SIMULATION MODEL FOR DESIGN AND MANAGEMENT OF WATER RECIRCULATING SYSTEMS IN AQUACULTURE

BY

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Abbreviations

AB	Size of airblower, hp
AP	*Ammonia production rate, mg/kg fish.hour.*
BM	Biomass, kg-fish
CC	Carrying capacity, Kg L^{-1} per min
C_p	Specific heat of air at constant pressure (kJ $kg^{-1}K^{-1}$)
DGR	Daily growth rate, g
DO_B	Dissolved oxygen consumption through the biofilter
DO_{FR}	Dissolved oxygen consumption through fish respiration
DO_N	Dissolved oxygen consumption through nitrification
DO_{PF}	Dissolved oxygen addition through pipe flow
DO_{sup}	Total dissolved oxygen demand, kg-O_2/day
E	Efficiency, %
e_a	Air vapor pressure (Pa)
e_s	Saturated vapor pressure (Pa)
FC	Feed conversion rate, g feed g^{-1} fish weight
FI	Feed intake, g
FR	Feeding ratio, % of body fish
g	Gravitational acceleration (9.81 m s^{-2})
h	Heat transfer coefficient (kW m^{-2} K^{-1})
h_{fg}	Latent heat of vaporization (kJ kg^{-1})
HLR	Hydraulic loading rate (m^3 m^{-2} h^{-1})
HPC	Horsepower to watts conversion factor, 0.7467 kW/hp
k	Thermal conductivity coefficient (kW m^{-1} K^{-1})

k_{air}	Thermal conductivity of the air (kW m^{-1} K^{-1})
Lng	Longitude of the pond (degrees)
Lnt	Longitude of the standard time meridian (degrees)
LST	Local standard time
NPU	Net protein utilization
Nt	Final number of fish in the tank
n_{water}	Index of refraction of water
OC	Oxygen consumption rate, mg O_2/kg fish.hour.
PC	Pump cycle length, hr
P_f	Decimal fraction of protein in feed
Pka	Negative log of the acid dissociation constant for ammonia
Pr	Prandtl number
q	Total energy (kJ) at any given time (t) in the pond
Q	Water flow rate, m^3/day
q_{back}	Rate of heat loss due to back radiation, kW m^{-2}
q_{cond}	Rate of heat exchange with the wall, kW m^{-2}
q_{conv}	Rate of heat exchange with the air by convection, kW m^{-2}
q_{drain}	Rate of bulk energy lost to the overflow of water, kW m^{-2}
Q_e	Water lost to evaporation (m^3 s^{-1})
q_{evep}	Rate of heat lost through the evaporation of water, kW m^{-2}
q_{in}	Rate of bulk energy gain from makeup water, kW m^{-2}
q_{other}	Rate of energy transfer from or to other sources, kW m^{-2}
Q_{out1}	Flow rate leaving the lateral drain, m^3/day
Q_{out2}	Flow rate leaving the main drain, m^3/day

q_{rain}	Rate f bulk energy gain due to rainfall, kW
$q_{reflected}$	Rate of solar energy reflected a way from the system,kW
q_{sky}	Rate of energy gained by long wave radiation from the sky, kW
q_{solar}	Rate of energy gained by radiation, kW
q_{t-1}	Heat stored in water volume v at time t-1 (kJ)
R	Fraction of reflected radiation
R.S.A.	Required surface area, m^2/kg fish
Re	Reynold's number
RH	Relative Humidity (%)
SAE	Standard aeration efficiency, kg-O_2/kW-hr
S_b	Specific surface area, m^2 m^{-3}
S_c	Solar constant (1353 W m^{-2})
SGR	Specific growth rate, (% or g day^{-1})
$SS_{f\ in}$	Suspended solids at the inlet the screen filter, mg L^{-1}
$SS_{f\ out}$	Suspended solids at the outlet the screen filter, mg L^{-1}
$SS_{h\ in}$	Settleable solids at the inlet the hydrocyclone, mg L^{-1}
$SS_{h\ out}$	Settleable solids at the outlet the hydrocyclone, mg L^{-1}
SSR_f	Suspended solids removed, kg m^{-3}
SSR_h	Settleable solids removed, kg m^{-3}
T.S.A.	Total surface area, m^2
TAN	Total ammonia-nitrogen, g/kg feed
TS_{in}	TS concentration entering unit, kg m^{-3}
TS_{out1}	TS concentration leaving the lateral drain, kg m^{-3}

TS_{out2} TS concentration leaving the main drain, kg m^{-3}

TS_P TS production rate, kg TS produced per day

English Symbols

A Area (m^2)

BOD_5 Average unfiltered BOD_5 excretion rate, 2160 mg-O_2/kg fish. day

Ci-Cm Dissolved oxygen available for respiration, mg L^{-1}

D Distance from the Earth to the sun (km)

d Water depth (m)

D_0 Mean distance from the Earth to the sun, 1.496 x 10^8 km

e Average emittance of the atmosphere (dimensionless)

f Pumping frequency, l hr^{-1}

f Relative feeding level ($0 < f > 1$, dimensionless).

m Constant

n Day of the year (on January 1st , n = 1)

n_{air} Index of refraction of air (1) and

NH_{3in} Ammonia concentrating at inlet the fish tank, mg L^{-1}

NH_{3out} Ammonia concentrating at outlet the fish tank, mg L^{-1}

R_{feed} Feeding rate, kg feed per kg fish per day

s Constant

OTR Oxygen transfer rate, kg-O_2/hr

t Time, day

T Water temperature, °F.

T_{fluid} Temperature of the cooling (or heating) fluid (K).

Ti	Temperature of the inner surface (K)
T_{max}	Above this temperature fish stop eating, ºC
T_{min}	Below this temperature fish stop eating, ºC
T_o	Temperature of water volume v at time t=0 (K)
T_{opti}	Optimum temperature for fish taking food, ºC
T_{pond}	Temperature of the pond (K)
T_{air}	Absolute air temperature 2 m above the water surface (K)
$T_{surface}$	Temperature of the surface (K)
T_t	Temperature of water volume v at time t (K)
T_{water}	Temperature of the water.
v	Kinematic viscosity of the fluid ($m^2\ s^{-1}$).
V_2	Wind velocity 2 meters above the pond surface ($m\ h^{-1}$)
v_{air}	Kinematic viscosity of the air ($m^2\ s^{-1}$)
V_{air}	Velocity of the air ($m\ s^{-1}$)
V_b	Required volume of biofilter media, m^3
v_s	Particle mean settling velocity ($m\ h^{-1}$)
V_{tank}	Volume of water contained within culture tank, m^3
W	Average of individual fish weight, g
W_f	Final weight, g
WG	Weight gained, g
W_i	Initial weight, g
W_t	Total weight of fish, kg
x	Length in the direction of wind flow
Z	Thickness of material (m)

Greek Symbols

α,β, γ	Constants
α	Thermal diffusivity of the fluid ($m^2\ s^{-1}$)
α_{air}	Thermal diffusivity of the air ($m^2\ s^{-1}$)
β	Coefficient of thermal expansion (K^{-1})
δ	Dissolved oxygen factor ($0 < \delta > 1$, dimensionless).
η_{bf}	Ffficiency of biological filter (%)
η_f	Screen filter efficiency for suspended solids (%)
η_h	Removal efficiency for settleable solids (%)
θ_{water}	Refracted angle of the beam
θz	Zenith angle and
ρ_{air}	Density of air ($kg\ m^{-3}$)
ρ	Density of water ($kg\ m^{-3}$)
ρ_{fish}	Density of fish in the culture tank, kg fish per m^3
τ	Temperature factor ($0 < \tau > 1$, dimensionless).
φ	Unionized ammonia factor ($0 < \varphi > 1$, dimensionless).
ψ	"Clearness" factor (1 on clear days, 0.2 on cloudy days)
ω	Hour angle (degrees)
ω_{time}	Solar time (degrees)
κ	Photoperiod factor ($0 < \kappa > 1$, dimensionless).
K_{min}	Coefficient of fasting catabolism at T_{min}, $g^{1-n}\ hr^{-1}$
$\dot{m}$	Mass flow rate of water into (or out of) the system,
$m^{\bullet}_{evap}$	Rate of evaporation ($kg\ s^{-1}$)

