literature had to be used. Below is a description of the numerical formulation for each of those terms:

**Shortwave Radiation**

Incident shortwave (solar) radiation has the largest impact in the thermal budget of the pond [61], therefore, accurate characterization of the \( \phi_{sw} \) term is important. For a given control volume, \( i \), the net penetrating shortwave radiation may be calculated using the Beer-Lambert law, given by:

\[
\phi_{sw,i} = E_e(e^{-\eta(z_i - \frac{1}{2}t)} - e^{-\eta(z_i + \frac{1}{2}t)}) \quad (3.2)
\]
where: $\phi_{sw,i}$ is solar radiation in control volume $i$ ($J/m^2 \cdot s$), $E_e$ is the solar irradiance incident on the water surface ($J/m^2 \cdot s$), $\eta$ is the measured light extinction coefficient ($m^{-1}$), $z$ is the mid-point depth of control volume $i$ ($m$), and $t$ is the thickness of control volume $i$ ($m$).

As sunlight strikes the water surface of the pond, a portion of the shortwave solar energy penetrates the water and the remainder is reflected. The reflectivity of solar radiation varies with the angle of incidence of the incoming radiation, the characteristics of the water surface, the local atmospheric conditions, and the topography of the surrounding region. One generic formulation for an approximation of surface reflectivity is given by [63]:

$$R_s = A \left( \frac{180\lambda}{\pi} \right)^B$$

(3.3)

where:

- $R_s$ Reflectivity of a smooth water surface
- $\lambda$ Solar altitude angle (rad)
- $A$ & $B$ Empirical coefficients based of sky conditions (see Table 3.2)

<table>
<thead>
<tr>
<th>Weather Condition</th>
<th>C</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear</td>
<td>0.0</td>
<td>1.18</td>
<td>-0.77</td>
</tr>
<tr>
<td>Scattered Clouds</td>
<td>0.1 - 0.5</td>
<td>2.2</td>
<td>-0.97</td>
</tr>
<tr>
<td>Broken Clouds</td>
<td>0.6 - 0.9</td>
<td>0.95</td>
<td>-0.75</td>
</tr>
<tr>
<td>Overcast</td>
<td>1.0</td>
<td>0.35</td>
<td>-1.45</td>
</tr>
</tbody>
</table>

In order to simulate the effects of wind-induced roughness on the optical reflectivity of the water surface, Losordo et al. formulated the following equation [63]:

$$R = R_s(1 - 0.08W)$$

(3.4)
where:

\[ R \] Reflectivity adjusted for water surface roughness

\[ W \] Wind speed above the water surface (m/s)

Finally, energy losses from the surface control volume due to reflected shortwave radiation (\( \phi_{\text{swr}} \)) may be calculated as:

\[
\phi_{\text{swr},1} = \phi_{\text{sw},1} R
\] (3.5)

### Long Wave Radiation

For clear skies, the long wave radiative atmospheric flux to the top layer of the pond is given by Stefan-Boltzmann’s fourth power law as:

\[
\phi_{\text{lw}} = (1 - r) \varepsilon_a \sigma T_a^4 (1 - R_{\text{lw}})(1 + 0.17 C_{\text{cloud}}^2)
\] (3.6)

where:

\[ r \] Water surface reflectance to longwave radiation \( \approx 0.03 \) [71]

\[ \sigma \] Stefan-Boltzmann constant \( (J/m^2 \cdot s \cdot °K^4) \)

\[ T_a \] Absolute temperature of the air at the water surface \( (°K) \)

\[ \varepsilon_a \] Emissivity of air, given empirically by \( \varepsilon_a = 0.398 \times 10^{-5} T_a^{1.48} \) [72]

\[ C_{\text{cloud}} \] Cloud cover fraction

Similarly, long wave radiative heat losses from the surface of the pond are given by:

\[
\phi_{\text{rlw}} = -\varepsilon_{\text{water}} \sigma T_w^4
\] (3.7)

where \( T_w \) is the absolute temperature of the water at the surface \( (°K) \) and \( \varepsilon_w \approx 0.96. \) [59]

### Evaporation

Evaporative heat losses from water bodies are dependent primarily on wind speed and relative humidity of the surrounding air. Fritz et al. recommended that the
evaporative heat flux for small waste stabilization ponds be estimated using a Dalton-type equation which is based on two two factors: The vapor pressure deficit between the water and atmosphere, and an empirical wind function applied to the wind speed measured at 2 m above the water surface [63]. This equation is given by:

$$\phi_e = -NW(e_s - e_a)$$ (3.8)

where $N$ is an empirical coefficient given as $672 \text{ J/m}^3 \cdot \text{Pa}^{-1}$, and $W$ is the wind speed 2 m above the water surface ($\text{m/s}$). The terms $e_s$ and $e_a$ represent the saturated vapor pressure and vapor pressure above the pond surface respectively ($\text{Pa}$). They may be calculated using [73]:

$$e_s = 3.4 \times 10^3 \exp\left(17.62 - \frac{5.271}{T_w}\right)$$

$$e_a = \text{RH} \times 3.4 \times 10^3 \exp\left(17.62 - \frac{5.271}{T_a}\right)$$ (3.9)

where RH is the relative humidity.

**Sensible Heat Transfer**

Heat losses from the water surface to the surrounding air via conduction or convection, as well as heat transfer into the water due to conduction at the air-water interface, is referred to as sensible heat transfer. While it is possible to estimate conductive and convective heat losses as distinct heat sources and sinks in the system, the most appropriate empirical model combines the two into a single term. Additionally, greater uncertainties arise when trying to formulate generic equations for convection due to inconsistent wind fetch across the surface of the water.

Sensible heat transfer is considered to be a function of the wind velocity, atmospheric pressure, and the temperature gradient in the air above the water body. An estimation of the sensible heat transfer to or from a small body of water can be obtained as a function of wind speed, water temperature and air temperature such that [63]:

50
\[
\phi_c = 1.57W(T_w - T_a)
\]  
(3.10)

where \(T_w\) is the water temperature above at the surface (\(^\circ\)\(K\)) and \(T_a\) is the air temperature (\(^\circ\)\(K\)).

**Water Column Diffusive and Advective Heat Transport**

As outlined in Section 2.6, vertical heat exchange occurs primarily by turbulent convection within the water column. In the present model, it is assumed that no mean water flow is allowed, but that mixing is influenced by water density stratification and the wind component at the air-water interface. For two adjacent control volumes, the diffusive heat transport is taken as [67]:

\[
\phi_d = \rho_w c_{p,w} K_z \frac{\Delta T}{\Delta z}
\]  
(3.11)

where \(\rho_w\) is the temperature-dependent water density (\(kg/m^3\)), \(c_{p,w}\) is the specific heat of water (\(J/kg \cdot ^\circ\)\(C\)), \(K_z\) is the eddy diffusivity coefficient (\(m^2/s\)), \(\Delta T\) is the temperature difference between the midpoints of the two adjacent control volumes (\(^\circ\)\(K\)), and \(\Delta z\) is the distance between the midpoints of the two adjacent control volumes (\(m\)).

In the absence of stratification, diffusion is dependent only on wind speed, and the value of the neutrally-buoyant diffusion coefficient at any depth, \(K_0\), in the water column may be calculated using [67]:

\[
K_0 = \frac{W^*}{30k^*e^{-k^*z}}
\]  
(3.12)

where:
$K_0$ Eddy diffusivity coefficient for an unstratified column ($m^2/hr$) 

$k^*$ Empirical decay coefficient, given by $6W^{-1.84}$ 

$u_s$ Drift velocity, given by $30W^*$ 

$W^*$ is the frictional velocity due to wind stress, given by $\sqrt{T_0/\rho_w}$ 

$\tau_0$ Shear stress imparted by wind action on the water surface, given by $\rho_uC_wW^2$ 

$C_z$ is coefficient of aerodynamic resistance; at a reference height of $z = 10$ m, it has been empirically determined to be $\approx 1 \times 10^{-3}$ for $W \leq 5$ m/s 

For a stratified water column, the value of $K_0$ must be adjusted for the density gradient across the depth of the pond. Sundaram and Rehm proposed the relationship which relates the value of $K_0$ to the effective turbulent eddy diffusivity coefficient, $K_z$, at a particular depth, as a function of the Richardson number; the resultant equation can then be used to estimate turbulent diffusion between two control volumes in the temperature model during periods of stratification. This equation is given by [65]: 

$$K_z = \frac{K_0}{1 + \sigma Ri_z} \quad (3.13)$$

where $K_z$ is the effective eddy diffusivity coefficient at depth $z$, adjusted for the water column density gradient ($m^2/h$), $\sigma$ is an empirical coefficient, given as $\approx 0.05$ for a small pond [63], and $Ri_z$ is the Richardson number at depth $z$; this number may be approximated using [67]:

$$Ri_z = \frac{\alpha_v g z^2 \Delta T}{W^*^2 \Delta z} \quad (3.14)$$

where $\Delta T$ is the temperature difference between the midpoints of two adjacent control volumes (°C), and $\Delta z$ is the distance between the midpoints of two adjacent control volumes (m), $g$ is gravitational acceleration ($m/s^2$), $\alpha_v$ is the volumetric coefficient or thermal expansion of water (°K$^{-1}$), which may be estimated using [65]:

$$\alpha_v = 1.5 \times 10^{-5}(T - 277) - 2 \times 10^{-7}(T - 277)^2 \quad (3.15)$$
where $\bar{T}$ is the average temperature of two adjacent control volumes ($^\circ K$).

As explained in Section 2.6, the rate of convective mixing was estimated by calibrating the model such that $K_z$ takes on a maximum value $K_{z,\text{conv}}$ when buoyant flow conditions are present - that is, when the bottom control volume is warmer than the surface control volume. The calibrated value used for the validation simulations of this model is included in Table 3.3. Convective flows are calculated the same way as diffusive flows, using the following equation:

$$\phi_{\text{conv}} = \rho_w c_{p,w} K_{z,\text{conv}} \frac{\Delta T}{\Delta z}$$

(3.16)

### 3.2.2 Model Implementation and Results

The equations governing the energy balance in the pond were computationally integrated in time using MATLAB to produce the pond’s temperature profiles. The full formulation of this code is attached in Appendix B. Using 15 minute time steps and two control volumes, the temperature at each time step was calculated using:

$$T|^{t, CV} = T|^{t-1, CV} + \left(\frac{dE}{dt}\right)_{CV} \frac{1}{\rho_w t z_{CV} c_{p,w}} \Delta t$$

(3.17)

where:

- $T|^{t, CV}$ Temperature for the current control volume and time step ($^\circ C$)
- $T|^{t-1, CV}$ Temperature for the current control volume and previous time step ($^\circ C$)
- $\left(\frac{dE}{dt}\right)_{CV}$ Net heat flux in the control volume ($J/m^2 \cdot s$)
- $\rho_w t$ Water density for the current time step ($kg/m^3$)
- $z_{CV}$ Height of volume element ($m$)
- $c_{p,w}$ Specific heat of water ($J/kg \cdot ^\circ C$)
- $\Delta t$ Time step length ($hr$)

All inputs to the model were from field measurements and are summarized in Table 3.3. In order to validate the model, simulations were run for a number of
days and compared against temperature readings from the dissolved oxygen loggers. While several months' worth of meteorological readings were available for both sites, wind data from the cup anemometers installed in Vietnam and in the first 4 months in Bangladesh produced excessively high temperatures since the anemometer’s cut-in speed was too high, resulting in a severe underestimation of evaporative losses from the pond surface. Only after the ultrasonic wind anemometer was installed was suitable wind data for the site available. The days of June 21 through June 23, 2016 were therefore picked as the benchmark timeframe for model validation.

Table 3.3: Thermal Stratification Model Inputs

<table>
<thead>
<tr>
<th>Input Variable</th>
<th>Units</th>
<th>Bangladesh</th>
<th>Vietnam</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Irradiance</td>
<td>$W/m^2$</td>
<td>time series</td>
<td>time series</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>°C</td>
<td>time series</td>
<td>time series</td>
<td>NCEI Atlas [74]</td>
</tr>
<tr>
<td>Pond Bed Temperature</td>
<td>°C</td>
<td>time series</td>
<td>time series</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>$m/s$</td>
<td>time series</td>
<td>time series</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Relative Humidity</td>
<td></td>
<td>time series</td>
<td>time series</td>
<td>NCEI Atlas [74]</td>
</tr>
<tr>
<td>Anemometer Height</td>
<td>$m$</td>
<td>1.5</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Latitude</td>
<td></td>
<td>24.313271</td>
<td>21.1057</td>
<td></td>
</tr>
<tr>
<td>Longitude</td>
<td></td>
<td>91.685271</td>
<td>106.04227</td>
<td></td>
</tr>
<tr>
<td>Light Extinction Coefficient</td>
<td>$m^{-1}$</td>
<td>0.1524</td>
<td>0.33</td>
<td>Pyranometer</td>
</tr>
<tr>
<td>Convection eddy diffusivity constant</td>
<td>$m^2/hr$</td>
<td>0.052</td>
<td>N/A</td>
<td>Calibration</td>
</tr>
</tbody>
</table>

Figure 3-8 illustrates the comparison between the experimental and predicted temperature profiles for the three simulated days. For both the surface and bottom control volumes, the pairwise linear correlation coefficient with observed measurements was found to be over 0.95, indicating good statistical agreement between the measured and simulated temperature profiles; for the surface volume simulations, the average absolute error in the afternoon peaks was 0.4 °C and 0.52 °C for the pre-dawn trough. On all three days, the simulated maxima and minima were within 45 minutes of the logged measurements.

On the final day, however, some deviation between simulated and measured temperatures in both control volumes was apparent; this was likely due to the model’s
very high sensitivity to wind measurements, which affected both the evaporative and sensible heat transfer terms for the surface control volume. Additionally, a sensitivity analysis on the empirical coefficients for the aforementioned heat flux terms were seen to shift peak temperatures by several degrees for very small incremental changes. One other potential sources of error is the reliance on weather station data from NOAA for air temperature and relative humidity; much of this data was spaced at 3 hour intervals and interpolations had to be carried out to approximate a daily profile for both time series variables. Finally, the effect of rainfall was omitted from the model since no installed sensor or weather stations monitored precipitation local to the pond under study.

With regards to the bottom control volume temperature, the eddy diffusivity method for approximating turbulent heat transport from the top layer of the pond proved useful on most days, albeit, if the simulation were to be carried forward several extra days, the overall error would likely significantly rise due to the simplifications involved in the method, as well as the errors outlined above. In order to better model diffusive and advective flows, the most accurate method would likely be numerical
simulation using a 3D CFD model of the pond. This, however, requires substantially more information regarding the pond’s optical properties in order to correctly simulate the heat flux penetration of shortwave radiation. All other heat budget inputs and outputs, however, would be the same, and would be implemented as time-series user-defined-function source terms to the pond.

Figure 3-9 displays the relative contributions of the various heat flux elements to the net energy change in the surface control volume. For this figure, it is apparent that, for the three days studied, atmospheric longwave radiation and pond radiation generally canceled out except during dusk and dawn hours. Solar radiation was mainly responsible for temperature raise at daytime, whereas conduction and evaporation were the main contributors to cooling at dusk.

Overall, the model provides encouraging results which, if found to be site- and season-independent, could aid in the modeling and verification of dissolved oxygen dynamics in fish ponds, which is discussed in the following section.
3.3 Dissolved Oxygen Modeling

To evaluate the impact of the proposed aeration device, a versatile, mechanistic dissolved oxygen model which accurately predicts oxygen dynamics in aquaculture ponds is necessary. This model is described hereunder and follows a similar methodology to the temperature model described in the previous section.