ABSTRACT

A simulation model for design and management of water recirculating aquaculture systems was developed. The model is able to predict the water temperature and energy consumption at different air ambient temperature (23, 25, 27, 29 and 31 ºC) and to predict the oxygen consumption, ammonia production and nitrate production at different water temperatures (24, 26, 28, 30 and 32 ºC). Also, the model is able to predict the solids generation at different water depths (0.8, 1.0, 1.2, 1.4 and 1.6m) and different settling velocities (1.25, 1.67, 2.08, 2.5 and 2.9 m/h). Experiment was carried out to validate the model results which include: water temperature, dissolved oxygen, ammonia, nitrite, nitrate, solids, pH, alkalinity and fish mass. The results indicated that the average hourly temperature predicted by the model was in a good agreement with those measured by the system, where, it ranged 25.00 to 30.90˚C experimentally, while it was from 24.20 to 29.86˚C theoretically. The predicted oxygen consumption values were in the range 189.13 to 457.56 mg O_2/kg fish per hour and the measured oxygen consumption values were from 197.42 to 467.61 mg O_2/kg fish per hour. The ammonia production from the system ranged from 10.56 to 52.96 mg NH_3/kg fish.hour experimentally while it was from 10.45 to 48.61 mg NH_3/kg fish.hour theoretically. The nitrate

production in the system ranged from 41.61 to 222.31 mg NO_3/kg fish.hour experimentally, while it was from 45.34 to 210.97 mg NO_3/kg fish.hour theoretically. The efficiency of the biological filter for ammonia removal from the system ranged from 11.11 to 63.64 %. The settleabe solids removal was determined and was found to be between 0.0304 to 0.0556 kg m^{-3} (30.40 to 55.60 mg l^{-1}) while it was 0.039 kg m^{-3} (39 mg l^{-1}) theoretically. The suspended solids removal was found to be between 0.0123 to 0.0806 kg m^{-3} (12.30 to 80.60 mg l^{-1}) while it was from 0.0124 to 0.1425 kg m^{-3} theoretically. The hydrocyclone and screen filter efficiency to remove the solids from the system ranged from 27.4 to 57.79 % and15.46 to 74.41 %, respectively. The daily average fish growth rate from the system ranged from 0.26 to 1.46 g/day experimentally, while it was from 0.11 to 1.96 g/day theoretically. The weight of individual fish from the system ranged from 4.00 to 115.79 g experimentally, while it was from 4.00 to 130.80 g theoretically. The feed conversion rate ranged from 0.61 to 2.25 kg feed / kg fish actually, while, it was estimated to be from 0.50 to 1.94 kg feed / kg fish theoretically. The actual and theoretically energy consumption by whole system during the whole day was 377252.50 and 359896.5 kJ.day, respectively. The model results were in a reasonable agreement with the experimental ones.

1. INTRODUCTION

Aquaculture is defined as being the art and science of rearing aquatic organisms, which include aquatic plants, such as seaweed and algae, shelfish, such as oysters and mussels, ornamental and food fish. The origin of aquaculture is accredited to ancient China where it is throught to be initiated between 4000 and 3500 BC. The earliest text on aquaculture was written by a Chinese man named Fan Li in 460 BC, entitled Yu Ching Treatise on Fish Breeding. Aquaculture was not only exploited by the Chinese but there is also evidence that it was practiced in ancient Egypt, by the Romans, and by the Japanese as early as 3000 BC **(DFO, 2005)**.

While aquaculture was growing in Europe and other parts of world, in North America it was primarily used to enhance wild fish stocks. In Canada, aquaculture was not viewed as necessary due to the abundant resources. However, it arose out of the possibility of financial benefits and employment opportunities. In New Brunswick, aquaculture developed in the Bay of Fundy centered around the Fundy Isie region. The industry started with one site trying to over winter Atlantic salmon in 1979, and grew to 40 seacage sites in 1988 with a production rate of 1,334 Mg to 64 production sites with a production rate of 10,145 Mg in 1993 **(Boghen, 1995)**.

Historical production data for aquaculture together with agricultural production data, show that aquaculture has been the fastest growing food production sector in the world, over the last few decades. Since 1984, global aquaculture output has increased at an average annual rate of about 10%, compared with a 3% increase for livestock meat and a 1.6% percent increase for capture fisheries. Aquaculture provided 8% of global fishery

production (11% of food fish) in 1984, increasing to 22% (29% of food fish) in 1996 and increasing to 51% (68% of food fish) in 2010 **(FAO, 2010)**.

The aquaculture industry places great demands on water resources requiring anywhere from 200 – 600 m^3 of water for every kilogram of fish produced **(Kioussis *et al.*, 2000)**. Although some aquaculture systems (raceways and pond culture) are much more water consumptive than others (reciculating systems), the aquaculture generally requires more water per unit area or per unit of product than most other plant or animal production systems **(Lawson, 1995)**. Consequently, aquaculture operations produce large quantities of effluent containing particulate and dissolved organic matter and nutrients. Depending on the species and culture technique, up to 85% of phosphorus, 80 – 88% carbon and 52 – 95% of nitrogen input into a fish culture system may be lost to the environment through uneaten feed, fish excretion, fecal production and respiration **(Wu, 1995 and Cripps and Kumar, 2003)**.

There is no doubt that the country faces a real problem with regard to the production of fish. Under the current system (open system) of fish farming, the total production accounted 673 thousands tons in 2009, which represents 2.75 tones/ha annually, i.g., 275 gm/m^3 **(G.A.F.R.D, 2009)**. The most of these produced fish are contaminated according to a report issued by the Ministry of Irrigation, besides, most of these farms are using the contaminated agricultural drainage water because the irrigation law prohibits using the irrigation water in fish farming. On the other hand, using the open systems caused a huge losses of water due to the evaporation which amounted by 10000 m^3 per

Fadden. Since the area of fish farming is around 300,000 faddens that means the total losses from evaporation are up to 3 billion cubic meters of water which is enough to reclaim 500 000 faddens.

In recirculating aquaculture systems maintaining acceptable water quality is in itself a significant challenge, but is particularly difficult when addressing the buildup of fine colloid waste less than 50 μm in diameter, because the particles are not easily removed by standard conventional filtration techniques. **Libey (1993)** showed that the smallest particle sizes (5-10 μm), which cause the greatest problems to the fish culture **(Chen *et al.*, 1993)**, are also the most difficult to remove from the system. For this reason a cumulative effect occurs where the concentration of fine particulates builds up over time **(Ebeling *et al.*, 1997)**.

Land-based aquaculture facilities and especially recirculating aquaculture systems (RAS) have gained attention in the last decade due to the lack of optimum sites suitable for marine aquaculture cages, more environmentally friendly operations and better control on the production parameters **(Losordo, 1998)**. Unlike flow through systems where new water is added consistently to the tanks and evacuated from the system without any treatment, recirculating systems use treatment processes to recycle the water at a high rate and send it back to the fish tanks. The degree and cost of the treatment systems depend on the species cultured, the optimum growth temperature and optimum water quality criteria. Recirculating aquaculture typically uses 160 to 2100 times less water per kilogram of fish produced than other types of land-based aquaculture **(Timmons**

***et al.*, 2001)**. The volume of waste effluent produced is therefore minimized and can be treated in small lagoons or by local wastewater treatment plants, which reduces the impact on the environment **(Timmons and Losordo, 1994)**.