3.3.1 Model Setup

Correct modeling of dissolved oxygen concentrations in an aquaculture pond is dependent upon an accurate description of those factors contributing to oxygen entry into the pond, oxygen removal from the pond, and oxygen distribution within the pond. The general form of the net oxygen change in the pond water column can be described as:

$$\frac{d[O_2]}{dt} = P - R + k([O_{2,\text{sat}}] - [O_2]) / z$$  \hspace{1cm} (3.18)

where:

- $\frac{d[O_2]}{dt}$ Net dissolved oxygen change ($mg_O_2/m^3 \cdot hr$)
- $P$ Instantaneous rate of photosynthetic oxygen production in the pond ($mg_O_2/m^2 \cdot hr$)
- $R$ Instantaneous rate of respiration in the pond ($mg_O_2/m^2 \cdot hr$)
- $k$ Molecular diffusivity of oxygen between air and water ($m/hr$)
- $O_{2,\text{sat}}$ Dissolved oxygen concentration at atmospheric equilibrium ($mg/m^3$)
- $O_2$ Dissolved oxygen concentration ($mg_O_2/m^3$)
- $z$ Mixed layer depth ($m$)

To simplify this calculation, the same procedure carried out in Section 3.2 is used, wherein the pond is divided into a number of control volumes. For each control volume, oxygen sources and sinks and identified and quantified using equations that are simple enough to be used with the available meteorological inputs (See Figure 3-10). For each control volume, the rate of change of dissolved oxygen may then be calculated as:
\[
\frac{d[O_2]}{dt}_{CV} = (DO_{ph} - DO_{pr}) - DO_{fr} - DO_{wcr} \pm DO_{air} - DO_{sed} \pm DO_d \pm DO_{conv}
\]  

(3.19)

where:

\[
\frac{d[O_2]}{dt}_{CV}
\]
Net dissolved oxygen change in the control volume

\(DO_{ph}\)
Photosynthetic oxygen production by phytoplankton

\(DO_{pr}\)
Respiration by phytoplankton (commonly referred to as photorespiration)

\(DO_{fr}\)
Respiration by cultured fish

\(DO_{wcr}\)
Water column respiration by other plankton-based biomass

\(DO_{air}\)
Diffusive oxygen exchange with the surrounding air

\(DO_{sed}\)
Respiration by benthic organisms in the sediment

\(DO_d\)
Diffusive oxygen transport between adjacent control volumes in the pond

\(DO_{conv}\)
Convective oxygen transport between adjacent control volumes in the pond

Note: All the terms in Equation 3.19 above are in units of \(mg_{O_2}/m^3\cdot hr\).

### 3.3.2 Sources and Sinks of Dissolved Oxygen

**Photosynthesis**

In most ponds used for aquaculture, phytoplankton provide the major source and sink for dissolved oxygen. The productivity of major phytoplankton species in the water column are affected by many factors, including intensity of photosynthetically active solar radiation (PAR), water column light attenuation, water temperature, pH and dissolved nutrient concentration. However, due to measurements limitations, only the effects of PAR are considered in the present model.

In estimating the rate of phytoplankton oxygen production, one of the most commonly used formulations is Steele’s equation, which has been successfully applied to several ecological models for aquaculture purposes [15]. Steele’s equation expresses
Figure 3-10: Dissolved Oxygen Model Simplified Diagram; Note that Items in Green are Oxygen Sources, Items in Red are Oxygen Sinks, and Items in Black May be Either

the gross primary production (GPP) rate in terms of three variables: light, phytoplankton light saturation, and maximum production rate, and can be written as [67]:

$$P = P_{\text{max}} e \left( I - \frac{I}{I_{\text{sat}}} \right) \frac{I_{\text{sat}}}{I}$$  \hspace{1cm} (3.20)

where P is the rate of photosynthetic oxygen production \((mgO_2/mg_{chl-a} \cdot hr)\), \(P_{\text{max}}\) is the maximum photosynthetic production rate \((mgO_2/mg_{chl-a} \cdot hr)\), I is the instantaneous PAR \((\mu mol/m^2 \cdot s)\), and \(I_{\text{sat}}\) is the PAR intensity at which light saturation
occurs \((\mu mol/m^2 \cdot s)\).

For use in the present model, Equation 3.20 was integrated to determine the total PAR absorbed in a given control volume using the following relation [67]:

\[
P_i = \frac{P_{\text{max}} e \left( e^{-\left(\frac{I_{\text{sat}}}{I_i}\right)} e^{-n_{i+1}} - e^{-\left(\frac{I_{\text{sat}}}{I_i}\right)} e^{-n_i} \right)}{\eta \Delta z} \tag{3.21}
\]

where \(P_i\) is the rate of photosynthetic oxygen production for volume element \(i\) \((mgO_2/mgchl-a\cdot hr)\), \(\eta\) is the light extinction coefficient \((m^{-1})\), \(z_i\) is the depth of the upper boundary of volume element \(V_i\) \((m)\), \(z_{i+1}\) is the depth of its bottom boundary \((m)\), and \(\Delta z\) is the thickness of the control volume.

Finally, to calculate the dissolved oxygen production as a function of time for a particular layer, the calculated GPP value is multiplied by the chlorophyll-a concentration, such that:

\[
DO_{ph_i} = P_i \cdot chl - a \tag{3.22}
\]

where \(DO_{ph_i}\) is the rate of oxygen production due to photosynthesis in control volume \(i\) \((mgO_2/m^3 \cdot hr)\) and \(chl - a\) is the concentration of chlorophyll-a in the pond \((mgchl-a/m^3)\).

Due to limitations on the data available from the ponds, some simplifications had to be carried out in order to estimate some of the variables in Equation 3.23. First, in determining \(I_{\text{sat}}\), the present model assumed that for locally adapted phytoplankton populations, no light inhibition occurs. Therefore, the value used for \(I_{\text{sat}}\) for a given simulation run was set equal to the maximum PAR intensity recorded at the pond surface at a particular site for the particular day being simulated. Second, the inclusion of some sort of substitute for \(P_{\text{max}}\) was also needed for the model present since detailed phytoplankton productivity studies were not carried out for this project. Typically, \(P_{\text{max}}\) is dependent upon the rate of carbon fixation by the phytoplankton and the particular species of phytoplankton. For this model, it was estimated as a temperature dependent variable, given by [75]:

60
\[ P_{\text{max}} = 9.6 \times \theta_P^{(\bar{T}_{V_i}-20)} \]  

(3.23)

where \( \bar{T}_{V_i} \) is average temperature of volume element \( i \) (°C) and \( \theta_P \) is an empirical photosynthetic primary production coefficient, empirically estimated as 1.036. While this approximation is not particularly accurate and could be the source of much error in the model, it has been used successfully in characterizing oxygen dynamics in inland lakes in the north-central United States [75].

Finally, an approximation of the chlorophyll-a concentration in the pond had to be implemented since attempts to sample and test water directly provided erroneous results. No universal method exists to estimate the concentration of phytoplankton, therefore chlorophyll-a concentration had to be calibrated for the model through trial-and-error. For trophic ponds, there is no typical range of values for chlorophyll-a concentrations, however, normally, it is rarely below 50 mg/m³ or above 500 mg/m³, and it was therefore ensured that the selected figure does not fall outside those bounds.

**Phytoplankton Respiration**

There are two aspects to phytoplankton respiration, depending on the time of day this respiration is taking place. During daytime, phytoplankton undertake photosynthesis in conjunction with respiration (hereafter referred to photorespiration). Depending on the amount of sunlight, the former typically dominates, and the overall impact is a rise in dissolved oxygen concentration in the water inhabited by the plankton. The rate of photorespiration has commonly been represented as some proportion of the rate of photosynthesis. For this model, the rate of photorespiration was taken to be 10% of the rate of photosynthetic oxygen production [76].

While the present model has to rely on this crude assumption, research on the subject has shown that, under most circumstances, this approximation has proved satisfactory for similar models of shallow ponds. Further, based on research by Giovannini, this rate of photorespiration was seen to persist up to three hours after sunset, indicating that phytoplankton continue to respire at this repressed rate before shifting
to the baseline nighttime respiration rate [76].

In estimating nighttime oxygen consumption, the respiration rate of the entire water column, including baseline phytoplankton respiration, zooplankton respiration, and respiration by other bacteria, had to be considered. Estimations of this water column respiration rate are most conveniently made using dark bottle incubations of water sampled from the water column. In this experiment, a water sample is taken from the pond and stored in a jar in a dark place for some period of time. Dissolved oxygen is measured before and after the experiment, and the difference is taken as the water column respiration rate.

Five such experiments were carried out in Vietnam, and four were carried out in Bangladesh, and results from those experiments were implemented in the dissolved oxygen model by adjusting the rate for water temperature as follows:

\[
DO_{wcr} = DO_{DB} \theta_r^{(T_w - T_{DB})}
\]

where \(DO_{DB}\) is the rate of water column respiration from the dark bottle experiment \((mg_O_2/m^3 \cdot hr)\), \(\theta_r\) is an empirical temperature adjustment, taken as 1.047 for this model [75], \(T_w\) is the instantaneous water temperature \(^\circ C\), and \(T_{DB}\) is the temperature at which the dark bottle experiment was run \(^\circ C\); this temperature was taken as the average temperature between the two recordings taken during the experiment.

**Sediment Respiration**

Sediment oxygen demand results from organic matter being deposited in the lakebed and decomposed by benthic organisms. This rate mainly depends on the temperature and the physical, chemical and biological characteristics of the bed. The equation for SOD is given by Thomann and Mueller as [77]:

\[
DO_{sed} = \frac{1}{z_{sed}} S_{20} \theta_s^{(T_w - 20)}
\]

where \(S_{20}\) is the known sediment oxygen demand at 20 \(^\circ C\) \((mg/m^2/h)\), \(\theta_s\) is an empirical thermal coefficient for benthic oxygen demand, taken as 1.065 for this model.
\[ T_w \] is the instantaneous water temperature (°C), and \( z_{sed} \) is the sediment control volume thickness (m).

Since sediment oxygen demand was not measured for either test site, values from literature had to be sampled and considered in the model. Studies in eutrophic estuarine ponds have found that \( S_{20} \) varies between 0.024 and 0.125, and as such, the model had to be calibrated to choose a suitable value that lies within those bounds.

**Fish Respiration**

Fish respiration is a complex process which depends upon the metabolic rate of the species of fish being cultured, nutrient availability, the age of the fish, its weight, its average swimming speed and temperature. For Vietnam, the exact types of species being cultivated, as well as their average adult weight and stocking density was provided by NISTPASS. In Bangladesh, however, only cursory knowledge of the stocking density is known, therefore simplifying assumptions had to be made in trying to estimate biologic oxygen demand from fish.

Boyd et al. formulated the following generic empirical equation relating the respiration rate of an average adult fish per unit weight (regardless of species) and water temperature [76]:

\[
R_f = 10^{(-1-9.57 \times 10^{-4}m_f + 6 \times 10^{-7}m_f^2 + 3.27 \times 10^{-2}T_w - 8.7 \times 10^{-6}T_w^2 + 3 \times 10^{-7}m_f T_w)} 
\]

(3.26)

where \( R_f \) is the respiration rate per weight of fish \( (mg_{O_2}/kg \cdot hr) \) and \( m_f \) is the average fish weight (g). In order to calculate the full community oxygen demand, the following equation is used:

\[
DO_{fr} = R_f \frac{Nm_f}{V} 
\]

(3.27)

where \( N \) is the number of cultured fish in the pond and \( V \) is the total volume of water in the pond \( (m^3) \). In order to account for the fact that fish will avoid areas of low dissolved oxygen in ponds, the model also took into account vertical migration.
by fish throughout the day. At each time step, the calculated dissolved oxygen concentration is compared with a reference value of 5 mg/L, considered to be the lower limit for survivability of most cultured fish species. If the calculated dissolved oxygen concentration is below this reference value, the model shifts the biomass of the fish in the bottom element to the middle volume element. The same procedure is then repeated for the middle volume element. In the event that the calculated dissolved oxygen concentration in all three volume elements is below the reference value, all of the fish biomass is considered to reside in the surface volume element. This fish distribution model is based on field measurements carried out by Lefevre et al. on Pangasius ponds in the Mekong Delta in Vietnam, with pond properties very similar to the ones being simulated in the present model [51].

Re-aeration

Diffusion of oxygen to or from the water surface and the overlying atmosphere is one of the most important factors under consideration for this model since it is the primary mechanism on which all aerators rely to increase dissolved oxygen content in a given pond. Re-aeration depends upon the difference between the saturation concentration of oxygen in the pond water and the actual dissolved oxygen concentration present in the surface water layer; in cases where oxygen exceeds the saturation limit in the thin water film close to the air layer, oxygen will diffuse out of the water. The mass rate of oxygen transfer has been shown to be a function of an oxygen transfer coefficient as:

$$DO_{air} = \frac{1}{z_1}K_L(C_S - C)$$

(3.28)

where $DO_{air}$ is the rate of diffusion across the air/water interface ($mgO_2/m^3\cdot hr$), $K_L$ is the oxygen transfer coefficient ($m/h$), $C_S$ is the saturation concentration of dissolved oxygen in water at a given elevation, salinity and temperature ($mgO_2/m^3$), $C$ is the instantaneous dissolved oxygen concentration ($mgO_2/m^3$), and $z_1$ is the thickness of the first volume element in the model. $C_S$ may be calculated using Equation 2.1,
which is given by:

\[ C_S = 1.43 \exp \left( -173.43 + 249.63 \left( \frac{100}{T_w} \right) + 143.35 \ln \left( \frac{T_w}{100} \right) - 21.85 \left( \frac{T_w}{100} \right) \right) \]  \hspace{1cm} (3.29)

where \( T_w \) is the water temperature (°C). Since all ponds used for this study were freshwater ponds, no salinity compensation was necessary in calculating the saturation limit.

Finally, to compute the oxygen transfer coefficient, \( K_L \), the equation discussed by Crusius and Wanninkhof, which was used successfully for research on low wind shear rates over a lake, was applied as [78]:

\[ K_L = 0.0036(8.43\sqrt{W} - 3.67W + 0.43W^2) \]  \hspace{1cm} (3.30)

where \( W \) is the wind speed at a reference height of 2 m above the water surface (m/s).

**Diffusion Across the Water Column**

Effective diffusion of oxygen in the present model is assumed to follow that of energy diffusion described for the temperature model in Section 3.2. While there might be other ways in which to conceptualize and define the effective diffusion of oxygen within the pond water volume, the successful use of this assumption by Losordo recommended identical treatment of oxygen diffusion in the present model [67]. The calculation of the diffusion of oxygen between water volume elements is therefore:

\[ DO_{d,V_i} = \frac{1}{(z_{i+1} - z_i)^2} K_z (DO_{V_{i+1}} - DO_{V_i}) \]  \hspace{1cm} (3.31)

where:
\( DO_{d,V_i} \) Net diffusive oxygen flow into volume element \( i \) \( (mgO_2/m^3 \cdot hr) \)

\( K_Z \) Diffusion coefficient at depth \( z \) \( (m^2/hr) \) - See Equation 3.13

\( z_i \) Depth of the center of mass of volume element \( i \) \( (m) \)

\( z_{i+1} \) Depth of the center of mass of volume element \( i+1 \) \( (m) \)

\( DO_{V_i} \) Dissolved oxygen concentration in volume element \( i \) \( (mgO_2/m^3) \)

\( DO_{V_{i+1}} \) Dissolved oxygen concentration in volume element \( i+1 \) \( (mgO_2/m^3) \)

### 3.3.3 Model Implementation and Results

Once the equations governing all sources and sinks of dissolved oxygen in the system were formulated, a time-series simulation of the model was set up in MATLAB with 15 minute time steps, equivalent to the logging intervals of the weather station sensors. As with the thermal stratification simulations, all inputs to the model were obtained directly from field observations and are summarized in Table 3.4. The full formulation of the MATLAB code used for the current model is attached in Appendix C. For each control volume and time step in the simulation, the dissolved oxygen is calculated as:

\[
DO_{t,CV}^t = DO_{t-1,CV}^{t-1} + DO_{net}^{t,CV} \Delta t
\]

where:

- \( DO_{t,CV} \) Dissolved oxygen concentration for the current time step \( (mgO_2/m^3) \)
- \( DO_{t-1,CV} \) Dissolved oxygen concentration for the previous time step \( (mgO_2/m^3) \)
- \( DO_{net} \) Rate of change of dissolved oxygen for the current time step \( (mgO_2/m^3 \cdot hr) \)
- \( \Delta t \) Time step length \( (hr) \)

In order to check for the accuracy of the model, the same three days in Bangladesh used to validate the temperature model, were chosen as a test case for the current model; those days were June 21 through June 23, 2016. The results of this simulation are shown in Figure 3-11; on the chart, the markers represent recorded measurements.
from dissolved oxygen loggers placed in the top and bottom control volumes respectively, and the solid lines represent the simulated dissolved oxygen concentrations for the same time period.