Although recirculating aquaculture systems (RAS) have a relatively high initial investment cost that can represent 40% of the total fish production cost **(Timmons and Losordo, 1994)**. The control of rearing parameters allows faster fish growth and a proportionally faster arrival on the market compared to sea cage aquaculture. It is also estimated that the system costs could decrease by 25% with improved system design and technology advances **(Timmons *et al.*, 2001)**. Treatment system development could therefore contribute to the widespread expansion of this type of aquaculture.

The most important factors affecting the fish production are water temperature, dissolved oxygen, ammonia, nitrite, nitrate, solids, pH, alkalinity, and feeding. Controlling these factors is very difficult to achieve. Therefore, the main objectives of the current investigation are:

1- Develop a simulation model to manage and optimize the main factors affecting the performance of the system (RAS). This could be achieved by:
   - Studying of water temperature, oxygen consumption, ammonia production, nitrate production, biological filter volume, solids generation, fish growth rate, specific growth rate, feed conversion rate and system energy consumption at different conditions.
   - Building a physical model and carrying those with corresponding predicted values.

- Complete analysis of the system to:
  - Find the interrelation between various variables and parameters influencing the system.
  - Verify this relation and selecting the most appropriate.

2- Validating the developed simulation model to achieve this a physical model was constructed. An experiment was carried out to measure: water temperature, oxygen consumption, ammonia, nitrite, nitrate, solids, fish growth rate, specific growth rate, feed conversion rate and system energy consumption.

3- Experimentation with the model.

2. REVIEW OF LITERATURE

2.1. Aquaculture:

Aquaculture is the art of cultivating the natural products of water. By "aquacultural systems" we mean the commercial production systems of aquatic animals either in controlled or uncontrolled environment **(Bala and Satter, 1989).** Aquaculture is the science and technology of producing aquatic plants and animals **(Lawson, 1995 and Losordo *et al.*, 2000)**.

Aquatic production systems are typically classified according to type (static system "open system" flow-through system "recycle system". Raceway "reuse system" and Cage system). Biomass density (extensive, semi – intensive, intensive and super intensive), and feeding practices (natural and artificial feeding), as reported by **Krom *et al.* (1989) and Ridha and Cruz (2001).**

2.2. Water Systems:

Water systems employed for use in aquaculture may be classified as either static or flowing.

2.2.1. Static Systems:

In static culture systems there is no exchange of water during the culture period; however, water may need to be added intermittently to offset losses from seepage and evaporation **(Lawson, 1995)**. The most widely used static systems use ponds as culture units. Maintenance of adequate water quality for fish production relies upon natural physical, chemical and biological processes occurring in the pond **(Lawson, 1995)**. Static pond culture is usually extensive because of problems associated with maintaining water quality when large masses of organisms are cultured in static water. Increasing biomass of cultured

organisms requires addition of fertilizers and supplementary feeds to maintain productivity and management of water quality problems including unacceptable levels of nitrogenous compounds and low dissolved oxygen levels **(Stickney, 1994 and Appleford *et al.*, 2003)**.

2.2.2. Flowing Systems:

In flowing culture systems water continuously enters and exits the culture units. The time required to completely replace the water volume in the culture chamber varies considerably and depends on the type of aquaculture system utilized and the density and type of organism cultured. Flowing culture systems may be open, semi-closed or recirculating (closed) **(Lawson, 1995)**.

2.2.2.1. Open Systems:

In open culture systems, water leaving the culture units is released directly into a receiving water body. There is no artificial circulation of water through or within the system and water quality is maintained by natural processes **(Appleford *et al.*, 2003)**. One example of an open aquaculture system is cages placed within a large body of water such as an ocean or an estuary. In these cage systems, there is typically a high density of cultured organisms, artificial feed is supplied and water quality is maintained by natural currents and tides. A second example of an open aquaculture system is bivalve culture on rafts or longlines placed in the open water. In these systems, water quality is maintained by natural currents and tides and the organisms feed by filtering phytoplankton from the water column. Open culture systems are prone to a number of problems, including: (a) lack of control over water quality and seasonal variations in environmental factors such as temperature

and salinity which may result in large variations in growth rates, (b) difficulty selecting an appropriate site for the farm and (c) increased susceptibility to disease and predation **(Stickney, 1994 and Appleford *et al.*, 2003)**.

2.2.2.2. Semi-closed Systems:

Semi-closed culture systems fall between static and open system in terms of water exchange, which is substantially greater than in static systems and much less than in open systems. In these systems, there is a greater degree of control over water quality to the extent that water flow can be increased, decreased or stopped. In semi-closed culture systems, ponds, tanks and raceways are typically used as culture units **(Stickney, 1994 and Appleford *et al.*, 2003)**.

2.2.2.3. Recirculating Systems:

In recirculating culture systems, water exiting the culture units undergoes some form of treatment to improve its quality and is then recycled back into the system **(Appleford *et al.*, 2003)**. Water parameters requiring regulation include particulate matter resulting from unconsumed feed and feces, nitrogenous wastes, dissolved gases, pathogens, pH and alkalinity **Lin *et al.*, 2005)**. Recirculating systems generally consist of three basic components: one or more settling tanks, a biological filter and the culture units. Water exiting the culture chambers typically enters a primary settling tank where solids are removed. Particulate matter may also be removed from aquaculture effluent by mechanical filtration through sand or other filter media. The water is then passed into a biofilter where nitrification of ammonia occurs **(Lin *et al.*, 2005)**. Rotating biological contactors, expandable media (sand, plastic beads) and fluidized bed biofilters are currently considered the most

viable treatment options for nitrification **(Rakocy and Hargreaves, 1993)**. Biofilters for nitrification perform optimally within a temperature range of 25 – 30 °C, a pH range of 7.5 – 8.0, at a saturated dissolved oxygen concentration, a low BOD concentration (< 20 mg L^{-1}) and a total alkalinity of 100 mg L^{-1} as $CaCO_3$ or greater **(Rakocy and Hargreaves, 1993)**. The biofilter is usually followed by a secondary settling tank where bacteria flocs from the biofilter are removed. After secondary settling, mechanical aeration and sterilization with ozone or ultraviolet radiation may be provided before the water is returned to the culture chambers. In most recirculating systems some of the water is discharged and replaced each day to offset the effects of evaporation and incidental losses and to help maintain water quality **(Stickney, 1994 and Appleford *et al.*, 2003)**.

2.3. Recirculating Aquacultural Systems (RAS) and its Components:

Recirculating aquaculture systems (RAS) offer an alternative to large water supplies through water treatment and reuse. Recirculating aquaculture systems are usually land-bases facilities that use tanks as the holding system for the aquatic crop. With recirculating systems, water is reused through pumping systems as well as water treatment facilities to ensure quality of the water is maintained. The technologies associated with recirculating systems are costly, but the level of control as well as the concentration of improving the manageability is worthwhile **(Losordo, 1997)**.

Recirculating aquaculture systems (RAS) consist of an organized set complementary unit processes that treat water for

reuse, holding, and culturing fish. These systems integrate an intensive fish production component with an extensive, multiple-use water reservoir to accomplish water quality management. The intensive component is characterized by moderate (2-15 kg m^{-3}) to high (> 100 kg m^{-3}) fish density, moderate (0.3-5% day^{-1}) to high (50-100% day^{-1}) volumetric exchange rate, and supplemental aeration **(Hargreaves *et al.*, 1996)**.