Table 3.4: Dissolved Oxygen Model Inputs

<table>
<thead>
<tr>
<th>Input Variable</th>
<th>Units</th>
<th>Bangladesh</th>
<th>Vietnam</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photosynthetically Active Radiation</td>
<td>μmol/m²/s</td>
<td>time series</td>
<td>time series</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>m/s</td>
<td>time series</td>
<td>time series</td>
<td>Weather Station</td>
</tr>
<tr>
<td>Water Temperature</td>
<td>°C</td>
<td>time series</td>
<td>time series</td>
<td>Temperature Model</td>
</tr>
<tr>
<td>Water Column Respiration Rate (WCRR)</td>
<td>mg/L/hr</td>
<td>0.5</td>
<td>N/A</td>
<td>Dark Bottle Experiment</td>
</tr>
<tr>
<td>WCRR Temperature</td>
<td></td>
<td>26</td>
<td>N/A</td>
<td>Dark Bottle Experiment</td>
</tr>
<tr>
<td>Total Fish Biomass</td>
<td>kg</td>
<td>800</td>
<td>1,800</td>
<td>Field Measurement</td>
</tr>
<tr>
<td>Fish Count</td>
<td>g</td>
<td>400</td>
<td>472</td>
<td>Field Measurement</td>
</tr>
<tr>
<td>Secchi Disk Depth</td>
<td>in</td>
<td>6</td>
<td>13</td>
<td>Field Measurement</td>
</tr>
</tbody>
</table>

The simulations appeared to track the diel pattern well, with good overall agreement on all three days, in spite of the largely disparate wind, temperature and irradiance profiles over that period. A larger simulation timeframe could have provided a better assessment of the modeled dissolved oxygen levels, however, severe sedimentation on the dissolved oxygen logger sensor membranes in the ensuing days, coupled with terrestrial sensor malfunctions, reduced the number of available inputs and made it impossible to produce a model or to carry out any meaningful validation. This sedimentation is suspected to be due to soil particles dislodging from the pond bed and depositing onto the dissolved oxygen sensor membrane. A precaution currently being undertaken to tackle this problem is to cover the areas below the loggers with an impermeable tarp in order to reduce the amount of suspended soil particles near the sensor membranes.

In addition to diel tracking, the onset of nighttime partial destratification, which is reflected by the end-of-day rise in dissolved oxygen in the bottom volume, is predicted well by the model. On the third day, however, the model predicted some mix of diffusive and convective circulation in the early hours, leading to a rise in the bottom dissolved oxygen level that is not reflected in the field measurements. It is speculated that this divergence may have been caused by membrane fouling in the bottom dis-
solved oxygen logger during those hours, since it is extremely unlikely for water to have been consistently completely anoxic during that time. Additionally, since the simulated top control volume results were slightly higher than the field measurements during the early hours of the third simulation day, the amount of dissolved oxygen being transported to the bottom volume due to the diffusion or convection may have
been overestimated.

Regarding the peaks and troughs of the simulated dissolved oxygen profiles, the model seems to produce good results, with agreement within 15% of the peaks and troughs of the recorded measurements. The singular exception was the second day, during which the simulated results correctly reflected the double-peak in dissolved oxygen but failed to accurately predict the value of the apex of the second peak. In studying the PAR plot for that day, however, it was peculiar that dissolved oxygen spiked significantly higher on the second peak than the first since the integrated area underneath the PAR curve - the indicative measure of cumulative dissolved oxygen buildup due to photosynthetic production - was only slightly larger for the second peak than the first (See Figure 3-13).

Figure 3-13: Measured PAR and Dissolved Oxygen Curves for June 22, 2016

One potential source of error that may have resulted in this deviation from field values is the simulation’s granularity due to the model’s long-duration time steps, as well as the lengthy logging intervals for the weather station and loggers; shorter time steps could better resolve fluctuations in the measurements, producing a better model fit to the field measurements. Additionally, it is possible that the 1-D eddy diffusivity model may be overestimating inter-layer diffusion, resulting in a large amount of oxygen being transported away from the top volume and into the bottom one.

While the implementation of the eddy diffusivity model in its current form pro-
vides reliable oxygen transport figures most of the time, the method of accounting for convection by assigning a maximum $K_z$ value and calibrating it for the model results in large spikes in oxygen transport (see Figure 3-12), which are likely not reflective of actual advective transport phenomena. A formulation which involves calculating the Nusselt number and estimating convective transport accordingly was attempted, but due to the presence of only two control volumes, the results produced were just as granular - and more unstable - than the eddy diffusivity method. As with the temperature model, if more field data was available, the best approximation for oxygen distribution may be achieved by using a CFD model which incorporates as source terms the various sources and sinks of dissolved oxygen; those terms would be implemented as time series user-defined functions which are based on the equations described in the section herein.

Ultimately, however, the predictive accuracy of the dissolved oxygen model remains quite high in spite of the mass-balance modifications and model simplifications. Its largest benefit is that it can be initialized using the temperature model using few field inputs, and then in turn, it may be used to predict and optimize the performance of the aeration system, the modeling of which is discussed in the section below.

### 3.4 Proposed Concept and CFD Modeling

In this section, the proposed design for inducing convective circulation in the pond is described conceptually, followed by a detailed discussion of Computational Fluid Dynamics (CFD) models carried out on geometries representative of the concept. This includes the model setup, key numerical simulation parameters, Design of Experiments (DOE), and a performance estimate for the device. Ultimately, full-scale prototypes designed around this concept have been constructed and tested. A discussion of the mechanical design aspects of those prototypes, as well as the results of field trials, is covered in chapter 4. Only the CFD modeling for the Vietnam prototype is covered under the scope of this thesis.
3.4.1 System Conceptualization

Borrowing from the working principle of solar updraft towers, the concept put forth to stimulate passive circulatory destratification in fish ponds utilizes a solar collector, which conducts heat through a partially-insulated heating element to the deeper, colder strata of the pond. This heat induces convection in the surrounding water column, resulting in oxygen-deficient water rising through a draft tube to the surface, whereupon it is oxygenated on contact with the air. Meanwhile, oxygen-rich water at the surface sinks to the bottom, increasing the overall dissolved oxygen content of the deeper layers of the pond. This process would serve to overcome the natural stratification of the pond and provide the fish with a greater habitable volume where they can both respire comfortably and remain away from the warm water at the surface. In order to minimize heat losses from the device, the bottom of the solar absorber as well as a portion of the heat conductor would have to be thoroughly insulated. A diagram of the concept is shown in Figure 3-14.

![Diagram](image_url)

**Figure 3-14: Diagram of the Proposed Solar-Thermal Circulation System**
3.4.2 CFD Model Setup

A two-dimensional, axisymmetric geometry representative of the conceptual configuration outlined above was sketched using ANSYS Fluent. A schematic of this geometry is shown in Figure 3-15 (Note that only half the geometry is sketched since the model is mirrored about the z-axis). In this model, a number of dimensions were held constant for all simulations: First, the height of the fluid domain, 2 m, was dictated by the pond dimensions in Vietnam. Second, regarding the width of the fluid domain, it was observed that the smaller the radius, the better the circulatory performance, however, it was also desired to maximize the radius of influence of the device; through preliminary simulations, it appeared that circulation diminishes rapidly past 5 m, therefore it was selected as the domain width. Third, the height of the collector above the water surface was specified as 15 cm as a matter of practicality; a 0 cm gap would be more favorable from a performance and cost standpoint since it reduces the length of the heat conductor, however, it was expected that during the mechanical design phase, some space would be required during installation. Finally, the gaps between the water surface and the draft tube, as well as the pond bottom and the draft tube were selected to be approximately 20 cm since they had little influence on the upward mass flowrate through the draft tube during operation.

The remaining dimensions, hereafter referred to as factors, labeled A through D on Figure 3-15, were chosen by sampling the design space using the Taguchi Method for Design of Experiments (DOE). For this process, each of the four factors were assigned three feasible dimensions, hereunder referred to as levels. A summary of those factors and levels are compiled in Table 3.5 below. A Taguchi 3^4 L9 Orthogonal Array was then set up for the design space using the statistical software package Minitab 17, which specified 9 experiments with 9 combinations of levels. Those experiments were then run in Fluent sequentially; for every run, the mass flowrate through the draft tube was monitored for the entire duration of the transient simulation. The average mass flowrate for the simulation was then inserted in Minitab, which assessed the results for the Main Effects and Dependencies between levels for each factor. Further
discussion of the results of the DOE study follows in Section 3.4.5 below.

3.4.3 Numerical Parameters

Boundary Conditions

The boundary conditions used for momentum and energy equations in the CFD model are summarized in Table 3.6. For the top surface of the solar collector absorber, a user-defined function (UDF) consisting of hourly recorded solar heat flux values from the Vietnam weather station, is implemented as a transient heat generation thermal condition. To account for radiative heat losses from the plate, external radiation parameters, including emissivity ($\epsilon$) and sky temperature ($T_\infty$) were also specified for the top of the absorber plate; since air temperature data for the site was sporadic and spaced at long time intervals, it was not possible to formulate a UDF for the sky temperature; instead, a constant number was estimated as $T_\infty = 0.95T_{amb}$ [79],

Figure 3-15: Model Geometry With Dimensional Variables

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Table 3.5: Factors and Levels for Taguchi DOE

<table>
<thead>
<tr>
<th>Factors</th>
<th>A (Absorber Length)</th>
<th>B (Conductor Diameter)</th>
<th>C (Conductor Length)</th>
<th>D (Draft Tube Gap)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Levels</strong></td>
<td>0.5 m</td>
<td>0.5 in</td>
<td>1 m</td>
<td>6 in</td>
</tr>
<tr>
<td></td>
<td>0.625 m</td>
<td>1 in</td>
<td>1.25</td>
<td>8 in</td>
</tr>
<tr>
<td></td>
<td>0.75 m</td>
<td>2 in</td>
<td>1.5 m</td>
<td>10 in</td>
</tr>
</tbody>
</table>

where $T_{amb}$ was the taken as the average ambient air temperature for the site as obtained from NCEI GIS maps for a ground weather station in Srimangal, Bangladesh [74]. Convective losses from this the solar thermal collector surface were ignored in the model since it was decided to glaze the absorber with a glass cover. With the exception of the bare section of the conductor rod and the water surface, adiabatic boundary conditions were set for all external domain walls; the former’s thermal boundary condition specified using a UDF containing hourly recorded water surface temperatures from dissolved oxygen loggers in the field.

Table 3.6: Model Boundary Conditions

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Momentum</th>
<th>Thermal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Absorber</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Face</td>
<td>-</td>
<td>Insolation UDF, Radiative Losses</td>
</tr>
<tr>
<td>Sides and Bottom</td>
<td>-</td>
<td>Adiabatic</td>
</tr>
<tr>
<td><strong>Heat Conductor</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulated Section</td>
<td>No-slip</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>Bare Section</td>
<td>No-slip</td>
<td>Coupled</td>
</tr>
<tr>
<td><strong>Pond</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Surface</td>
<td>Free-slip</td>
<td>Temperature UDF</td>
</tr>
<tr>
<td>Sides</td>
<td>No-slip</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>Bottom</td>
<td>No-slip</td>
<td>Adiabatic</td>
</tr>
<tr>
<td>Draft Tube</td>
<td>No-slip</td>
<td>Adiabatic</td>
</tr>
</tbody>
</table>

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Initial Conditions

For all transient simulations, the timeframe was the 12 hours during which solar irradiance was not zero; solar heat flux and water surface temperature data for any given day were derived from field and were inserted into the simulations using UDFs at 10 minute intervals. As such, the pond and device were assumed to be in equilibrium at $t = 0$, with the initial temperature being equal to the first temperature in the field data time series. Future work will investigate the means to model thermal stratification, and therefore study its impact on water flow and heat transfer from the device.

Physics Model and Solver Setup

For free convection flows caused by a heat flux input, the Rayleigh number is used to compute an approximation of a solution for buoyant flows. In this case, it may be used to characterize the nature of the flow regime in the boundary layer around the heating wall, and it is given by the following equation:

\[ Ra_L = \frac{\dot{q}_w g \beta L^4}{\nu \alpha \lambda} \]  

(3.33)

where:

- $\dot{q}_w$ heat flux from the heating surface to the water per unit area ($W/m^2$)
- $\beta$ volumetric coefficient of expansion of water ($K^{-1}$)
- $L$ length of the exposed heating surface in water ($m$)
- $\nu$ coefficient of dynamic viscosity ($Pa.s$)
- $\alpha$ thermal diffusivity of water ($m^2/s$)
- $\lambda$ thermal conductivity of water ($W/m.K$)

For systems where all the parameters in Equation 3.33 are known, the Rayleigh number may be calculated and then, depending on its value, used to calculate the Nusselt number using a series of empirical equations. The Nusselt number can then, in turn, used to estimate an approximate buoyant flow velocity. However, for the
given system, assuming perfect glazing, the overall energy balance on the system is given by:

\[ \dot{q}_w = \dot{q}_{solar} - \dot{q}_{rad} \]  

\[ (3.34) \]

where \( \dot{q}_{rad} \) is the radiative heat loss from the upper face of the collector.

Since \( \dot{q}_w \) and \( \dot{q}_{rad} \) are interdependent and neither can be ascertained, a unique value of \( Ra_L \) cannot be determined, and it is therefore not possible to analytically characterize the flow regime or velocity. This necessitates the use of numerical simulations, which simultaneously solve the Continuity, Navier-Stokes, and Energy equations to arrive at a converted flow regime. In this case, flow was known to be turbulent in the boundary layer around the uninsulated section of the conduction rod, since preliminary estimates of \( \dot{q}_w \) determined that \( Ra_L \) would always greater than \( 10^9 \), the threshold for turbulent flow. Since turbulent flow is both time- and space-dependent, it becomes necessary to split the instantaneous velocity and pressure variables in the Navier-Stokes equation into two parts, one representing the mean component and one representing the fluctuating component, in a process known as Reynolds Decomposition. The resulting time-averaged equation of motion is referred to as the Reynolds-averaged Navier-Stokes (RANS) equation, and is given by:

\[
\frac{\partial (\rho \bar{U}_i)}{\partial t} + \frac{\partial}{\partial x_j} \left( \bar{U}_i \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \right) = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \right) - \frac{\partial}{\partial x_j} \rho \left( \bar{u}'_i \bar{u}'_j \right) + \rho g \]  

\[ (3.35) \]

where \( \bar{U}_i \) is the fluid velocity, \( \bar{P} \) is the fluid pressure, \( \rho \) is the temperature-dependent fluid density, and \( \mu \) is the fluid dynamic viscosity. The different terms correspond to the inertial forces, including a time-varying term (1), pressure forces (2), viscous forces (3), a nonlinear term owing to the fluctuating velocity field, \( \tau_{ij} = -\bar{u}'_i \bar{u}'_j \), known as the Reynolds Stress Tensor (4), and the buoyancy force (5).

Since the introduction of mean and fluctuating components to the field variables adds two unknowns embedded in the Reynolds Stress Tensor, additional equations
are needed to close the RANS equation. Those equations are collectively referred to as turbulence model equations. Multiple approaches to formulate those turbulence equations exist, therefore a literature evaluation was necessary to choose a computationally economical and robust model for the simulations.

For most turbulence models, the basis for formulating a RANS-closing equation is the Eddy Viscosity Model (EVM). This method relates the Reynolds stresses to the mean velocity gradients as

\[-\overline{u'_i u'_j} = 2\nu_t S^*_{ij} - \frac{2}{3}K \delta_{ij},\]

where \(S^*_{ij}\) is the mean strain-rate tensor, \(\delta_{ij}\) is the Kronecker delta, \(K\) is Turbulence kinetic energy, and \(\nu_t\) is the kinetic eddy viscosity. To solve the latter two terms, and therefore characterize the turbulence in the model, several options exist. Results published by Wu et al. show that for a differentially-heated enclosed square cavity filled with air, the SST k-\(\omega\) model has the best overall performance in terms of reproducing time-averaged turbulent quantities compared to four other RANS models investigated in the study [80]. Ganguli et al. demonstrated good agreement between experimental results and predictions of the SST k-\(\omega\) model applied to a cylindrical container filled with water and heated by an axially-aligned cylinder [81]. Those results were satisfactorily reproduced in benchmark simulations in Fluent, and therefore it was decided to proceed with the SST k-\(\omega\) model for turbulence characterization. The RANS equations for the model include two turbulence terms, one for turbulent kinetic energy (k), and one for specific dissipation rate (\(\omega\)), to solve for \(K\) and \(\nu_t\). In Fluent, all the default closure coefficients are used.

To account for the buoyant aspect of the flow, the full formulation of the RANS equations may be numerically solved. However, in this case, since the expected temperature difference between the submerged heating surface and surrounding water is less than 40 °C, the Boussinesq approximation is used. Using this method, density variations may be ignored in the RANS equation for every term except the body force term. This results in the equation:

\[
\rho_0 \left( \frac{\partial \tilde{U}_i}{\partial t} + \tilde{U}_j \frac{\partial \tilde{U}_i}{\partial x_j} \right) = - \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \tilde{U}_i}{\partial x_j} + \frac{\partial \tilde{U}_j}{\partial x_i} \right) \right) - \rho_0 \frac{\partial}{\partial x_j} \left( \overline{u'_i u'_j} \right) + \rho g \quad (3.36)
\]
where \( \rho_0 \) is a constant reference density term selected to be as close to the operating temperature as possible.