Fisheries researchers have used recirculating systems for nearly three decades, but attempts to advance these systems to commercial-scale food fish production has increase dramatically in the last decade **(Masser *et al.*, 1999)**. However, these have been few documented cases of successful production large-scale fish production in recirculating systems. Most reports of successful production have been from small (less than 100,000 pounds per year) system supply fish to local niche markets at high prices **(Losordo *et al.*, 1992)**. These high priced markets have been necessary for financial success because of the high cost of fish production in recirculating systems **(Hargreaves *et al.*, 1996; Losordo *et al.*, 1992; Heinsbroek and Kamstra, 1990)**. Other investigators have found that RAS is economically viable **(Liao and Chen, 1983)** and are characterized by low cost with high productivity, 100 kg m^{-2} **(Yong-liang, 1990)**.

Since the fixed cost of developing recirculating systems is usually higher than that for an equivalent pond production system, these must always operate near maximum production (maximum risk) capacity to be economical **(Masser *et al.*, 1999)**. Fortunately, the culture of aquatic organisms in small enclosures permits a near total control of the environment of the production unit. **Suresh and Lin (1992)** reported that the net yield of red *Oreochromis* increased non-linearly with increasing stocking

densities up to 200 fish m^{-3} but higher net yields are possible at still higher densities.

Water recycle system is consists of four main components:

2.3.1. Fish Tank:-

Tanks of nearly any shape are available and are used for various functions in fish culture. However most tanks can be classified as circular, rectangular, or oval with a dividing wall. Circular tanks are often used, with the water inlet providing tangential velocity component. This component causes a rotary tank circulation. Discharge typically is through the tank center by means of a standpipe or bottom drain, **(Wheaton 1993; Lawson, 1995; Soderberg, 1995).**

Circular tanks are good culture vessels because they provide virtually complete mixing and a uniform culture environment. When properly designed, circular tanks are essentially self-cleaning. This minimizes the labor cost associated with tank cleaning. Typically, water is introduced into a circular tank at the perimeter and is directed tangential to the tank wall. The income water imparts its momentum to the mass of water in the tank, generating a circular flow pattern. The water in the tank spins around the center drain, flowing an inward spinal to the center of the tank. Centrifugal forces and the inward, spiraling flow patterns transport solids wastes to the center drain area where they are removed. Once the mass of water in the tank is set into motion, very little energy is required to maintain the velocity of water movement in the tank. The momentum of the water circling the center drain helps sustain the circular flow. One can easily demonstrate this fact by swirling the water in a bucket with

one's hand. The water will continue to spin for several minutes after the hand is removed. A good rotational velocity can be generated in the tank through the use of spray bars or airlift pumps positioned at the perimeter of the tank **(Wyk, 2008).**

The primary disadvantage of circular tanks is that they do not use space efficiently. A circular tank of a given diameter will have about 21% less bottom culture area than a square tank whose sides are the same length as the diameter of the circular tank. This means that that if circular tanks are used there will be a 21% loss of potential production area in a given amount of space. If production is being carried out inside buildings or greenhouses the cost of enclosing a given amount of production area will be higher for circular tanks than for rectangular tanks **(Wyk, 2008).**

2.3.2. Waste Solids Removal:-

The decomposition of solid fish waste and uneaten or indigestible feed can use a significant amount of oxygen and produce large quantities of ammonia-nitrogen. There are three categories of waste solids settleable, suspended, and fine or dissolved solids. There are three methods that are used to remove solids from fish culture water. There are gravity separation, filtration, and fractionation. These classification of methodology are based on the removal mechanisms used to effect the removal (fractionation is sometimes considered as another kind of gravity separation, but it is a different principle of application so it is described separately). Large particles (larger than 100 μm) can be effectively removed by settling basins or mechanical screen filtration. However, fine particles cannot be removed effectively by either gravity separation or granular filtration methods.

Granular filters are effective only in the removal of particles larger than 20 µm (**Vinci *et al.*, 2001).**

a- Gravity Separation:

Gravity separation works on the principle of sedimentation and settling velocities. Unit processes in this category include clarifiers (settling tanks), tube settlers, and hydrocyclones. The actual process of particle removal can be accomplished with either screen, granular media (GM), or porous media (PM) filters (**Vinci *et al.*, 2001)**.

a_1- Sedimentation:

Sedimentation occurs due to the density difference between the solid particles and water. Assuming a particle to be heavier than water, under the force of gravity it will fall through the water with increasing speed until it reaches a terminal value for its settling velocity. Assuming spherical particles, the settling velocity can be calculated by the following equation **(Montgomery, 1985).**

$$V_s = \sqrt{\frac{4g(\rho_p - \rho)D_p}{3C_D\rho}} \qquad (2.1)$$

Where: V_s = Velocity of settling particles, m s^{-1}

g = Gravitational acceleration, 9.81 m s^{-2}

ρ_p = Density of particles, kg m^{-3}

ρ = Density of water, kg m^{-3}

D_p = Diameter of particle, m

C_D = Drag coefficient, dimensionless

For a small particle having a low Reynolds number, Stoke's Law applies and Eq. 1 can be rewritten as

$$V_s = \frac{g(\rho_p - \rho)D_p^2}{18\mu} \qquad (2.2)$$

Where: μ = Dynamic viscosity, Pa.s.

Both Eqs. 2.1 and 2.2 indicate that denser and large particles will settle out of water faster than smaller, less dense particles. This is true for all types of removal processes and why you should do everything possible to maintain large particle sizes. The best technique for maintaining large particle sizes is to remove the particles as quickly as possible from the fish culture vessel and before any pumping has occurred. Also, you should try to minimize any turbulence / falling water situations prior to the primary total settleable solids capture event.

a_2- Settling velocities:

Settling velocities for fish faces have been reported at 1.7-4.3 cm /s **(Warren-Hansen, 1982).** In tests they conducted, the authors measured settling velocities by using cylindrical beads (each 3 mm in length by 3 mm o.d.) with a specific gravity of 1.05, to simulate tilapia feces. The beads exhibited settling velocities of 3.8 cm/s. These results are similar to the settling velocity reported for fecal matter by **(Warren-Hansen, 1982)**. Certain species produce fecal matter with even lower specific gravities **(Robertson, 1992)**, trout fecal matter is typically 1.005 specific gravity. This is reflected in slower settling velocities of these wastes. **Wong and Piedrahita (2000)** reported that the median settling velocity on a mass-basis for the settleable solids from rainbow trout is 1.7 cm/s.

This similarity in settling velocity also suggests that specific weight of feces would be found them to have a much more rapid settling velocity, e.g., 14 cm/s, than the plastic beads. This finding is similar to that reported by **Juell (1991)** of 15-33 cm/s. However, finer and/or less dense particles can be produced in RAS, which may settle at only 0.01 cm/s **(IDEQ, 1998).**

These particles would not center of dual-drain tanks, thus staying in the water column until removed by some other process.

a_3- Hydrocyclones:

Hydrocyclones employ the principle of centrifugal sedmentation, i.e., the suspended solid particles are subjected to centrifugal acceleration, which mackes them separate from the liquid more rapidly by effectively increasing their density. Hydrocyclones are also called swirl separators and tea-cup settles. The Cornall dual-drain is effective because the tanks are operated as swirl separators. The rotational flow of the inlet water imparts a centrifugal motion in the particles that causes the heavier particulate material to move to (or remain at) the outer portion of the vessel. Simultaneously, the particles are affected by gravity, which causes them to fall through the water, and move towards the bottom center drain. Here, at the bottom center drain, a small percentage of the total flow is removed, which is referred to as the underflow **(Vinci *et al.*, 2001)**.

The underflow in a swirl separator should be about 5 to 15% of the total flow, which is the same percentage used for the Cornell dual-drain in the culture tank vessel. Downward spiral flow moves dominantly along the outside walls and creates an inward spiral flow in the center. Between these two spirals there is a layer, called the mantle, where zero vertical velocity exists. The entrance to the outlet pipe should be placed at the center of the mantle. This mantle plane is located at a distance equal to 1/2 to 2/3 (the diameter of the vessel) below the top surface of the water. Strategic placement of the outlet takes advantage of the zero vertical velocity condition by minimizing TSS in the outlet flow. Ideally, it particular waste water should be tested prior to full design implementation to have any reasonable chance of

getting it right, or design the swirl separator so that adjustments in outlet placement can be made during operation **(Vinci *et al.*, 2001)**.

b- Filtration:

Particle removal from the water can be accomplished by one or more filtration process. These are sedimentation, straining, Brownian diffusion and interception. These processes are impemenred in filtration systems by screen **(Davidson and Summerfelt, 2005)**.

b_1- Screen filters:

Screen filters for filtration are popular because they require minimal labor and floor space in comparison to settling basins. As in filters remove solids by virtue of physical restrictions (or straining) on a media when the mesh size of the screen is smaller than the particles in the wastewater. Screen filters are commercially available in a variety of different configurations. Typical screen filters used in a aquaculture are the drum filter, disk filter, and inclined belt filter **(Timmons *et al.*, 2001).**

Vinci *et al.* (2001) summarized the relative operational advantages, drawbacks and costs of three types of waste water filters. All three types of screen filters are similar in that they have a separate solids waste stream that must be managed to result in a complete waste management system. This waste stream is a higher-solids, screen backwash flow. The backwash flow will vary in volume and solids size, type of backwash control employed, frequency of backwash and influent TSS load on the filter. Backwash flow is generally expressed as a percentage of the filter treats, with reported backwash flows ranging from 0.2 to 1.5% of the treated flow **(Summerfelt,**

1999). This discharge is typically directed to a settling pond or other such device for final solids capture and storage.

c- Fractionation Process:

In fractionation process, particles attach onto air bubbles and are separated from water. The fractionation process involves all the transport mechanisms that occur in a filtration process with the exception of straining **(Timmons and Ebeling, 2007)**.

Foam fractionation is considered one of the few processes that is effective in removal of fine solids from RAS. In fact, foam condensate consists mostly of dissolved organics and particles smaller than 30 μm. Removing and disposing of the foam is one of the problems encountered when using foam fractionators. Plan ahead to determine what you will do with the foam condensate, e.g., collection vats that must be emptied, or direct drainage to a floor drain. Foam fractionators have been well reviewed in the literature **(Chen, 1991; Chen *et al.*, 1992; Chen *et al.*, 1994a and b).**

2.3.3. Biological Filter:-

Biological filtration is defined as the bacteriological conversion of organic nitrogenous compound into nitrate. The primary purpose of a biological filter is conversion of ammonia to nitrite, and nitrite to nitrate. This conversion is of great importance in culture of aquatic organisms because ammonia is highly toxic metabolic waste discharge directly by many cultured organisms and generated as a by product by many bacteria. Nitrite is some what less toxic than ammonia. Nitrate is considered relatively nontoxic to most aquatic organisms **(Wheaton, 1993).**

Biological filtration in the broadest sense includes any filtration technique that utilizes biological (living) organisms to

remove impurities from the water. Although biological filtration can include living plant filters, nitrification identification, extended aeration systems and a host of other types of filters of unit processes **(Wheaton *et al.*, 1991).**

Biological filtration is often employed as a water purification method in high density, semi-closed or closed aquaculture facilitates the growth of nitrifying bacteria, which oxidize ammonia via nitrite to nitrate **(Rijna and Rivera, 1990).**

There are many descriptions of water recirculation systems using biological filters for intensive cultivation of various species, but few authors discuss the basis for their choice of biological filter evaluation parameters **(Rogers and Klemetson, 1985).**

Liao and Mayo (1974) and Speece (1973) have proposed two important biological filters design methods. These methods are based primarily on nitrogen production of the species to be cultured. Both design method, are based on limited data, were developed for cold fresh water species, and are limited in application **(Wheaton, 1993).**

a- Biological filter types:-

Wheaton (1993); Lawson (1995) and Timmons *et al.* (2001) reported that, there are many types of biological filters. Those most often used in aquaculture include submerged, trickling, biodrums, and biodisks in recent, however, the types like rotating biological contactors and fluidized beds have been shown to be more efficient at ammonia removal.

a_1- Submerged filter:

Essentially it is a volume of solid media, with water passing over it. The distinguishing feature of submerged filters is that all of the media is submerged. Flow may be from the bottom (downflow), or from bottom to top (upflow), because the bacteria are below the water. This is one of the most restrictive limitations on submerged biological filters. Energy usage in submerged filters depends on the height water must be pumped to enter the filters. Usually, energy use is low because the head loss through the filter is low **(Wheaton, 1993 and Lawson, 1995)**.

a_2- Trickling filter:

Trickling filters look and operate much like a downflow-submerged filter except the media are kept wet but not submerged. Because the filter is not filled with water, air can circulate through the filter bringing oxygen to the bacteria. Energy use by these filters is the energy to pump water to the top of the filter **(Lawson, 1995)**.

a_3-Biodrums filter:

Biodrums filters consist of a perforated cylindrical container filled with some type of media that has as much specific surface area and as great a void volume as possible. The cylindrical container is mounted to a shaft passing through its center. The assembly is then mounted in a tank with the axis horizontal. Water level in the tank is increased unit about one-half of the drum is submerged. A motor attached to the drum axis rotates the drum slowly so the bacteria growing on the media are alternately submerged in the water and exposed to the air. Flow of the waste water through the tank may be in a direction parallel to or perpendicular to the drum axis. Energy

use in biodrums is primarily to rotate the drum (**Timmons *et al.*, 2001)**.

a_4-Biodisk filter:

Biodisk filters are very similar to biodrum filters except the perforated biodrum is replaced with disks that are spaced slight apart along the axis. Disk spacing should be as close as possible to maximize the specific surface area per unit volume but far enough apart to allow space for a bacterial layer to build up on both faces of each disk and to allow water circulation between the bacteria coated disks. Although biodisks create some turbulence in the tank they do not create as much as biodrums do. Energy is required to rotate the biodisks. However, this energy demand is less than for biodrum filters **(Vinci *et al.*, 2001)**.

a_5-Fluidized bed filters:

Fluidized bed filters consist of a cylindrical tube with fittings on one end to admit water and on the other to release water. The tube is filled with some fairly heavy, small sized particulate media (e.g. sand) that has a high specific surface area per unit volume. Water is pumped into the bottom of the filer at a sufficient flow rate to suspend (i.e., fluidize) all the particles in the filter in the rising stream. The flow rate through the filter must be controlled to prevent washing the media out of the filter. Bacteria grow on the fluidized bed media and remove ammonia from the water flowing past. Oxygen for these filters is supplied from the water, but the flow rates are usually high enough that, if the influent is nearly saturated with oxygen, sufficient oxygen is available for the filter. Fluidized beds require high water flow rates per unit area but are relatively small in size for the amount of specific surface area available. They do not clog easily and

once established operate quite reliably. The major energy use in fluidized beds is for pumping water through the filter. Energy use is a function of head loss and flow rate (**Timmons *et al.*, 2001)**.

a_6-Rotating Biological Contactor (RBC):

The rotating biological contactor consists of circular, either flat or corrugated, attached perpendicularly to a central shaft. The plates are placed in a tank to a depth of about 40 % of their diameter and the shaft is rotated (**Timmons *et al.*, 2001)**.