Under the Boussinesq approximation, the density term in the buoyancy force can be rewritten as \((\rho_0 + \Delta \rho)g\), where \(\Delta \rho = \rho - \rho_0\) represents the density variation with respect to the reference density \(\rho_0\). This yields:

\[
\rho_0 \left( \frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} \right) = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \bar{U}_i}{\partial x_j} \frac{\partial \bar{U}_j}{\partial x_i} \right) \right) - \rho_0 \frac{\partial}{\partial x_j} \left( u'_i u'_j \right) + (\rho_0 + \Delta \rho)g 
\]

To eliminate the numerical dependence of the fluid density on the local temperature, the modified buoyancy term can further be rewritten as \((\rho_0 + \Delta \rho)g = -\rho_0 \beta (T - T_0)g\), where \(\beta\) is the coefficient of thermal expansion. The equation finally simplifies to:

\[
\rho_0 \left( \frac{\partial \bar{U}_i}{\partial t} + \bar{U}_j \frac{\partial \bar{U}_i}{\partial x_j} \right) = -\frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \left( \frac{\partial \bar{U}_i}{\partial x_j} \frac{\partial \bar{U}_j}{\partial x_i} \right) \right) - \rho_0 \frac{\partial}{\partial x_j} \left( u'_i u'_j \right) - \rho_0 \beta (T - T_0)g 
\]

where \(T_0\) is the reference temperature for \(\rho_0\). In applying this approximation, the variable \(\rho\) term is removed from the RANS equation and is replaced with a constant reference density the value of which scales with temperature increases in the fluid domain. This increases the numerical stability of the simulations and allows for faster convergence.

For the numerical solution setup in Fluent, a pressure-based solver with the Pressure Implicit with Splitting of Operators (PISO) algorithm was used to solve discretized numerical equations for continuity, energy, and momentum. Density was defined according to the Boussinesq Approximation. The second order upwind scheme was used for spatial discretization for energy and momentum, while a second order implicit formulation was used for the transient analysis. Finally, the under-relaxation factors used were 0.3, 0.1, 0.9 for the pressure, velocity, and energy calculations respectively.
At every time step, 20 iterations were performed to ensure convergence, with scaled residual criteria set at $10^{-4}$ for continuity, momentum, k, and $\omega$. and at $10^{-7}$ for energy.

**Model Assumptions**

The following simplifying assumptions were made in the model:

- Convective losses from the top surface of the solar collector were neglected due to the use of glazing in the design. While the solar collector cover does reduce convection, some amount of conjugate heat transfer will take place with the surrounding air as long as the gap between the absorber and cover is not vacuum. Those losses were not been accounted for in the model due to the complexity of parameterizing all the aspects of this type of heat transfer.

- Heat transfer at the water surface was not modeled, and neither was stratification through the water column, due to the difficulty in estimating convection transfer and stratification coefficients throughout the day. Instead, a time-series temperature UDF boundary condition was applied at the top surface of the water.

- Insulating materials were perfect (i.e. zero heat losses on the insulated surfaces) Insulation materials were assumed to have zero thickness.

- Contact resistance at the weld is not considered in the model.

- The water properties (specific heat, thermal conductivity and viscosity) were assumed to be constant and independent of the other thermodynamic characteristics in the system.

- The model was solved as a 2D axisymmetric geometry and not in 3D. This decision was informed by two findings: First, when 3D models for the same geometry were analyzed, they produced sufficiently similar results to the 2D
axisymmetric case, albeit at the expense of longer convergence times and numerical instabilities. Second, a study conducted by Ganguli et al. on natural convective flows in enclosed cavities experimentally validated the axisymmetric assumption [81]. In that study, a cylindrical glass tank with thermally insulated sides was set up. An axially-aligned tube carrying steam at a controlled flow rate served as a constant heat flux input to the fluid domain. Velocity data was then acquired using PIV, and streamlines of the flow were plotted. When compared against 2D CFD simulations of half the geometry rotated about the central axis, excellent agreement was found. Those results were further reinforced by a similar study carried out by Gandhi et al. which investigated the same type of flow, albeit at higher Rayleigh numbers.

3.4.4 CFD Model Rigor

Mesh Independence

In order to ensure mesh independence in the DOE simulations, a number of simplified transient simulations with long time steps were run for 4 mesh geometries with progressively smaller cells. For all simulations, all dimensions and input parameters were kept constant, and the model’s numerical parameters were fixed and made consistent with the criteria outlined in Section 3.4.3 above. The time-varying UDF components for insolation and water surface temperatures, however, were replaced with constant values in order to arrive at converged solutions in shorter times.

One complicating factor in this study was that the fluid geometry was split into multiple zones strategically sized to permit for differential sizing of the mesh cells throughout the domain and to provide an even a mapped-mesh as possible. That is, not all cells in the fluid zone were sized equally, but rather some parts were more finely-sized than others. The aim of this strategy was to concentrate the fine cells in the boundary condition, where the required mesh resolution is high, and reduce it in other areas where the flow dynamics do not require a fine mesh size. Additionally, an appropriate inflation layer thickness was applied on all boundaries to accommodate
for the thermal and hydraulic boundary layer thickness, which provided an extra variable for mesh independence.

Figure 3-16: Refined Final Mesh

To simplify the process, a sufficiently small mesh size was selected for those parts of the domain away from the heating section, and only the mesh in the vicinity of the heat conductor, where the convective boundary layer exists, was varied for three runs. For each run, the mass flow rate through the draft tube was calculated, and it was assured that the $y^+$ value in the boundary layer did not exceed one; if it did, further refinement of the inflation layer was carried out. The final mesh setup the results of which showed mesh-independence is shown in Figure 3-16.

**Time Step Independence**

The time step, $\Delta t$, is an important setting for any transient CFD simulation; too small a time step will result in very long processing times, and too long a time step will not resolve time-dependent features in the flow. While adaptive time-stepping may be carried out by the Fluent solver to efficiently adjust the time step size depending on the state of the flow field, this function was found to make the simulations unstable. Therefore, a fixed global time step size was used. Several guidelines are available to aid in the initial selection of an appropriate time step. One option, offered by Fluent, is to select the time step such that it is equal to the the typical cell size divided
by the expected characteristic flow velocity. A slightly more refined alternative is to calculate the time step as [82]:

\[ \Delta t \approx \frac{\tau}{4} \]  

(3.39)

where \( \tau \), the time constant, is given by:

\[ \tau = \frac{L}{U} \sim \frac{L^2}{\alpha \sqrt{PrRa}} = \frac{L}{\sqrt{g\beta \Delta TL}} \]  

(3.40)

For most simulations, the necessary time step was estimated to be \( \approx 0.5 \) s. However, transient sensitivity testing for higher time steps found that adequate convergence and repeatable results can be acquired at \( \Delta t = 2s \), which became the basis for most subsequent simulations.

A time step study by Khabbazi et al. on a similar convective circulation device, albeit with a different design, validated the choice of a 2s time step [83]. The study found that, for transient simulations, convergence at 7,200 s may be achieved at a time step as large as 8 s (See Figure 3-17). The authors note, however, that their models assumed a constant heat flux on the solar collector, which meant that poor resolution due to excessive time steps at the beginning of the simulation (0-2400 s) had little bearing on the final outcome, since all simulations ultimately converged to one mass flow rate. However, for a transient simulation with a time-varying heat flux, such as the one being implemented for this project, good resolution is necessary throughout the simulation to arrive at an accurate diurnal snapshot of the device’s performance. From a plot of the results, it was qualitatively observed that the resolution benefit gained from using 2s time steps is minimal, while an appreciable loss in resolution was seen going from 2s to 3s.

3.4.5 Results

Once the model was set up, it was parametrized and all nine DOE simulations were run. In order to preserve time for those simulations, a fixed heat flux was applied to the solar collector and the energy equation was allowed to solve transiently until
the temperature of the rod was sufficiently high in the water; at that point, the flow and turbulence equations were turned on, and the simulation was ran until the mass flow rate reached steady state. The time series UDF data for all simulations was derived from field measurements logged on April 16th, 2016 in Vietnam, and upward mass flowrate through the draft tube was used as the response data for the DOE array. Those responses were then analyzed in Minitab, and the results are shown in Figure 3-18. The four charts show the main effect plots for each factor over the range of chosen levels. The greater the mean of means for a given level, the more positive is the correlation between that level and the resultant mass flow rate, and vice versa. Additionally, the more steep the transition from one level to the next, the more pronounced its effect on the simulation result.
As expected, for the absorber length and conductor diameter, the largest dimension proved to have the strongest positive impact on mass flowrate. For the conductor length, little statistically significant difference in the response is seen, indicating that this dimension has little impact on convection circulation; this is likely due to the fact that temperature dissipates rapidly along the length of the rod due to the high heat capacity of the water, as well as the high thermal conductivity of the aluminium. As a result, to reduce the cost and weight of the device, it was decided to proceed with the smallest length. Finally, for the draft tube gap, the smaller the tighter the draft tube, the better the flow. This is due to the fact that convection primarily takes place within the boundary layer of the heated surface; beyond that layer, the streamlines begin to shed off the wall and vortices that counter the upward flow form in the gap between the draft tube and the heat conductor. Therefore, it is desirable to keep this gap as tight as possible.

Figure 3-19: Vector Plot for Selected Device Dimensions at $q_{solar} = 650 \ W/m^2$

Once the DOE was complete, a final geometry with the chosen dimensions was sketched, meshed, and simulated. A vector plot of velocity and a contour plot of the temperature distribution are given in Figures 3-19 and 3-20 respectively. Those plots represent snapshots of the flow near peak solar irradiance (650 W/m²) in the
insolation UDF time series. Peak velocities can be observed within the local boundary layer between the heating surface and the draft tube. A number of secondary flows are also visible near the draft tube opening and corners of the flow domain; those counter-flows and vortices reduce the overall upward mass flowrate and may be inhibited by further reducing the draft tube diameter. Figure 3-20 shows temperature contours on the absorber, as well as along the length of the conduction rod. The net temperature difference inducing buoyancy in the surrounding water occurs on a small section of the exposed length of the rod. This difference ranges between 3-4 °C. The local temperature increase in the water is limited to just beyond the thermal boundary layer along the conduction rod. The use of a lower-conducting material such as steel instead of aluminum would result in a higher temperature difference, but dissipation along the conduction rod would be too rapid as to create a consistent column of upward flow in the draft tube with minimal shedding.

During mid-day, the rate of heat transferred to the surrounding water per unit area of the heating surface, $q_w$, was determined to be 940 $W/m^2$. Equation 3.33 then yields the Rayleigh number $Ra_L = 3.3 \times 10^{10}$, which classifies the convective flow around the conduction rod as being turbulent. This validates the assumption made
earlier for the use of a 2-equation turbulence model.

### 3.4.6 Predicted Effect on Dissolved Oxygen

![Graph showing dissolved oxygen transport rates](image1)

**Figure 3-21: Calculated Oxygen Transport Rates due to Device Circulation**

![Graph showing dissolved oxygen profile prediction](image2)

**Figure 3-22: Dissolved Oxygen Profile Prediction with Aeration Device**

A plot of the dissolved oxygen convective flowrate through the draft tube for
the entire duration of the simulation is shown in Figure 3-21. Also overlaid on the graph is the solar irradiance for that day. For clear days such as the one chosen for this simulation, the peak mass flow coincides with the peak irradiance. However, on days where irradiance is irregular, peak mass flow often lags peak irradiance due to the thermal inertia of the system. Integrating the area under the flowrate curve, the total water mass displaced by the device by circulation is found to be 580 kg. This equates to an average circulation rate of 49 kg/hr, with a peak flow of 69 kg/hr.

In order to assess the impact of this flowrate on the dissolved oxygen distribution in the pond, the CFD mass flowrate results were coupled with the dissolved model discussed in Section 3.3. This was carried out by adding a time-series variable, \(DO_{conv}\), comprising the mass flowrates from the CFD model, to the dissolved oxygen model. The resultant dissolved oxygen profiles was then plotted alongside the simulated profile without the device. Those results are shown in Figure 3-22. Two improvements are observed from those simulations: First, the dissolved oxygen concentration in the bottom control volume increased by almost 60 %, while the concentration in the top control volume was almost unchanged. While the peak dissolved oxygen concentration for the upper control volume is slightly lower with the device, the overall content is largely unchanged due to re-aeration and fewer diffusive losses to the bottom layer later on in the day. Second, the onset of de-stratification is advanced by almost 2 hours, resulting in post-sunset dissolved oxygen values that are almost 30% higher on average than in the absence of the device. Most importantly, the number of hours during which the dissolved oxygen concentration in the bottom control volume is above the limit is above 4 mg/L - the limit below which Pangasius growth is adversely affected - increases from 2 hours to 5.75. This provides the fish a greater habitable volume to swim in, and therefore permits the farmer to increase their stocking density.

While dissolved oxygen in the later hours of the day eventually drops almost to zero in a single day’s simulation, over several sunny days, it would be expected that nighttime dissolved oxygen would plateau at higher levels, thereby alleviating some of the oxygen stress fish suffer at night.
3.5 Summary

In this chapter, a description of the test sites used for meteorological data collection for the project was provided, in addition to an outline of the sensor layout at both sites. This was followed by an examination of two mechanistic pond stratification models, one for temperature and one for dissolved oxygen. The aim of developing those models was to gain a better understanding of dissolve oxygen dynamics in fish ponds and to assess the effect of the proposed convective circulation device on the cumulative oxygen levels in the pond. Finally, in an attempt to select dimensions for the prototypes, a CFD model was developed using result from a Taguchi Design of Experiments (DOE) 9-experiment orthogonal array. Based on the results of the DOE, dimensions were selected for prototypes to be installed in Vietnam and Bangladesh. Those dimensions are outlined in Tables 3.7 and 3.8 respectively. Of note is that, for the Vietnam design, the draft tube diameter is larger than that estimated by the DOE mean of means results; this is due to the fact that this aspect of the design was not modeled correctly prior to the construction of the prototype. The procedure for sizing the Bangladesh prototype was outside the scope of this project and was therefore not covered in the chapter.

Table 3.7: Prototype Sizing for Vietnam

<table>
<thead>
<tr>
<th>Item</th>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Collector</td>
<td>L x W x Th</td>
<td>1.25 m x 1.25 m x 5/16 in</td>
</tr>
<tr>
<td>Heat Conductor Element</td>
<td>DIA</td>
<td>2 in</td>
</tr>
<tr>
<td>Draft Tube</td>
<td>ID x Th</td>
<td>8 in x 0.25 in</td>
</tr>
<tr>
<td>Weight</td>
<td>Wt</td>
<td>90 kg</td>
</tr>
<tr>
<td>Buoys</td>
<td>Vol</td>
<td>55 L</td>
</tr>
</tbody>
</table>
Table 3.8: Prototype Sizing for Bangladesh

<table>
<thead>
<tr>
<th>Item</th>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Collector</td>
<td>L x W x Th</td>
<td>1.25 m x 1.25 m x 5/16 in</td>
</tr>
<tr>
<td>Heat Conductor Element</td>
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<td>90 kg</td>
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<tr>
<td>Buoys</td>
<td>Vol</td>
<td>55 L</td>
</tr>
</tbody>
</table>
Chapter 4

Prototype Design, Implementation and Results

In order to assess the manufacturability and performance of the device under real-world conditions, a number of prototypes were constructed and installed in the same fish ponds used for data collection in both Vietnam and Bangladesh. In this chapter, a description of the design methodology and fabrication of the prototypes is provided, followed by an analysis of field trial results.

4.1 Prototype Mechanical Design

Vietnam

The aeration device, which was conceptually described in Section 3.4.1 and the basic dimensions of which were outlined in Section 3.4.5, consists of a solar collector and heat conduction element connected to a steel frame. The frame comprises a $\frac{1}{4}$ inch triangular plate with a 10 inch diameter circular cut at its center, through which a steel tube is welded. Three vertical round bars are welded to the plate at one end and are threaded on the other end to the solar collector using lock nuts. Secured to the frame are three equiangular brackets, each of which is connected with a pin to a pivot arm. At the end of each pivot arm, a welded clevis attaches to a shackle
connected to a buoy which floats the assembly above the water surface. Finally, a flexible air hose is affixed to the bottom of the tube in the steel frame with a pipe clamp, extending to the bottom of the pond, 1 foot above the bed. In order to adjust the height of the device off the surface of the water three turnbuckles are attached at one end to the bottom of the solar collector, and at the other end to the pivot arm. A rendering of the device is shown in Figure 4-1 and a close-up diagram with labels of each component is presented in Figure 4-2.