2.3.4. Aeration Tank:

Aeration is used here to refer to the dissolution of oxygen from the atmosphere into water, the transfer of pure oxygen gas to water is referred to as oxygenation:

a- Aeration:

Air-contact aeration systems transfer all gases present in atmospheric air into water. These systems can only increase dissolved oxygen concentrations to saturation, and the efficiency of oxygen transfer declines as the dissolve oxygen concentration in water increase **(Boyd, 1982).** Air-contact aerators actually transfer oxygen from water to air if the water is supersaturated with oxygen – they become de gassers. Gravity aerators rely on available head require no external power; water simply falls over a weir, flows through a series of expanded metal screens, or splashes onto a surface. Gravity aerators often are used in raceways and where well water is discharged into ponds or fish – holding tanks **(Boyd, *et al.*, 1978).**

Mechanical surface aerators splash water into the air to accelerate the rate of oxygen absorption **(Ray, 1981).** Subsurface diffused –air aerators consist of an air blower or air compressor

that forces air into an air-delivery system that is suspended in the pond bottom **(Ray, 1981).**

Colt and Orwicz (1991) and Boyed and watten (1989) reported that the aeration devices can be classified as:-

-Surface aerator

-Subsurface aerator and

- Gravity aerator.

b-Oxygenation:

Pure oxygen is used in recirculating systems when the intensity of production causes the rate of oxygen consumption to exceed the maximum feasible rate of oxygen transfer through aeration. Sources of oxygen gas include compressed oxygen cylinders, liquid oxygen and on-site oxygen generators. In most applications, the choice is between bulk liquid oxygen and an oxygen generator. The selection of the oxygen source will be a function of the cost of bulk liquid oxygen in your area (usually dependent on your distance from the oxygen production plant) and the reliability of the electrical service needed for generating oxygen on-site **(Boyd and watten, 1989).**

Adding gaseous oxygen directly into the culture tank through diffusers is not the most efficient way to add pure oxygen gas to water. At best, the efficiency of such system is less than 40 percent. A number of specialized components have been developed for use in aquaculture application **(Boyd and Watten, 1989)**. The more commonly used components follows:

- Down– flow bubble contactor.
- U-tube diffusers.
- Low head oxygenation
- Pressurized packed columns.

2.4. Water Quality Management:

The water quality criteria required for maintaining healthy and fast growing fish environment are the basis for designing water reuse processes for closed system aquaculture. Water quality parameters are of concern in fish culture if they stress the fish, reduce the fish's growth rate, or cause fish mortality. Water quality is also of concern if the effluent characteristics (e.g., phosphorus) of the culture facility must be controlled to meet water pollution; reduced growth due to water quality limitations is undesirable. As well, growth is a measure of the overall state of health of the fish **(Meade, 1989a)**. However, stress, defined as the sum of all the physiological responses by which an animal tries to maintain or reestablish a normal metabolism in the face of a physical or chemical force, may not be quantified by reduced growth, but measured by stress-induced physiological changes (histological, hematological, and immunological) in the culture organism. The reduction in water quality which leads to stress and the deterioration of fish health will increase the risk of disease and catastrophic loss of fish, even if it does not have an immediate impact on production **(Meade, 1989a)**.

The availability of a high quality water supply greatly influences the success of any aquaculture operation and is the first factor considered during site selection **(Ackefors *et al.*, 1994)**. Table (2.1) presents water quality criteria for the culture of fish, crustaceans and mollusks. The tolerance limits of the various water quality parameters depend on the species cultivated **(Pillay, 1992)**.

Table (2.1) Water quality standards for aquaculture **(Meade, 1989 and Lawson, 1995).**

Parameter	**Recommended Limits**
Acidity	pH 6 – 9
Arsenic	<0.05 mg l^{-1}
Alkalinity	10 – 400 mg l^{-1}
Aluminum	<0.075 mg l^{-1}
Ammonium (UN-ionized)	<0.02 mg l^{-1}
Cadmium	<0.0005 mg l^{-1} in soft water; <0.005 mg l^{-1} in hard water
Calcium	>5 mg l^{-1}
Carbon dioxide	<5 – 10 mg l^{-1}
Chloride	>4.0 mg l^{-1}
Chlorine	<0.003 mg l^{-1}
Copper	<0.0006 mg l^{-1} in soft water <0.03 mg l^{-1} in hard water
Gas supersaturation	<110% total gas pressure
Hydrogen sulfide	<0.003 mg l^{-1}
Iron	<0.01 mg l^{-1}
Lead	<0.02 mg l^{-1}
Mercury	<0.02 mg l^{-1}
Nitrate	<3.0 mg l^{-1}
Nitrite	<0.1 mg l^{-1}
Dissolved Oxygen	5 mg l^{-1}, cold-water fish 3 mg l^{-1}, warm-water fish
Selenium	<0.01 mg l^{-1}
Total Dissolved Solids	<200 mg l^{-1}
Total Suspended Solids	<80 mg l^{-1}
Turbidity	<20 NTU over ambient level
Zinc	<0.005 mg l^{-1}

Aquaculture systems produce large quantities of effluent containing particulate and dissolved organic matter and nutrients, primarily nitrogen and phosphorus, which are generated from uneaten or regurgitated food, fish excretion, fecal production and fragmented tissue **(Cripps and Kumar, 2003)**. Depending on the species and culture technique, up to 85% of phosphorus, 80 – 88% of carbon and 52 – 95%
of nitrogen input into a fish culture system may be lost to the environment through feed wastage, fish excretion, fecal production and respiration **(Wu, 1995)**. In recirculating systems, addition inputs may come from filter media or bacterial flocs escaping from water conditioning devices **(Cripps and Kumar, 2003)**. One of the most important sources contributing to organic and nutrient loading is feed wastage, which may range from 1 – 38% depending on the feed type, feed practices, culture methods and may species **(Wu, 1995)**. High organic and nutrient loading in aquaculture effluent exert adverse environmental impacts when discharged untreated into receiving water bodies. The environmental impacts associated with the discharge of aquaculture effluent depend on a number factors, included (a) species cultured, (b) culture methods, (c) stocking density, (d) feed type, (e) feeding technique and (g) hydrography of the site **(Wu, 1995 and Cripps and Kumar, 2003)**.

The parameters of primary concern in recycle aquaculture are dissolved nitrogen compounds such as ammonia (NH_3), ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-); organic compounds that are dissolved or exist as suspended or settleable solids: dissolved oxygen (O_2), carbon dioxide (CO_2), and nitrogen (N_2) gases; and alkalinity. These parameters are a concern because their production or reduction during recycle

aquaculture can lead to concentrations which affect the growth and health of the fish. However, it is not only the individual component, but the aggregate of all the water quality components which affect fish growth and health **(Meade, 1989a)**.

In recirculating systems, good water quality must be maintained for maximum fish growth and for optimum effectiveness of bacteria in the biofilter. Water quality factors that must be monitored and/or controlled include temperature, dissolved oxygen, carbon dioxide, pH, ammonia, nitrite and solids. Other water quality factors that should be considered are alkalinity, nitrate and chloride **(Masser *et al.*, 1999)**.

2.4.1. Water Temperature.

One of the problems of using tilapia for pond culture is their inability, in general, to survive water temperature below 10°C for more than a few days. The influence of temperature on survival and growth has been studied through field observations, laboratory investigations and a few physiological experiments designed specifically to determine thermal effects **(Chervinski, 1982)**.

Soderberg (1995) and Swann (2009) reported that, the maximum and minimum temperatures that fish can be tolerate is genetically determined but is also influenced to some extent by variables such as length of time allowed for acclimation, dissolved oxygen concentration. For this reason, thermal death point temperatures are not fixed values but can vary by several degrees. Thermal death points are usually of limited interest in hatchery work. Approximate values for a few economically important species: rainbow trout, 0 and 26°C; carp, 0 and 30°C; channel catfish, 4 and 35°C; tilapia, 10 and 38°C.

Tilapia, a widely cultured tropical fish, show several clinical signs of distress as the water temperature is slowly lowered below their optimum temperature range of 20 – 30°C. At about 18°C, reproductive behavior begins to be affected. Feeding and growth cease at about 15°C and the fish become inactive and disoriented. Below about 10°C, most tilapia species become comatose suffering what is commonly termed chill coma. During chill coma, serum total protein, sodium and chloride ion concentrations, and plasma osmotic pressure steadily decline. Death occurs due to osmoregulatory collapse and renal failure **(Soderberg, 1995 and Swann, 2009)**.

Temperature must be maintained within the range for optimum growth of the cultured species. At optimum temperatures fish grow quickly, convert feed efficiently, and are relatively resistant to many diseases. Biofilter efficiency also is affected by temperature but is not generally a problem in warmwater systems. Temperature can be regulated with electrical immersion heaters, gas or electric heating units, heat exchangers, chillers, or heat pumps. Temperature can be manipulated to reduce stress during handling and to control certain diseases **(Masser *et al.*, 1999)**.

The majority of aquaculture species are poiklothermic meaning that their body temperature is controlled by ambient conditions or by behavior. Poikilothermic organisms have no internal metablic mechanism for regulating their body temperatures **(Poxton and Allouse, 1982)**. Temperature affects all physiological processes including: respiration, feeding and assimilation, excretion, growth, behavior and respiration as well as susceptibility to diseases, parasites and txic compounds **(Stickney, 1994 and Poxton, 2003)**. A temperature increase of

10 ˚C will generally cause rates of chemical and biological reactions to double or triple **(Lawson, 1995)**. Optimal temperature for growth vary depending on factors such as species, life-cycle stage, age, salinity, diet and crowding **(Ackefors *et al.*, 1994 and Poxton and Allouse, 1982)**. **Cotton et al. (2003)** concluded that juvenile black sea bass (Centropristis striata) show optimal growth at 25 ˚C. **Gunnes (1979)** concluded that the optimal temperature for incubation of Atlantic salmon (Salmo salar) eggs is 10 ˚C and **Otterlei *et al.* (2000)** reported that the optimal temperature for growth of early juvenile cod (Gadus morhua) occurred at 14 – 16 ˚C and decreased rapidly at higher temperatures.

Fish can be broadly classified as cold-water, cool-water and warm-water species depending on the thermal regime to which they are naturally adapted **(Ackefors *et al.*, 1994 and Lawson, 1995)**. Cold water species such as trout and salmon prefer water temperatures of 15 ˚C or less, cool-water species such as yellow perch and pike perch are naturally adapted to water temperatures ranging from 15 – 20˚C and warm-water species such as catfish and large mouth bass are naturally suited to water temperatures above 20˚C **(Lawson, 1995)**. Table (2.2) presents optimum rearing temperatures for various aquaculture species.

Water temperature may be the single most important factor affecting the welfare of fish. Fish are cold-blooded organisms and assume approximately the same temperature as their surroundings. The temperature of the water affects the activity, behavior, feeding, growth, and reproduction of all fishes. Metabolic rates in fish double for each 18°F rise in temperature. Fish are generally categorized into warm water,

cool water, and cold water species based on optimal growth temperatures **(Swann, 2009)**.

Table (2.2): Optimum rearing temperatures for selected aquaculture species **(Lawson, 1995).**

Species	Temperature (˚C)
Brook trout	7 – 13
Brown trout	12 – 14
Rainbow trout	14 – 15
Atlantic salmon	15
Chinook salmon	10 -14
Coho salmon	9 – 14
Sockeye salmon	15
Sole	15
Turbot	19
Plaice	15
European eel	22 – 26
Japanese eel	24 – 28
Common carp	25 – 30
Mullet	28
Tilapia	28 – 30
Channel catfish	27 – 29
Brine shrimp	20 – 30
Brown shrimp	22 – 30
Pink shrimp	> 18
American lobster	24
American oyster	> 8

Temperature also determines the amount of dissolved gases (oxygen, carbon dioxide, nitrogen, etc.) in the water. The cooler the water the more soluble the gas. Temperature plays a major role in the physical process called thermal stratification. As mentioned earlier, water has a high-heat capacity and unique density qualities. Water has its maximum density at 39.2°F. In spring, water temperatures are nearly equal at all pond depths. As a result, nutrients, dissolved gases, and fish wastes are evenly mixed throughout the pond. As the days become warmer, the surface water becomes warmer and lighter while the cooler-denser water forms a layer underneath **(Swann, 2009)**.

2.4.2. Oxygen:

Oxygen is often the limiting factor in the culture of aquatic organisms **(Willoughby, 1968; Liao, 1971)**. Therefore, to increase production, an increase in the amount of dissolved oxygen is required in most situations. The use of supplemental oxygen can increase the carrying capacity of a fish culture system if dissolved oxygen is the most limiting factor. This can allow increased fish density, water reuse, or reduce water requirement, all of which can have a significant impact on production economics **(Gowan, 1987; Severson *et al.* 1987)**.

Oxygen supplementation commonly increases carrying capacity but this is not always the case and the conditions under which this does not occur are not fully understood by fish culturists **(Colt and Watten, 1988)**. Aeration or the addition of supplemental oxygen to the pond water provides adequate aerobic conditions to support aquatic life and improve water quality **(Rogers, 1989)**.

The level of dissolved oxygen (DO) available to organisms in an aquaculture system is the most critical water

quality parameter because it is essential to the metabolism of the majority of cultured fish and crustaceans **(Stickney, 1994)**. Fish oxygen consumption rates depend on various factors including: water temperature, environmental DO concentration, fish size, activity level and time after feeding **(Lawson, 1995)**. Reduced oxygen levels have been shown to cause lethal and sub-lethal effects including: reduced feeding and growth rates, lower food conversion efficiencies and higher susceptibility to disease in various aquatic organisms **(Poxton, 2003)**.

Most warm water species can survive long periods at dissolved oxygen concentrations of 2-3 mg L^{-1} **(Boyd, 1982; Stickney, 1979)**, but cold water species require a minimum of 4-5 mg l^{-1} **(Liao, 1971; McLarney, 1984)**. **Willoughby (1968); Smith and Piper (1975); Westers and Pratt (1977); Stickney (1994) and CCME (1999)** suggested that aquaculture facilities for trout be designed so that fish are exposed to a minimum dissolved oxygen concentration of 5.0 mg L^{-1}. A minimum criteria of 6.0 mg L^{-1} is recommended for all juvenile fish and crustaceans **(Huguenin and Colt, 1989). Burrows and Combs (1968)** recommended a dissolved oxygen minimum of 6.0 mg L^{-1} for salmon. Minimum dissolved oxygen concentration in outlet water from fish tank is estimated to 5 mg L^{-1} **(Brett and Blackburn, 1981).** Practically all species can survive for short period at dissolved oxygen concentrations less than optimum, but feeding and growth is poor, and they are more susceptible to infectious diseases **(Lawson, 1995).**

Rates of oxygen consumption by aquatic organisms vary with species, size, activity, temperature, nutritional status, and other factors **(Boyd, 1982)**. The rate of oxygen consumption of fish is limited by low dissolved oxygen availability and also by

such parameters as size, species, activity, condition, daily ration, and water temperature **(Boyd and Watten, 1989; Smart, 1981).**

The oxygen consumption of fish in intensive culture systems can be increased both by fish cultural procedures and by natural process. Of these, stress resulting from handling, increased swimming activity resulting from excitement, and the natural processes of feeding and digestion are probably the most important **(Soderberg, 1995)**.