![Figure 4-1: Conceptual Rendering of Device Prototype](image)

Once assembled, the surface of the absorber plate is covered with two coats of black paint to increase its absorptivity, and the remainder of the device is sealed and painted to decelerate corrosion of the steel components. Of great concern during fabrication was the weldability of the 2 inch diameter aluminium heating element to the solar collector, since the high heat conductivity of the parent material can result in rapid heat dissipation away from the weld zone. Nevertheless, inspected weld samples from a Vietnam manufacturer using Tungsten Inert Gas (TIG) welding showed very good fusion between the two parts (see Figure 4-3). Measurement of thermal conductivity across the weld - an important thermodynamic aspect of the joint for the required application - was not measured, however, it is understood that conductivity across the
Figure 4-2: Prototype Design for the aeration device, showing (A) Solar Collector Plate with Glass Cover (B) Height Adjustment Turnbuckle (C)Pivot Arm (D) Draft Tube (E) Heat Conduction Element (F) Buoy

weld will be adversely affected due to microstructure deformations in and around the Heat Affected Zone (HAZ), the presence of pores in the weld, and misalignment and growth of Al grains at the boundary between the melt pool and the HAZ [84]. Further, there is an inherent thermal resistance in the joint which is a function of several geometric, physical, and thermal parameters such as surface roughness and waviness, surface microhardness, contact pressure, as well as the presence of any contaminants and interstitial substances. Bolting of the heat conductor to the absorber plate was considered in lieu of welding, however, one study which investigated thermal resistance across two bolted 6061 Aluminum sheets found that contact conductances rarely exceed $6 \text{ kW/m}^2\cdot\text{K}$ under most circumstances, and even then, very careful surface preparation and very high bolting torques are required [85]. This compares with an estimated contact conductance for welded Aluminum joints between 7.1 and 62.5 $\text{kW/m}^2\cdot\text{K}$ [86]. It was therefore decided to proceed with welding as the best option for creating a joint with the most favorable thermal contact properties.
As described in the previous chapter and shown conceptually in Figure 4-1, this design aims to provide a passive, sustainable means of creating circulation in the pond. The device requires little maintenance apart from occasional removal of biofouling from the conduction element, cleaning of the solar collector, and periodic checks to ensure the draft tube does not hit the bottom of the pond. Additionally, once the design is refined, it can be locally-fabricated using basic raw materials and distributed to fish farmers in the locale. However, since it is reliant solely on solar heat, it only lends itself to areas that receive persistently high insolation. Coincidentally, it is those areas with high insolation that would benefit from such a device, since the intensity of pond stratification is proportional to the amount of incident solar radiation.

Bangladesh

Following the fabrication of the Vietnam prototype, a more simplified device was designed for the field trial in Bangladesh in an attempt to reduce cost and complexity. For that design, the steel structure and buoys were substituted for barrels placed directly underneath the solar collector for flotation. Ballast was achieved by attaching weights from a number of uniformly-spaced eyebolts attached to the underside of the collector. In all other respects, however, the two devices were identical.
4.1.1 Solar Collector

In the design of the solar collector, a transparent insulating sheet atop a wooden frame was attached to the aluminum absorber plate to act as a convection-barrier. This decision was informed by research on solar-thermal systems, in which glazing the collector is understood to improve the thermodynamic efficiency of the device as well as the surface temperatures of the collector. For example, one study by Tripaoladosado et al. comparing the thermal outputs and efficiencies of various thermosiphon PV/T systems found that output water temperature is higher for glazed collectors than unglazed collectors, and thermal efficiency is up to 30% higher [87].

While the application of an antireflective coating, the use of unstructured glass with low iron content, and the vacuum-sealing of the solar collector are highly advisable practices for solar absorber applications, the methods used for this project were more modest due to cost, material access, and fabrication limitations. In Vietnam, commercial-grade untreated window glass with a typical incidence transmittance of 0.87 was used, and in Bangladesh, a clear acrylic sheet was used. In the latter case, the sheet was attached to the wooden frame using screws, resulting in warping of the sheet as it thermally expanded and contracted during operation. At peak irradiance, the warping was so pronounced that large gaps between the acrylic and the frame began to form, reducing the convection-barrier effect of the solar collector cover. Further, acrylic is prone to degradation, scratching, and has lower transmissivity values. It was used, nevertheless, due to its ease of handling and lower cost compared to glass.

Of critical importance to the performance of the solar collector is the thickness of the air gap between the cover and the absorber. Convective heat transfer across this gap presents the most significant uncertainty of analytical models. All available correlations are based on experiments or numerical simulations with isothermal boundaries and are valid for Rayleigh Numbers up to $10^5$. Under controlled conditions where the Nusselt number is known, it is possible to select an air gap that is suitable for the application, or alternatively, CFD modeling using known field parameters could be used to estimate performance and optimize the gap thickness [88]. For the purposes
of this project, an experimental method was used to approximate the actual performance of the solar collector cover. This was done using an acrylic box within which 4 interior slots were milled; in the bottom slot, an 8 inch × 8 inch × 1/4 inch thick steel plate painted black was placed. Of the remaining slots, which were spaced 1 inch apart, only one would be fitted with a 1/4 inch thick acrylic cover sheet at a time to inspect the effect of a single cover sheet on the temperature of the absorber. Temperature was recorded using a thermocouple connected to an Arduino Datalogger provided by the University of Toronto Blue Sky Solar Team (See Figure 4-4).

For the experiment, the solar collector box was placed outdoors for a number of hours alongside an uncovered plate which was also painted black. Temperature was recorded at the center of both plates and two runs were carried out: One with the acrylic cover placed 2 inches above the collector, and the other with the cover at 4 inches above the collector.

Results from the experiment are shown in Figure 4-5. Overall, observed temperatures for the glazed absorbers were consistently higher than for the bare plate at all times, corroborating the benefit of the cover as a convection-barrier. Additionally, when comparing the temperature improvement as a result of the cover, there is a modest improvement going from a 4 inch gap to a 2 inch gap, as evident by the percentage difference in temperature between the glazed absorber and the bare one.
(46% vs 42%). As a result, it was decided to make the gaps for the prototype solar collectors 2 inches thick.

A separate concern was that the solar collector - due to its size and weight - may deform during operation at the edges. To address this issue, a simple FEA model of the aluminum and steel assembly was carried out in SOLIDWORKS. For this model, a uniform standard mesh with four-node tetrahedral solid elements was used due to the simplicity of the structure being analyzed. Starting with a conservative global element size equal to one quarter the thickness of absorber plate, simulations were run for three smaller element sizes and it was found that the results were mesh-independent for the initial mesh size selected. During each run, the element aspect ratio was assured to be below 10 for all elements in the mesh, and at least 70% of the elements had a ratio less than 3 to ensure the model would be numerically stable. The only support condition in the model was a rigid boundary at the bottom of the triangular base representing the buoyant force holding the device above the water. Finally, a simple gravity loading condition was applied to the entire frame, along with a thermal condition of 55 °C representing the expected temperature of the absorber during peak irradiance.

Displacement and strain plots from the simulation, displayed in Figures 4-6
Figure 4-6: Absorber Displacement Plot  
Figure 4-7: Absorber Strain Plot

4-7 respectively, show that, as expected, the largest deviation takes place at the tips of the absorber with the maximum displacement equating to 3.6 cm. While this is a somewhat large value, the respective strain on the aluminum is far below the plastic deformation limit, with the maximum strain in fact occurring around the mounting holes on the absorber and not the edges where displacement is largest. The resultant stresses - not shown in the plots below - were found to be largest near the mounting holes as well (124 MPa), however even with a 1.2 Factor of Safety, they fall well short of the yield stress of 6061 Aluminum (276 MPa). It was therefore safe to proceed with the design as it was. In addition, since the absorber was affixed with a solar collector cover, it was assured that the wooden beams making up the sides of the collector would reduce the displacement by increasing the overall stiffness of the absorber assembly.

4.2 Prototype Installation

Vietnam

Once all design considerations were addressed, engineering drawings were drafted and forwarded to a manufacturer in Hanoi. Two designs were fabricated: One with a 1.25 m × 1.25 m × 5/16 inch thick absorber and solar collector cover, and the other with a bare 1.5 m × 1.5 m × 5/16 inch thick absorber. The aim was to compare the performance of both devices during the period of data collection. Both devices were placed along the long axis of the pond approximately 60 m apart, well outside
the radial influence of one another. A floating platform with two hanging dissolved oxygen loggers was placed in between the two devices to act as a control for the field trial. Photos of the installed devices are shown in figures 4-8 and 4-9.

![Installed Device with Cover](image1.jpg) ![Installed, Uncovered Device](image2.jpg)

Figure 4-8: Installed Device with Cover  Figure 4-9: Installed, Uncovered Device

Due to limitations on the number of available dissolved oxygen loggers (only four could be used in Vietnam), it was not possible to fulfill the goal of measuring and comparing the performance of both devices' impact on dissolved oxygen. Instead, since simulations and field temperature readings have shown that the covered device shows better promise, it was decided to single it out for comparison against a control location. The four dissolved oxygen loggers were placed in the pond such that two were attached to the device, one at the surface and one in the hypolimnion, 1.75 m below the surface, and another pair at the same depths but placed halfway across the pond. The latter pair were to act as control loggers. A diagram of the device and logger layout is shown in figure 4-13. The devices were installed on November 18, 2015 and data was collected for them continuously until March 17, 2016.

**Bangladesh**

In Bangladesh, two devices were constructed and installed in the same pond. The first - shown in Figure 4-11 - is identical in design to the Vietnam prototype. However, fabrication was carried out to a lower standard; surface preparation was not carried out, the aluminum components were not clean during welding, and due to the large
diameter of the heating element, it was not impossible to fuse the absorber to the heating element adequately since an oxyacetylene torch was used instead of a Gas Tungsten Arc Welding (GTAW) torch. Further, due to the excessive time the plate was subjected to the torch’s heat, the absorber was significantly warped during fabrication. While this warping has no impact on the thermodynamic performance of the device, the poor fusion of the rod to the absorber is speculated to have substantially hindered performance due to lower heat conductivity between the two components. The device was installed on June 16, 2015 and data collection is ongoing.

The second device - shown in Figure 4-12 - was an alternative experimental prototype which consisted of a single long aluminum sheet bent at two corners, forming a pair of protruding fins and a central absorber. The design parameters of this device and its results fall outside the scope of this project and are therefore not covered in this thesis.

Both devices were placed in a single 0.11 ha square pond along a diagonal. Each
device was nominally 6 feet from the nearest sidewall, with the weather station placed at the center of the pond. For each device, one dissolved oxygen logger was placed near the surface of the pond and one in the hypolimnion, 1.2 m below the surface to study the stratification patterns in the pond. A similar set of loggers were placed on the weather station as a control for the experiment. A diagram of the device and logger layout is shown in Figure 4-13.

![Diagram of device and logger layout](image)

Figure 4-13: Device Placement in Bangladesh Test Pond

### 4.3 Field Trial Results

#### 4.3.1 Dissolved Oxygen Logger Calibration

Before evaluating results, it was important to ensure that the measured dissolved oxygen values are independent of the location in the pond in which the measurements are made. This verification was carried out in Bangladesh, where three sensors were placed along the long diagonal of the pond approximately 12 feet apart from one another and 6 feet from the pond bas of nks. The sensors were sequentially denoted
Location 1, Location 2, and Location 3. Dissolved Oxygen was monitored for 9 days at all three locations and is displayed in Figure 4-14a. As shown, the readings were consistent at all three locations with little variation, except at solar noon during peak irradiance. Taking the average of each profile and comparing them against one another shows that the percentage difference between the three profiles ranged from -4.8% to 5.6%. As a result, in all future assessments of the performance of the device, any variance in dissolved oxygen values that falls within the range of ±5.6% will be considered insignificant, inasmuch as the device cannot be said to be performing well if it increases dissolved oxygen by less than 5.6%.
(a) Two-Panel Graph with (i) Top Panel Showing Recorded Solar Irradiance for the period between 6/20 and 6/29 in Srimangal, Bangladesh, and (ii) Bottom Panel Showing Dissolved Oxygen Profiles for Three Different Locations at the Pond Surface

(b) Observed Overall Dissolved Oxygen Percentage Differences Between the Three Surface Locations Surveyed

Figure 4-14: Dissolved Oxygen Recordings Showing Minimal Influence of Location on Measurements

Accounting for the sensor accuracy (± 0.2 mg/L for 0 to 8 mg/L and ± 0.5 mg/L for 8 to 20 mg/L), on average, 78% of dissolved oxygen recordings at a given location fall into the error bands of the other two loggers. This does not signify complete locational independence in the dissolved oxygen readings, nor does it suggest that
there are no localized effects in the pond, however it indicates that the impact of location is minimal. Therefore, when comparing dissolved oxygen between the device and control, there is little concern that the differences will be due to any phenomenon other than circulation.

### 4.3.2 Field Trial Findings

**Vietnam**

**Absorber Temperature**

Upon installation of both device prototypes in Vietnam, the surface of the device with the bare absorber was inspected with a FLIR T420 thermal camera around solar noon, and an infrared image was snapped (shown in Figure 4-15). The temperature of the plate was found to be $\approx 46.7 \, ^{\circ}C$ uniformly across the surface area of the plate.

![Infrared Image of Absorber Plate Around Solar Noon](image1)

![Temperature Plot of Absorber and Conductor At 1,000 W/m²](image2)

This figure compares closely with peak temperature measurements on the underside of the absorber plate, which were recorded by a pair of thermocouples (see Figure 4-17). In addition, it is in line with results from a preliminary 3D CFD model carried out in ANSYS Fluent for a device with the same geometry. This model found that temperature is approximately $55 \, ^{\circ}C$ across much of the absorber plate, however, with a marked decrease in temperature where the conductor connects to absorber (see Figure 4-16). Overall, the area-weighted average temperature is $52.1 \, ^{\circ}C$. The slightly lower observed temperature may be attributed to the assumptions made in the model.
which were necessary to achieve numerical stability for the mode. For example, the thermal boundary condition at the top of the absorber was specified as a radiation surface with a heat generation rate of 1,000,000 $W/m^3$, equivalent to an assumed 1,000 $W/m^2$ at solar noon, but with no convective losses to the air. In addition, the water surface and sides of the pond were specified as adiabatic walls, and no consideration was given to the contact resistance at the weld between the absorber and the head conductor. Nevertheless, the temperatures from the infrared image agree to within 10% with the model temperatures. The lack of a temperature drop around the heat conductor in the infrared image - which is predicted the CFD model - is most likely due to a lower thermal conductivity at the weld interface in the actual device than in the model, which assumes perfect contact between the two components.

![Figure 4-17: Thermocouple Recordings on Underside of Absorber Plate](image)

**Stratification**

In order to ensure that the device was destratifying the pond, it was important to observe temperature and dissolved oxygen patterns over the field trial period to gauge if indeed the pond experienced conditions conducive to stratification. This was done by comparing the recordings from the control loggers at the surface and bottom of the pond. From those readings, severe and persistent thermal and dissolved oxygen stratification patterns were observed for the entire duration data was being collected.
for the devices (see Figure 4-18). As expected, the only periods during which startification was subdued or absent (1/20 to 1/27) were cloudy periods, as evidenced by the depressed solar irradiance for that period. While the device would have no impact on the pond during persistently cloudy periods, this data shows that its predicted beneficial circulation would be of no impact since the pond will likely be destratified during those periods.

![Graphs showing temperature and dissolved oxygen stratification](image)

Figure 4-18: Left: Thermal Stratification, Right: Dissolved Oxygen Stratification in Vietnam Pond between 11/30 and 2/27 2016

**Results**

Few practical options exist when trying to assess the circulatory performance of a circulation device. Directly measuring the speed of the water is very difficult due to the expected updraft speeds from convection being quite low. For laboratory scale experiments, Particle Image Velocimetry (PIV) or other methods may be used. One project currently being pursued in conjunction with the work laid out in this thesis aims to validate CFD simulation results by measuring convective velocities on a bench-scale model of the device. For that project, electrolysis is used to visualize the path of water rising in the draft tube, and velocity is measured by tracking the distance the water travels in a given amount of time. Nevertheless, this method is unsuitable for field applications. As highlighted in Section 2.5.3, for full-scale circulators, a concentrated dye may be injected near the bottom of the pond and the time it takes from it to spread across the surface may be measured, however, this is an entirely impractical option for a live aquaculture pond.
It was therefore decided to directly measure the factor of greatest importance to this study - dissolved oxygen near the bottom of the pond - and comparing it at two locations: Near the device and at a control location known to be outside the radius of influence of the device. On Figure 4-13, those loggers are denoted by (2) and (4) respectively. The performance of the device will be gauged based on the percentage difference between those two loggers; the higher the dissolved oxygen near the device, the more the device can be said to be circulating water and oxygenating the pond as desired.

The first set of results, shown in Figure 4-19, found that the average dissolved oxygen near the device at 1.75 m below the surface is $6.23 \text{ mg/L}$ compared to $5.99 \text{ mg/L}$ for the control at the same depth. This represented an improvement of roughly 4%, which falls within the natural locational deviation of loggers as explained in Section 4.3.1. Excluding all the days where pond’s dissolved oxygen did not appear to be stratified - the improvement equates to 6.8%, a more encouraging figure, though still unsatisfactory.

Since the effects of wind shear on the surface of the water were not taken into account in the CFD models, it was speculated that water rising in the draft tube was spread over a wide surface area of the pond due to wind action, effectively subduing the circulatory action in the pond. In addition, it was likely that the surface area of the pond was too large to effectively form a circulation loop around the device. Therefore, a slight modification in the device setup was carried out.
To reduce the surface area of the pond and to increase the effective convective circulation, the two devices - covered and uncovered - were moved to within 3 meters of one another and placed on one side of the pond. This part of the pond was then sectioned off using a tarp 8 meters from the edge. This, then, reduced the surface area within which the devices were operating to $220 \text{ m}^2$. A photograph of this alternative setup is shown in Figure 4-20. This modification was carried out on February 27, 2016 and data was collected until March 4, 2016, after which the water level in the pond had dropped to the point where the dissolved oxygen loggers descended into the sediment and therefore produced unusable data.
Figure 4-20: Alternate Device Setup in Vietnam

Figure 4-21: Two-Panel Graph with (a) Top Panel Showing Recorded Solar Irradiance for the period between 2/27 and 3/4 next to Pond 1 in Bac Ninh, Vietnam, and (b) Bottom Panel Showing Dissolved Oxygen Profiles for the Control Site and In-Between the Two Devices in the Sectioned-Off Pond at 1.75 m Depth. Shaded Bars Denote Periods With Zero Solar Irradiance.

The results during that period are shown in Figure 4-21. The blue line represents
logged dissolved oxygen values between the two devices at 1.75 m below the surface, with the light blue band showing the reported measurement error of the device. The green line represents logged dissolved oxygen values at the control 1.75 m below the surface, with the light green band showing the same error range.

Compared with the previous set of results, this data shows dissolved oxygen near the devices is almost 18% than at the control. For the first two days when clouds were breaking solar irradiance, the plate was not maintaining high enough temperatures to aid in convection, however, by the third day when the sky was clear and solar irradiance was pronounced, circulation was evident and dissolved oxygen near the device was peaked at a value 9.6% higher than at the control. In the ensuing days, dissolved oxygen remained high near the device, even as daytime irradiance began to subside during the last two days.

It was important, nevertheless, to scrutinize whether the reported 18% improvement in dissolved oxygen is statistically significant compared to the accuracy of the loggers as well as the locational differences in dissolved oxygen. To that end, a one-tailed two-sample t-test with a significance level of 0.05 was carried out, for which the Null Hypothesis was specified as:

$$\mu_{device} - \mu_{control} \leq e$$

where:

- $\mu_{device}$ Mean of Dissolved Oxygen Values Near the Device (Sample 1)
- $\mu_{control}$ Mean of Dissolved Oxygen Values At the Control (Sample 2)
- $e$ Measurement Error of Device According to Manufacturer, given as $0.2$ mg/L, Plus 5.6% of the Average of $\mu_{device}$ and $\mu_{control}$

That is, if the null hypothesis is rejected, it can be said that there is a 95% probability that the difference between the means of dissolved oxygen values for the device and control is greater than the measurement error in the loggers, as well as the locational differences outlined in Section 4.3.1. Table 4.1 shows the sample sizes, means and variances of both samples, as well as two probability distribution
variables: skewness and kurtosis. Before proceeding with the hypothesis test, two checks were necessary to inform which type of t-test should be used. First, the probability distributions had to be approximately normal for the t-test to be valid. There are multiple ways to check for normality of data samples, including simple visual checks; in this case, the absolute values of their skewness and kurtosis were calculated and they were found to be below 1.96, the value representative of a 95% confidence interval for normal distributions. This implied that their distribution was indeed approximately normal. Second, to test the homogeneity of variances between the two samples, Levene’s ANOVA test was carried out with an \( \alpha \) value of 0.05. This test is preferred to the simple F-Test in cases where one cannot ascertain the normality of the samples with a high degree of confidence. For two sample subgroups, its test statistic, \( W \), is defined as:

\[
W = (N - 2) \frac{\sum_{i=1}^{2} N_i (\bar{Z}_i - \bar{Z}_.)^2}{\sum_{i=1}^{2} \sum_{j=1}^{N_i} N_i (Z_{ij} - \bar{Z}_i)^2}
\]

where:

- \( N \) is the Sample Size containing two subgroups representing the device and control
- \( Z_{ij} = |Y_{ij} - \bar{Y}_i| \), where \( \bar{Y}_1 \) is the mean of the ith subgroup
- \( Y_{ij} \) is the value of the measured variable for the jth case from the ith subgroup
- \( \bar{Z}_i \) are the group means of \( Z_{ij} \)
- \( \bar{Z}_. \) is the overall mean of \( Z_{ij} \)

Once statistic \( W \) is calculated, its significance is tested against \( F(\alpha, 1, N - 2) \), where \( F \) is the quantile of the F-Distribution, \( \alpha \) is the confidence interval (in this case, taken as 0.05), and \( (N-2) \) is the number of degrees of freedom of all dissolved oxygen measurements. This calculation was carried out in MATLAB, and based on the resulting p-value of 0.0001, the Null Hypothesis for the test was rejected, signifying that the variances can be assumed to be statistically non-homogeneous.

As a result, a modified t-test appropriate for comparing samples with unequal variances, known as Welch’s test, is used to compare the difference of means of the two dissolved oxygen samples. For this test, the statistic \( t \) is defined as
Table 4.1: Means and Variances For Dissolved Oxygen Readings

<table>
<thead>
<tr>
<th>Population</th>
<th>n</th>
<th>Mean</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>883</td>
<td>7.59</td>
<td>1.22</td>
<td>0.79</td>
<td>0.14</td>
</tr>
<tr>
<td>Control</td>
<td>6.55</td>
<td>2.35</td>
<td>-0.18</td>
<td>-0.71</td>
<td></td>
</tr>
</tbody>
</table>

\[ t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \]

where:

- $\bar{X}_1$ Sample mean for the Device Subgroup
- $\bar{X}_2$ Sample mean for the Control Subgroup
- $s$ Sample standard deviation for each respective subgroup (Device and Control)
- $N$ Sample size for each respective subgroup (Device and Control)

The degrees of freedom $\nu$ associated with this variance estimate is approximated using the Welch-Satterthwaite equation:

\[ \nu \approx \frac{\left( \frac{s_1^2}{N_1} + \frac{s_2^2}{N_2} \right)}{\frac{s_1^4}{N_1^2\nu_1} + \frac{s_2^4}{N_2^2\nu_2}} \]

where $\nu_1 = N_1 - 1$ and $\nu_2 = N_2 - 1$.

Once the $t$ and $\nu$ values are computed, they are used with the t-distribution to test the null hypothesis that the absolute difference in means between the two populations is greater than the measurement error of the dissolved oxygen loggers. This calculation was carried out in MATLAB, producing a t-statistic of 13.13 and a p-value of $\approx 0$. Since this p-value is less than the significance level of 0.05, the null hypothesis is rejected and it can be said with 95% certainty that the difference in dissolved oxygen means is greater than the error and locational variation in the loggers. Nevertheless, it should be noted that the sample size in this case is small, with the data spanning only one week. For more significant validation of the impact
of the device, further measurements and testing are required.

**Bangladesh**

Due to time restrictions and fouling issues with the dissolved oxygen loggers, only four days of reliable data are available for the device in Bangladesh. Dissolved oxygen logs for those days are shown in Figure 4-22. Over those days, dissolved oxygen values near the device can be seen spiking 12% higher than the control on the second day, during which pronounced irradiance was present, albeit with some cloudy periods. On the third and fourth days, as irradiance subsides, the peaks for the device are slightly less pronounced, however, they are still consistently higher than the control. Overall, the average dissolved oxygen value next to the device was 18.2% higher than at the control, signifying an increase in dissolved oxygen compared to the natural locational fluctuations of ±5.6% calculated during the calibration runs.

As with the Vietnam results, statistical analysis of the results using Welch’s t-test yielded a p-value well below the null hypothesis rejection threshold of 0.05, indicating that the differences observed were statistically significant compared to natural variations in the dissolved oxygen loggers’ measurements. As more data is collected, further statistical verification will be necessary to ensure the improvements are indicative of changes brought about by the device. Nevertheless, for the data available, there is clear indication of an improvement of overall dissolved oxygen around the device compared to areas outside its radius of influence.

### 4.4 Summary

In this chapter, a detailed description of the device prototypes was provided, including the rationale behind a number of mechanical design decisions. For this project, four prototypes were fabricated: two were installed in Vietnam and two in Bangladesh (of which only one is within the scope of the project). Due to a shortage of loggers, only one device could be assessed in Vietnam, and initial testing found that the device had little impact on dissolved oxygen. Speculating that it might be due to the size
of the pond and the overpowering wind fetch, the pond was sectioned off and the two devices were placed in the sectioned-off pond to reduce the effective surface area in which the devices were installed. Results from that modified layout showed much more promising results, increasing the dissolved oxygen at the bottom of the pond by 18% compared to a control spot in the pond. Further evaluation of those figures using Welch’s t-test for differences of means in MATLAB found that this increase was statistically significant relative to the measurement error of the loggers as well as the observed locational variation in the readings. Finally, in Bangladesh, a similar statistically significant improvement in dissolved oxygen was observed near the device, albeit only four days of results are available for assessment. Further data is needed to ascertain the true extent of benefits of the device as far as fish survivability, growth, and farmer income.
The main contribution of this thesis was developing a modeling approach and first experimental test of a novel, passive, solar-thermal aeration system for rural pond aquaculture. This work was motivated by the fact that aeration is not used by a large percentage of aquaculture practitioners in low-income countries. If employed, it may improve pond productivity for impoverished farmers by up to 47% [43].

The proposed device consists of a solar absorber and conduction rod, which transfer heat to the oxygen-deprived deeper layers of the pond. This induces convective circulation, which mixes oxygen across the water column while preventing oxygen losses to the atmosphere due to supersaturation at the surface. The result is an increase in the overall oxygen content of the pond, which improves the health of the fish and allows for greater pond yields.

System modeling for the device consisted of two approaches: First, in order to predict the device’s impact on dissolved oxygen distribution in the water column, two mechanistic models which characterize thermal and dissolved oxygen dynamics in aquaculture ponds were coupled to produce predicted dissolved oxygen distribution profiles. Second, to size the device, a Computational Fluid Dynamics (CFD) model of the device was constructed and simulations were coupled with a Design of Experiments matrix to select a set of device dimensions that maximize convective mixing in the pond. Next, the flow rates from the CFD model were incorporated back into the dissolved oxygen model to quantify the device’s impact on the pond’s
oxygen distribution. Those results showed that the device could potentially improve dissolved oxygen in the pond by 60%.

Finally, in order to evaluate the device’s performance under real pond conditions, prototypes of the device were built and installed in ponds in Vietnam and Bangladesh. In those tests, little improvement was observed when the prototype was placed in a large pond far from any walls. However, for experiments where the device was placed in a confined surface area close to a wall, an improvement in dissolved oxygen of 18% was observed.

5.1 Future Steps

By setting up the CFD simulation framework for predicting the performance of the device, and by developing versatile thermal and dissolved oxygen stratification models that can rely on easy-to-acquire field measurements, the work put forth in this thesis lays the groundwork for further development and optimization of the aerator design concept. While those models are currently limited in their applicability in some respects due to the lack of comprehensive field data, the factors that can enhance the accuracy of those models are now known and will be implemented in future work. Of highest priority among those factors is better knowledge of water quality metrics, including an improved measurement of water column and sediment respiration rates, chlorophyll-a concentrations as a function of the pond depth, and exact information on the species and number of fish being cultured in the pond. With those figures, the dissolved oxygen model can be made significantly more accurate, and therefore predictive estimates of device performance can become more reliable.

For the temperature model, more robust testing of the sensors and data acquisition systems needs to be carried out prior to site installation in order to minimize the frequency of malfunctioning sensors, a problem which was encountered frequently with the Bangladesh weather station. Additionally, exact and repeated measurements of light extinction using the pyranometers, as well as rainfall measurements could vastly improve the accuracy of the simulated temperature values.
Finally, for the CFD model, the numerous simplifying assumptions which were incorporated in the simulations, can be addressed in future modeling. Of greatest concern among those simplifications is the lack of vertical temperature stratification in the pond model during the simulation of the device performance; preliminary work on the subject has found that including stratification in fact suppresses circulation markedly, and therefore, more work should be directed toward modeling and incorporating this phenomenon in future simulations. Additionally, sizing the device prototypes using the Design of Experiments methodology only provides a rough approximation of the ideal dimensions to maximize circulation; rigorous numerical optimization, which can take into account disturbances in the water, as well as uncertainties in the model setup, should be pursued in the future in order to ascertain the most optimal design parameters for future designs.

Regardless of the aforementioned uncertainties, field testing of the first prototypes of the device in two different sites has shown a statistically-significant improvement in dissolved oxygen around the device, amount to an increase of 16% on average. This improvement, however, was measured directly next to the device. Future work should focus on measuring and maximizing the radius of influence of the device. Ultimately, the goal is to develop a decision-making tool which would ask for basic site inputs, such as meteorological data, pond location, and pond dimensions, and would output the required dimensions for a single device, as well as the required number of devices per pond to provide adequate oxygen for the fish to thrive throughout the grow out cycle.

Once such a robust tool is developed, the device’s effect on fish size, survivability, and health should be measured, and most importantly, its impact on farmer income should be assessed through a full grow-out cycle. Finally, more effort would be dedicated toward streamlining the manufacturability of the device and reducing its cost in order to bring it within reach of the budgets of fish farmers. Only though proven results and a suitable cost could impoverished farmers be convinced to invest in such an aeration device, and therefore both issues should be addressed in future research with equal priority.
5.2 Wind-Powered Aeration Device

During the conceptualization phase of this thesis, multiple alternative, sustainable aeration concepts were considered for further development. Of those, one of the most promising involves the use of a Vertical Axis Wind Turbine (VAWT) to drive a hydrofoil below the water surface in order to create circulation in the pond. This concept was explored to a limited extent and was found to be a potentially effective alternative to the solar-thermal aeration system discussed herein. Preliminary CFD simulations found that, for a turbine spinning at 30 rpm, mass flowrates of up to 1 kg/s may be accomplished.

A small prototype, consisting of a Savonius turbine with plastic scoops, an aluminum shaft, and a fan blade, was assembled and installed in Bangladesh in a pond adjacent to the one used for site testing for this project (See Figure 5-1). The device was fitted with two dissolved oxygen loggers, one at the surface and one at the bottom. In order to evaluate the device’s impact on dissolved oxygen, a third logger near the bottom of the pond was placed at a control location 30 meters away from the device.

![Wind Aeration Device Installed in Pond 2 in Srimangal, Bangladesh](image)

Figure 5-1: Wind Aeration Device Installed in Pond 2 in Srimangal, Bangladesh

Results for the first four days of operation are displayed in Figure 5-2. In spite of
quiescent weather and large trees and berms on the sides of the pond breaking the wind, the device was seen spinning most of the time, and its influence on dissolved oxygen was large. For those four days, a difference of approximately 70% in dissolved oxygen was observed between the device and the control, signifying that the device is likely circulating the water to a larger extent than the solar-thermal device.

It should be noted, however, that during those four days, severe fouling of the loggers was taking place, and therefore the difference observed might not entirely be due to circulation, but rather due to differential fouling. Further data acquisition may be needed to confirm the trend of higher dissolved oxygen near the device. If indeed a simple prototype of the device can improve oxygen by as much as 70% in a pond location with placid wind speeds, further investigation is warranted.

Figure 5-2: Two-Panel Graph with (a) Top Panel Showing Recorded Wind Speed for the period between 6/20 and 6/24 in Srimangal, Bangladesh, and (b) Bottom Panel Showing Two Dissolved Oxygen Profiles in the Pond Over the Same Period, One Below the Wind Aeration Device and One as a Control
Appendix A

Survey of Fish Farmers in Vietnam

Date: Saturday, March 26, 2016
Time: 8:30 to 11:30 am
Location: Department of Science and Technology, Bac Ninh Province
Participants:

- A representative of Bac Ninh Aquaculture Division, Department of Agriculture and Rural Development, Bac Ninh Province
- A representative of the Department of Science and Technology, Bac Ninh Province
- A representative of Aquaculture Association, Bac Ninh Province
- 20 fish farmers in Bac Ninh Province.

At first, I introduce the new technology to all participants at the experimental pond and then get to the room for the discussion. The session is informal and all the participants feel free to discus. The result of the discussion is showing as follows:

The use of traditional aeration systems

Currently, fish farmers in Bac Ninh Province use different aeration systems. The most expensive system is approximately 12 million VND while the cheapest one may cost about 2 million VND. Which system a farmer is going to buy depend on the size of the farmer fish pond, density of fish stock and her/his financial conditions. Advantages of
the traditional aeration systems are as follows: (1) the effectiveness of the used system has widely been evidenced by real practices of fish raising in Vietnam in general and Bac Ninh province in particular; fish farmers have got used to operating the traditional systems over years. However, the traditional aeration systems have also consisted of a number of disadvantages. A disadvantage of the traditional aeration system is that there is a need of using electricity. It often takes months from registering and getting permission for electricity use to complete installation. The farmers who want to use the electricity often have to pay not small amount of "under table" money to the installation worker of the local electricity company (they are all state-owned enterprises in Vietnam). Another disadvantage of the traditional system is that each farmer must reserve an electricity generator to prevent a situation of the temporary no provision of the electricity (it sometimes happened in Vietnam, especially more often in rural areas of Vietnam). The use of the traditional systems is time and labor consuming. Showing this advantage a farmer said that "every day we have to install and operate the system. If we forget to operate the system for a several hours (e.g over sleeping or away from home and not to come back in time) there will be a high risk of fish death due to the shortage of oxygen in the pond". The participated farmers have shown that they have to pay between 200 000 and 300 000 VND per month. In addition to electricity cost farmers have to pay a certain amount of money for the maintenance of the system. It may cost 1 million VND per year.

**Potentials of the new aeration system**

All participated fish farmers have excited and expressed their interests in the new aeration systems. After the introduction to the new system, the participated farmers found a number of advantages of the new system:

- There is no need of consuming electricity for operating the new system. To emphasize this opinion a farmer said that "The system looks beautiful and we do not have to pay any money to the electricity delivering company and its worker". Referring to the money paid for the worker, another farmers indicated that "this is an under table money and quite big money compared to our income".
There is no need of the installation and operation of the system every day. Thus farmers do not have to concern about time and labor spending on the system operation. A participated fish farmer said that "fish raising is a very hard work; day and night we have to care of fish pond. If we forgot to operate the [traditional] system for several hours, there would be a high risk of fish death due to the lack of oxygen in the pond”.

There is a potential increase in the fish production because the new system can constantly provide oxygen dilution in the water pond. A farmer expressed his experience on fish production that "if the oxygen has constantly been provided day and night the fish stock would be growing faster”. For using traditional aeration systems, farmers have to operate their system in average about six hours per day.

According to the participated farmers a traditional aeration system is suitable to only several fish species while the new technology may be suitable to all kind of fish species.

**Concerns about the new technology**

A major concern about new aeration system is that the farmers wonder if the system has enough capacity of oxygen generation compared to the traditional ones. Thus the effectiveness of the new system is the first concern of the farmers. Another farmers’ concern about is that if the new system can provide oxygen during the days of bad weather, for example rainy day.

All the participated farmers have expressed that they would buy and use the new system if the new system were trusted. Therefore, the farmers would like to see a comparative experiment in two ponds using different aeration system: a traditional system in one pond and the new system in another one. If the experiment had been lasting for six months or one year the new system would receive the trust from farmers. Without seeing the comparative experiment the farmers feel that application of the new technology is very risk. Several of the participated farmers take an account for
fish production that every hectare of fish pond farmers can earn an income ranging from 100 - 150 million VND per year. If there were fish death in one hectare of fish pond the farmer may lose about 400 million VND. This is a huge money for all Vietnamese farmers.

Finally, all the participated farmers have also interested in the duration of the new system. A farmer said that "if the duration of the new system can be lasting for 5 or 7 years we will be very interested in the system. If the duration is only one or two years we will not be interested in the system any more".

Concluding Remarks

The new aeration system is promising for fish production in Bac Ninh province and may be for all northern provinces of Vietnam. The system has a number of advantages compared to the traditional aeration systems. However, there are also several concerns about new system regarding the effectiveness, the cost, the duration and the trust of the system. The representatives from the Aquaculture Division, local science and technology authority, Aquaculture Association are also expressed their strong interests in continuing the project. If the project is going on the next phase of comparative experiments their organizations will be happy to participate in and contribute to support and facilitate the project.
Appendix B

MATLAB Code for Thermal Stratification Model

```matlab
clc;
close all;
clear all;

% Import Site Data
[~, ~, raw] = xlsread('filepath', 'filename', 'Range');
% Create output variable
data = reshape([raw{:}], size(raw));
% Allocate imported array to column variable names
LT = data(:,1);
GSR = data(:,2);
T_a = data(:,9);
W_s = data(:,5);
RH = data(:,10);
T_sed = data(:,11);
T_pond_measured = data(:,3:4); %T_mid is interpolated
% Clear temporary variables
clearvars data raw;

% Import Water Data
[~, ~, raw] = xlsread('filepath', 'filename', 'Range');
% Create output variable
data = reshape([raw{:}], size(raw));
% Allocate imported array to column variable names
T_data = data(:,1);
H_data = data(:,10);
% Clear temporary variables
clearvars data raw;

% Import Air Data
```
[[-, -, raw]] = xlsread('filepath', 'filename', 'Range');
% Create output variable
data = reshape([raw{:}], size(raw));
% Allocate imported array to column variable names
T_air_data = data(:,1);
rho_air_data = data(:,2);
% Clear temporary variables
clearvars data raw;
%
%Site Location

%Bangladesh June 21
Longitude = 91.685271;
Latitude = 24.313271;
DOY = 173;
deltaGMT = -6;

%Vietnam
%Longitude = 106.04227;
%Latitude = 21.1057;
%DOY = 93;
%deltaGMT = -7;

%Site Characteristics
SDD = 0.1524; %6 inches
LW_albedo = 0.03; %Long Wave
beta = 0.03; %fraction of solar irradiance absorbed at surface of water
N = 5059.3; %empirical coefficient from Lake Hefner for Evaporation (J/m2.km.mmHg)
T_d = T_a(1) - 2 + 273.15; %Dew point temperature
eta_0 = 1.7 / SDD; %light extinction coefficient
c_p = 4181.6; %specific heat of water @STP (J/kg/K)
C_z = 1e-3; %coefficient of aerodynamic stress
k_sed = 2.53; %Approximate heat conductivity of soil
SBC = 2.04133e-5; %Stefan–Boltzmann constant (W/m2.h.K^-4)
emisivity_w = 0.97; %Emisivity of water

%Time step
interval = 15;
dt = interval/60;
timesteps = length(GSR);

%depths
numlayers = size(T_pond_measured,2);
length = 100;
width = 100;
SA = length*width;
depth = 1.2; %pond depth
fetch = width;
dz = depth/numlayers; %distance between layer COG

%Temperature Definition
T = zeros(timesteps, numlayers); %Initialize Temperature Array
T (1,1:numlayers) = T_pond_measured(1,1:numlayers);

%Meteorological condition (assumed constant)
C_cloud = 0.3;

%Control Volume Characterization
for q=1:numlayers
    z(q) = (q-1)*dz + dz/2;
    v(q) = length*width*dz;
end

%Begin Algorithm
for i=2:timesteps

%Calculate solar elevation
    [Elevation(i), Azimuth, declination, HRA] = SunPosition(
        Longitude, Latitude, DOY, LT(i), deltaGMT); %Provided by Professor Bilton

    if Elevation(i) <= 0
        Elevation(i) = Inf;
    end

%Calculate losses due to reflectance
    R_s (i) = 2.2*power(Elevation(i),-0.97); %Reflectivity of a smooth water surface; 2.2 and -0.97 and empirical coefficients from WRE, 1968
    R (i) = R_s (i) *(1-0.08*W_s(i)); %Adjusted for surface roughness due to wind action

%Penetrating shortwave solar irradiance
    for q = 1:numlayers
        refraction_angle (i) = asin( (90-Elevation(i)) )/1.33;
        eta_e = eta_0/cos(refraction_angle (i));
        Q_solar(i,q) = GSR(i) * (1-beta) * (1-R(i)) * exp(-eta_0 *
            *(z(q)-dz/2)) * 3600; %J/m2.hr
    end

%Atmospheric longwave solar irradiance
\[ \varepsilon_{\text{air}}(i) = 0.937e^{-5(T_a(i)+273.15)^2}; \]

for \( q = 1:\text{numlayers} \)
  \[ Q_{\text{atm}}(i,q) = \varepsilon_{\text{air}}(i) \times \text{SBC} \times (273.15+T_a(i)) \times 4 \times (1+0.17 \times C_{\text{cloud}}^2) \times (1-LW_{\text{albedo}}); \quad \%J/m^2/hr \]

end

end

% Radiant losses from water surface
for \( q = 1:\text{numlayers} \)
  if \( q == 1 \)
    \[ Q_{\text{ws}}(i,q) = -\text{emisivity}_{\text{w}} \times \text{SBC} \times (T(i-1,q)+273.15)^4; \quad \%J/m^2/hr \]
  end

end

%Sensible heat transfer
\[ \rho_w(i) = (0.99987+0.69e^{-5 \times \text{mean}(T(:,q))}-8.89e^{-6 \times \text{mean}(T(:,q))^2}+7.4e^{-8 \times \text{mean}(T(:,q))^3}) \times 1000; \]

for \( q = 1:\text{numlayers} \)
  if \( q == 1 \)
    \[ Q_{\text{c}}(i,q) = -1.5701 \times W_s(i) \times 3600 \times (T(i-1,q)-T_a(i-1)); \quad \%J/m^2/hr \]
  end

end

%Evaporative heat losses
\[ e_{\text{s}}(i) = 25.374 \times \exp(17.62 - 5271 / (T(i-1,q)+273.15)); \]
\[ e_{\text{a}}(i) = \text{RH}(i)/100 \times 25.374 \times \exp(17.62 - 5271 / (T_a(i-1)+273.15)); \]

for \( q = 1:\text{numlayers} \)
  if \( q == 1 \)
    \[ Q_{\text{evap}}(i,q) = -N \times W_s(i) \times 3.6 \times (e_{\text{s}}(i) - e_{\text{a}}(i)); \quad \%J/m^2/hr \]
  end

end

% Heat lost to sediment
for \( q = 1:\text{numlayers} \)
  if \( q == \text{numlayers} \)
    \[ \phi_{\text{sed}}(i,q) = k_{\text{sed}} \times ((T(i-1,q)-T_{\text{sed}}(i-1))/dz); \]
  end

end

% Interpolate and find temperature
for \( q = 1:\text{numlayers} \)
  if \( q == 1 \)
\( Q_{\text{net}}(i, q) = Q_{\text{solar}}(i, q) + Q_{\text{atm}}(i) + Q_{\text{evap}}(i) + Q_{\text{ws}}(i); \)

\[ T(i, q) = T(i-1, q) + \frac{Q_{\text{net}}(i, q)}{\rho_w(i) / c_p / \text{dz} \times \text{interval/60}}; \]

else
\( Q_{\text{net}}(i, q) = Q_{\text{solar}}(i, q); \)

\[ T(i, q) = T(i-1, q) + \frac{Q_{\text{net}}(i, q)}{\rho_w(i) / c_p / \text{dz} \times \text{interval/60}}; \]

end

\%Diffusion/Advection between layers

\( \rho_{\text{air}}(i) = \text{interp1 } (T_{\text{air data}}, \rho_{\text{air data}}, T(i, 1)); \)

\( \tau(i) = \rho_{\text{air}}(i) \times C_z \times (W_s(i))^2; \)

\( W_{\text{sa stress}}(i) = \sqrt{\tau(i) / \rho_w(i)}; \)

\( \text{decay}(i) = 6 \times \text{power}(W_{\text{sa}}(i), -1.84); \)

\( \text{v_drift}(i) = 30 \times W_{\text{sa stress}}(i); \)

\( \text{for } q = 1: \text{numlayers}-1 \)

\( \text{if } (\text{abs}(T(i-1, q+1) - T(i-1, q)) < 0.5) \quad \text{|} \quad (\text{abs}(T(i-1, q+1) > T(i-1, q))) \) \( E_z(i, q) = 0.05; \)

else
\( E_{\phi}(i, q) = (W_{\text{sa stress}}(i)^2 / \text{v_drift}(i) / \text{decay}(i)) \times \exp(-\text{v_drift}(i) \times (z(q) + \text{dz}/2)); \)

\( Z \)

\( a_v(i, q) = 1.5 \times 5 \times ((\text{mean}([T(i, q) \ T(i, q+1)])) + 273.15 - 277) - 2 \times 7 \times ((\text{mean}([T(i, q) \ T(i, q+1)])) + 273.15 - 277)^2; \)

\( \text{Richardson Number} \)

\( E_z(i, q) = 80 \times E_{\phi}(i, q) \times (1 + 0.05 \times \text{Richardson Number}); \)

\( \text{phi_diff_conv}(i, q) = -\rho_w(i) \times c_p \times E_z(i, q) \times (T(i, q)-T(i, q+1)) / \text{dz}; \)

end

\%Diffusion/Advection Adjustment

\( \text{for } q = 1: \text{numlayers}-1 \)

\[ T(i, q) = T(i, q) + \text{phi_diff_conv}(i, q) / \rho_w(i) / c_p / \text{dz} \times \text{interval/60}; \]

\[ T(i, q+1) = T(i, q+1) - \text{phi_diff_conv}(i, q) / \rho_w(i) / c_p / \text{dz} \times \text{interval/60}; \]

end
% Graph Settings

Xtick_Init = [{'6 am'}, {'12 pm'}, {'6 pm'}, {'12 am'}, {'6 am'}, {'12 pm'}, {'6 pm'}];

n = numel(T(:,1));

xdata = 1:timesteps;

% Plot Temperature

figure

n = numel(T(:,1));

for q=1:1

    xi = interp1(1:n, xdata, linspace(1, n, 0.4*n));

    yi = interp1(xdata, T(:,q), xi);

    plot(xi, yi, 'LineWidth', 2);

end

hold all;

xdata = 1:timesteps;

plot(xdata, T_pond_measured(:,1), 'x', xdata, T_pond_measured(:,2), 'x', 'MarkerSize', 20);

set(gca, 'Xtick', xdata, 'XtickLabel', '');

hx = get(gca, 'XLabel');  % Handle to xlabel

set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation', 45, 'HorizontalAlignment', 'right', 'FontSize', 20)
set(gca, 'XTick', ticksArray)
set(gca, 'FontSize', 20)
ylabel(sprintf('Temperature (%cC)', char(176)));
ylim([30 38])
legend('Surface (Simulated)', 'Bottom (Simulated)', 'Surface (Measured)', 'Bottom (Measured)')
set(gca, 'TickDir', 'in')

% Plot Heat Transfer
figure
Q_gains = [Q_atm*length*width*interval/60 (Q_atm+Q_solar(:,1))*length*width*interval/60];
Q_losses = [Q_ws*length*width*interval/60 Q_evap*length*width*interval/60 Q_c*length*width*interval/60];
Q_all = [Q_gains Q_losses];
area(xdata, Q_all);
colormap jet
legend('Atmospheric Radiation', 'Solar Radiation', 'Water Surface Radiation', 'Evaporative Heat Flux', 'Sensible Heat Flux')

set(gca, 'XTick', xdata, 'XTickLabel', ' ');
hx = get(gca, 'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation', 45, 'HorizontalAlignment', 'right', 'FontSize', 20)
set(gca, 'XTick', ticksArray)
set(gca, 'FontSize', 20)
ylabel('Heat Flux Contribution (W)')

% Cross Cor
[r, p] = corr(T(:,1), T_pond_measured(:,1))
[r, p] = corr(T(:,2), T_pond_measured(:,2))
Appendix C

MATLAB Code for Dissolved Oxygen Stratification Model

clear;
closall;
clearall;

% Import Site Data
[~, ~, raw] = xlsread('filepath', 'filename', 'Range');
% Create output variable
data = reshape([raw{:}], size(raw));

% Allocate imported array to column variable names
PAR = data(:,1);
T = data(:,2:3);
W_s = data(:,4);
DO_measured = data(:,5:6);
Mdot_water = data(:,7);

% Clear temporary variables
clearvars data raw;

% Import Air Data
[~, ~, raw] = xlsread('filepath', 'filename', 'Range');
% Create output variable
data = reshape([raw{:}], size(raw));
% Allocate imported array to column variable names
T_air_data = data(:,1);
rho_air_data = data(:,2);
% Clear temporary variables
clearvars data raw;

%%
% Model Setup

timesteps = length(PAR);
timestep_length = 15;  % minutes
numlayers = size(T,2);

% Site and pond conditions
E = 20;  % m elevation above sea level
Length = 100;  % Pond Length
Width = 100;  % Pond Width
Fetch = Width;  % Estimated wind fetch
Depth = 1.2;  % Pond Depth from Srimangal
S = 0.00001;  % Salinity
alpha = 0.0082;  % light PS parameter
SDD = 0.1524;  % Secchi disk depth
eta = 1.7/SDD;  % Light extinction coefficient
Cz = 1e-3;  % coefficient of aerodynamic stress
c_p = 4181.6;  % specific heat of water @ STP
dz = Depth/numlayers;

% Fish Conditions
N_f = 2000;  % Number fish in pond
W_n = 0.4;  % kg weight per fish
S_d = N_f*W_n/Length/Width/Depth;  % kg (fish)/m3 stocking density
LOWDO = 5;  % Cut off DO level below which fish migrate to upper pond segment

% Initial conditions
dz = Depth/numlayers;
DO_simulated = zeros(timesteps, numlayers);  % Initialize DO Array
DO_simulated (1,1:numlayers) = DO_measured(1,1:numlayers);  % Set DO start values for array

for q=1:numlayers
    z(q) = (q-1)*dz + dz/2;
    v(q) = Length*Width*dz;
end

% Coefficients and Calibrated Variables
theta_p = 1.036;  % Photosynthesis Coefficient
theta_r = 1.047;  % Respiration Coefficient
theta_s = 1.065;  % Sediment thermal coefficient
R = 0.9;  % Water column respiration rate from Dark Bottle Experiment
S = 0.02;  % Sediment respiration rate
T_DB = 25;  % Temperature of Dark Bottle Experiment
chla = 150;
K_om = 1.08e-3;  % mg m^-2 h^-1 oxidation of organic material
K_sed = 0.01;  % mg.m^{-2}.h^{-1}
phoerespire_counter = 0;

for i = 2: timesteps
  % Photosynthesis
  for q = 1: numlayers
    P_max(i, q) = 9.6 * theta_p * (T(i, q) - 20);  % mgO2/mgchla/h
    DO_ph(i, q) = (P_max(i, q) * (PAR(i) / max(PAR)) * exp(- (PAR(i) / max(PAR)) * exp(- eta * z(q))) - exp(-(PAR(i) / max(PAR)) * exp(- eta * (z(q) - dz/2)))) * power(eta * (dz), -1);
  end

  % Oxygen Consumption
  % Fish Respiration
  % Est stock density by depth
  if (DO_measured(i-1, end) < LOWDO)
    F_d = [0.9  0.1];
  else
    F_d = [0.5  0.5];
  end

  % Fish Respiration
  for q = 1: numlayers
    DO_pr(i, q) = R * theta_r * (T(i, q) - 25);
  end

  else
    if (PAR(i) - PAR(i-1)) <= 0  % Sunset,
      not sunrise
      phoerespire_counter = phoerespire_counter + 1;
for q=1:numlayers
    DO_pr(i,q) = mean([DO_pr(i-1,q) R*theta_r^(T(i,q)-25)]); %Ramping up respiration to baseline
end
else
    DO_pr(i,1) = 0.1*DO_ph(i,1);
    for q=2:numlayers
        DO_pr(i,q) = R*theta_r^(T(i,q)-25);
    end
end
else
    for q=1:numlayers
        DO_pr(i,q) = 0.1*DO_ph(i,q);
    end
end

%Sediment Respiration Rate:
DO_sed(i,numlayers) = S*theta_s^(T(i,end)-20)/dz;

%Diffusion/advection between layers
rho_air(i) = interp1(T_air_data, rho_air_data, T(i,1));
rho_w(i) = (0.99987+0.69*e^-5*mean(T(:,q))-8.89*e^-6*mean(T(:,q))^2+7.4*e^-8*mean(T(:,q))^3)*1000;
tau(i) = rho_air(i)*C_z*(W_s(i))^2;
W_s_stress(i) = sqrt(tau(i)/rho_w(i)); %Wind speed shear area
W_sa(i) = W_s(i)*Fetch;
decay(i) = 6*power(W_sa(i),-1.84);
v_drift(i) = 30*W_s_stress(i);
for q = 1:numlayers-1
    if (abs(T(i-1, q+1) - T(i-1,q)) < 0.2) | (abs(T(i-1, q+1) > T(i-1,q)))
        E_z(i,q) = 0.06; %Advection coefficient - calibrated
    else
        E_phi(i,q) = (W_s_stress(i)^2/v_drift(i)/decay(i))*exp(-v_drift(i)*(z(q)+dz/2)); %Diffusion @ depth z
        a_v(i,q) = 1.5*e^-5*(mean([T(i,q) T(i,q+1)])) +273.15 -277 -2*e^-7*(mean([T(i,q) T(i,q+1)])) +273.15 -277^2;
        Ri(i,q) = (a_v(i,q)*9.81*(z(q)+dz/2)^2/W_s_stress(i)^2)*(mean([T(i,q) T(i,q+1)])/dz); %
Richardson Number

\[
E_z(i, q) = E_{\text{phi}}(i, q) \times (1 + 0.05 \times R_i(i, q))^{\frac{-1}{2}};
\]

end

DO_diff(i, q) = \frac{-E_z(i, q) \times (DO_{\text{simulated}}(i - 1, q) - DO_{\text{simulated}}(i, q))}{dz}^2;

for q = 1: numlayers

DO_{\text{simulated}}(i, q) = DO_{\text{simulated}}(i - 1, q) + (DO_{ph}(i, q) - DO_{fr}(i, q) - DO_{pr}(i, q) - DO_{sed}(i, q)) \times \text{times step length} / 60;

end

for q = 1: numlayers - 1

if (DO_{\text{simulated}}(i - 1, q) - DO_{\text{simulated}}(i - 1, q + 1) < 0.5)

% if adjacent layers are almost at thermal equilibrium

DO_{\text{simulated}}(i, q) = DO_{\text{simulated}}(i, q) - DO_{\text{diff}}(i, q) \times \text{times step length} / 60;

DO_{\text{simulated}}(i, q + 1) = DO_{\text{simulated}}(i, q + 1) + DO_{\text{diff}}(i, q) \times \text{times step length} / 60;

else

DO_{\text{simulated}}(i, q) = DO_{\text{simulated}}(i, q) + DO_{\text{diff}}(i, q) \times \text{times step length} / 60;

DO_{\text{simulated}}(i, q + 1) = DO_{\text{simulated}}(i, q + 1) - DO_{\text{diff}}(i, q) \times \text{times step length} / 60;

end

end

K_L(i) = 0.0036 \times (8.43 \times \text{power}(W_s(i, 0.5) - 3.67 \times W_s(i) + 0.43 \times \text{power}(W_s(i), 2)))) \text{ oxygen transfer coefficient due to wind action}

C_s(i) = (1 - 0.001 \times E) \times 1.42905 \times \exp(-173.4292 + 249.6339 \times (100 / (T(i, 1) + 273)) + 143.3483 \times \log((T(i, 1) + 273) / 100) - 21.8492 \times ((T(i, 1) + 273) / 100)) \times \exp(S * (-0.033096 + 0.014259 \times ((T(i, 1) + 273) / 100) - 0.0017000 \times \text{power}((T(i, 1) + 273) / 100, 2)))) \text{http://water.usgs.gov/admin/memo/QW/qw11.03.pdf}

DO_{air}(i) = K_L(i) \times (C_s(i) - DO_{\text{simulated}}(i, 1)) / dz;

% Aeration Adjustment

DO_{\text{simulated}}(i, 1) = DO_{\text{simulated}}(i, 1) + DO_{air}(i) \times \text{times step length} / 60;

DO_{\text{simulated}}(DO_{\text{simulated}} < 0) = 0;

% Device Convection Adjustment
\( Q_w(i) = \text{Mdot\_water}(i) \times 10^6 \times 3600 / \text{rho\_water}(i) / 1000; \%[L/hr\ of\ water\ movement] \);

for \( q = 1:\text{numlayers}-1 \)
DO\_simulated\((i,q) = \text{DO\_simulated}(i,q) - (Q_w(i)\times\text{DO\_simulated}(i,q+1) / \text{v}(q) \times \text{timestep\_length} / 60; \)
DO\_simulated\((i,q+1) = \text{DO\_simulated}(i,q+1) - (Q_w(i)\times\text{DO\_simulated}(i,q) / \text{v}(q) \times \text{timestep\_length} / 60; \)
end

end

\%Graph\ Settings

```
Xtick_Init = [{'6 am'},{'12 pm'},{'6 pm'},{'12 am'},{'6 am'},{'12 pm'},{'6 pm'},{'12 am'},{'6 am'}];
```

ticksarray=[4 28 52 76 100 124 148 172 196 220 244 268];
tickslabels= {'6 am', '12 pm', '6 pm', '12 am', '6 am', '12 pm', '6 pm', '12 am', '6 am'};

```
figure
```

data = 1:length(\text{DO\_simulated}(1,1));
n = numel(\text{DO\_simulated}(1,1));

135
for q=1:numlayers
    xi = interp1( 1:n, xdata, linspace(1, n, 0.45*n) );
    yi = interp1(xdata, DO_simulated(:,q), xi);
    plot( xi, yi, 'LineWidth',2);
    hold all;
end
plot (xdata, DO_measured(:,1), 'x', xdata, DO_measured(:,2), 'x', '
    MarkerSize',20);
ylim([0 20]);
set(gca, 'Xtick', xdata, 'XTickLabel', '');
hx = get(gca, 'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
for i = 1:size(Xtick_Init)
    t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation',45, 'HorizontalAlignment', 'right', 'FontSize', 20)
set(gca, 'XTick', tickarray)
set(gca, 'FontSize',18)
ylabel('Dissolved Oxygen (mg/L)')
legend('Surface (Simulated)', 'Bottom (Simulated)', 'Surface (Measured)', 'Bottom (Measured)')

%% Graph 2: Multipanel
figure
%% Sub 1
subplot(3,2,1)
xdata = 2:length(DO_ph(:,1));
plot(xdata, DO_ph(2:end,1), 'b', xdata, DO_ph(2:end,2), 'r', '
    MarkerSize',20);
set(gca, 'Xtick', xdata, 'XTickLabel', '');
hx = get(gca, 'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
    t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation',45, 'HorizontalAlignment', 'right', 'FontSize', 14)
set(gca, 'XTick', tickarray)
set(gca, 'FontSize',16)
ylabel('DO (mg/L)')
title('Photosynthetic O2 Production')
legend('Surface', 'Bottom')
%% Sub 2
subplot(3,2,2)
xdata = 2:length(DO_air);
plot(xdata, DO_air(2:end), 'b', 'MarkerSize',20);
set(gca,'Xtick', xdata, 'XtickLabel', '');
hx = get(gca,'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation', 45, 'HorizontalAlignment', 'right', 'FontSize', 14);
set(gca,'XTick', ticksarray);
set(gca,'FontSize', 16);
ylabel('DO (mg/L)');
title('O2 Diffusion from Re-Aeration');
legend('Surface');

% Sub 3
subplot(3,2,3);
xdata = 2: length(DO_fr(:,1));
plot(xdata, DO_fr(2:end,1), 'b', xdata, DO_fr(2:end,2), 'r', '
MarkerSize', 20);
hx = get(gca, 'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation', 45, 'HorizontalAlignment', 'right', 'FontSize', 14);
set(gca,'XTick', ticksarray);
set(gca,'FontSize', 16);
ylabel('DO (mg/L)');
title('O2 Depletion Due to Fish Respiration');
legend('Surface', 'Bottom');

% Sub 4
subplot(3,2,4);
xdata = 2: length(DO_pr(:,1));
plot(xdata, DO_pr(2:end,1), 'b', xdata, DO_pr(2:end,2), 'r', '
MarkerSize', 20);
hx = get(gca, 'XLabel'); % Handle to xlabel
set(hx, 'Units', 'data');
pos = get(hx, 'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i), y, Xtick_Init(i,:));
end
set(t, 'Rotation', 45, 'HorizontalAlignment', 'right', 'FontSize', 14);
set(gca,'XTick', ticksarray)
set(gca,'FontSize',16)
ylabel('DO (mg/L)')
title('O2 Depletion Due to Nighttime Respiration by Phytoplankton')

legend('Surface','Bottom')

%% Sub 5
subplot(3,2,5)

xdata = 2:length(DO_pr(:,2));
plot(xdata,DO_sed(2:end,2),'r','MarkerSize',20);
set(gca,'Xtick',xdata,'XTickLabel','','');

hx = get(gca,'XLabel'); % Handle to xlabel

pos = get(gca,'Units','data');

for i = 1:size(Xtick_Init)
t(i) = text(xdata(i),y,Xtick_Init(i,:));
end

set(t,'Rotation',45,'HorizontalAlignment','right','FontSize',14)

set(gca,'XTick',ticksarray)
set(gca,'FontSize',16)
ylabel('DO (mg/L)')
title('O2 Depletion Due to Sediment Respiration')

legend('Bottom')

%% Sub 6
subplot(3,2,6)

xdata = 2:length(DO_diff(:,1));
plot(xdata,abs(DO_diff(2:end,1)),'b','MarkerSize',20);

set(gca,'Xtick',xdata,'XTickLabel','','');

hx = get(gca,'XLabel'); % Handle to xlabel

pos = get(hx,'Position');
y = pos(2);

for i = 1:size(Xtick_Init)
t(i) = text(xdata(i),y,Xtick_Init(i,:));
end

set(t,'Rotation',45,'HorizontalAlignment','right','FontSize',14)

set(gca,'XTick',ticksarray)
set(gca,'FontSize',16)
ylabel('DO (mg/L)')
title('O2 Inter-layer Diffusion and Advection')

%% Graph 3: Device Convection
figure

xdata = 1:length(Q_w);
plot(xdata,Q_w,'b','MarkerSize',20);

set(gca,'Xtick',xdata,'XTickLabel','','');
hx = get(gca,'XLabel'); % Handle to xlabel
```matlab
set(hx,'Units','data');
pos = get(hx,'Position');
y = pos(2);
for i = 1:size(Xtick_Init)
t(i) = text(xdata(i),y,Xtick_Init(i,:));
end
set(t,'Rotation',45,'HorizontalAlignment','right','Fontsize',14)
set(gca,'XTick',ticksarray)
set(gca,'FontSize',16)
ylabel('Diffusion of Dissolved Oxygen (mg/L)')
legend('Surface−Bottom')
grid

%% Export, plot in Excel

outputfilename = 'Results.xlsx';
col_header={'Time','DO Top − Simulated','DO Bottom − Simulated',
            'DO Bottom − Actual','DO Bottom − Actual','Average DO concentration'};
row_header = Xtick_Init;
xlswrite(outputfilename,col_header,'Results','A1');
xlswrite(outputfilename,row_header,'Results','A2');
xlswrite(outputfilename,DO_top,'Results','B2');
xlswrite(outputfilename,DO_bot,'Results','C2');
xlswrite(outputfilename,DO_top_actual,'Results','D2');
xlswrite(outputfilename,DO_bottom_actual,'Results','E2');
xlswrite(outputfilename,DO_net_avg,'Results','F2');

hExcel = actxserver('Excel.Application')
hWorkbook = hExcel.Workbooks.Open('C:\Users\AHMED\Google Drive\Thesis\MATLAB\O2\New\10 mins\Results.xlsx')
hWorksheet = hWorkbook.Sheets.Item(1)
hWorksheet.Columns.Item(1).ColumnWidth = 50; %first column
hWorkbook.Save
hWorkbook.Close
hExcel.Quit

winopen(outputfilename)

% End
```
Bibliography