The natural processes of feeding and digestion also dramatically increase the oxygen consumption of fish because the caloric costs of digestion, absorption, and assimilation can amount to as much as 40% of the resting metabolic rate **(Brown and Cameron, 1991).**

The oxygen consumption rates for 13 common species of fresh water fish range from 205 to 888 mg O_2/kg fish.hour **(Basu, 1959)**. Oxygen consumption increases with increasing water temperature. In General, a 10 °C increase in water temperature will approximately doubles the respiration rates of aquatic animals **(Boyd, 1982)**.

Oxygen consumption increases substantially with activity. Nile tilapia (Tilapia nilotica) forced to swim against a current of 30 cm s^{-1} consumed 220 mg O_2/kg fish.hour; when forced to swim against a current of 60 cm/s, consumed 458 mg O_2/kg fish.hour **(Farmer and Beamish, 1969)**.

Small organisms use more oxygen than larger ones. The oxygen consumption rates for channel catfish of different individual weights were as follows: 5 g, 1225 mg O_2 kg^{-1}; 10 g, 1050 mg O_2 kg^{-1}; 50 g, 750 mg O_2 kg^{-1}; 100 g, 625 mg O_2 kg^{-1}; 500 g, 480 mg O_2 kg^{-1}; 1000 g, 340 mg O_2 kg^{-1}. Oxygen is consumed faster by channel catfish that have recently eaten than

by fasted catfish. Fish used 520 mg O_2/kg fish.hour immediately after eating, but they consumed only 380 mg O_2 /kg fish.hour when fasted overnight.

The concentration of dissolved oxygen also affects oxygen consumption. Channel catfish consumed 90 mgO_2 /kg fish.hour at 1 mg l^{-1} and 390 O_2 /kg fish.hour at 4 mg l^{-1}, dissolved oxygen **(Andrews and Matsuda, 1975)**.

Elliot (1969) studied the oxygen consumption rate of Chinook salmon between 1.85 and 17.5 g in weight. He measured the dissolved oxygen concentrations above and blow groups of fish under hatchery conditions and developed an empirical method for estimating their rate of oxygen consumption.

Liao's (1971) formula gives nearly identical values as **Elloit's (1969)** for the oxygen consumption rate of salmon and the two may be used interchangeably for fish smaller than 17.50 g.

Muller-Fuega *et al.* (1978) conducted an experiment with rainbow trout under hatchery conditions similar to **Liao's (1971)** investigation. They found a discontinuity in oxygen consumption vs., temperature at 10 °C. Their expression for predicting the oxygen consumption rate for rainbow trout is:

$$OC = \alpha W^{\beta} 10^{\gamma T} \qquad (2.3)$$

Where:

OC = Oxygen consumption, mg O_2/kg fish. h

W = average of individual fish mass, g

T = water temperature, °C

α,β, γ are constants. The constant values are as follows:

Constant	Temperature, °C	
	4-10	12-22
α	75	246
β	-0.196	-0.142
γ	0.055	0.024

Andrsewn and Matsuda (1975) presented oxygen consumption data for channel catfish of different sizes and at several temperatures. **Boyd *et al.* (1978)** applied multiple regression analysis to these data to obtain the following expression:

$$\text{LogOC} = -0.999 - 0.000957\ W + 0.0000006\ W^2 + 0.0327\ T + 0.0000087T^2 + 0.0000003WT \quad (2.4)$$

The correlation coefficient for the equation was 0.99. Data used in preparing the equation ranged from 2 to 1000 g for fish weight and from 24 to 30°C.

A general equation often is used for estimating the approximate respiration of warm water fish at 20-30 °C: **(Schroeder, 1975; Romaire *et al.*, 1978)**

$$OC = 0.001\ W^{0.82} \quad (2.5)$$

Knowledge of the oxygen consumption rate of fish allows direct calculation of their water requirement. For species fish**(Elliot, 1969; Liao, 1971; Muller-Fuega *et al.* 1978; Boyd *et al.* 1978)**:

$$CC = \frac{Ci - Cm}{OC} \times 60 \quad (2.6)$$

where:

CC = carrying capacity, kg L^{-1} per min

Ci-Cm = dissolved oxygen available for respiration, mg L^{-1}

Oxygen consumption was determined as a measure of fish metabolism. In each raceway, the specific oxygen consumption rate (O_c) of the turbot juveniles was determined based on the dissolved oxygen concentrations recorded during a 24 h monitoring trial and the mathematical relationship by **(Imsland *et al.*, 1995):**

$$OC = \frac{Q(DOout - DOin)}{B} \quad (2.8)$$

Where:

Oc = Oxygen consumption, (mg/kg fish.min).

Q = Water flow rate (L min^{-1})

DOin =Dissolved oxygen in the raceway influent (mg L^{-1})

DOout=Dissolved oxygen in the raceway effluent (mg L^{-1})

B= fish biomass in the raceway (kg).

Ali (1999) developed the following formula to estimate oxygen consumption rate for tilapia fish:

$OC=2014.45+2.75W–165.2T+0.007W^2+3.93T^2–0.21WT$ (2.8)

The correlation coefficient for the equation was 0.99. Data used in preparing the equation ranged from 20 to 250 g for fish weight and from 24 to 32°C.

2.4.3. Nitrogenous Compounds:

The chemistry of nitrogen is complex because of the many states in which the element can exist. The major forms of nitrogen discharged from aquaculture systems depend on a number of factors, including species cultivated, culture technique and feed type and practices **(Wu, 1995)**. The dominant inorganic nitrogen species include unionized (NH_3) and ionized ammonia (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3) while the organic froms of nitrogen include urea, amino acids, amines, purines and

pyrimidines **(Lawson, 1995 and EPA, 2000)**. Table (2.3) presents the major forms of nitrogen found in aquaculture systems. Nitrogen uptake by cultured organisms in aquaculture systems can vary from 20 to 50 % depending on the species while the remaining 50 to 80 % is lost from the system as ammonia-nitrogen, fecal organic nitrogen or in unconsumed or regurgitated feed **(Brune, 1995)**.

Table (2.3): The major forms of nitrogen in aquaculture systems **(Lawson, 1995)**

Form	Comments
Nitrogen gas (N_2)	Inert gas; transfer in and out from atmosphere; no significance
Organic nitrogen (Org-N)	Decays to release ammonia
Un-ionized ammonia (NH_3)	Highly toxic to aquatic animals, predominates at high pH levels
Ionized ammonia (NH_4^+)	Non-toxic to aquatic animals except at very high concentration; predominates at low pH levels
Nitrite (NO_2^-)	Highly toxic to aquatic animals; converted to nitrate by nitrifying bacteria
Nitrate (NO_3)	Non-toxic to aquatic animals except at very high concentrations; readily available to aquatic plants

2.4.3.1. Ammonia:

Ammonia is the main product of protein metabolism in fish and is mainly excreted via the gills **(Smith, 1929; Wood, 1958). Waarde (1983)** reported ammonia to be the major component of nitrogen excretion, and its production rate directly related to protein oxidation. The major source of ammonia in pond water is the direct excretion of ammonia by fish **(Tucker and Boyd, 1985).** Ammonia is the principle nitrogenous by – product of fish in its unionized from. The origin of metabolic ammonia is the deamination of amino acids utilized as energy. A metabolic nitrogen budget allows for the estimation of the contribution of dietary protein to the accumulation of ammonia in the water **(soderberg, 1995).**

Ammonia is the primary nitrogenous metabolite excreted by fish **(Brafield, 1985)**. Approximately 30 mg of ammonia are produced by fish per gram of feed consumed **(Piper *et al.*, 1982; Speece, 1973; and Liao and Mayo, 1974)**. Ammonia is also produced by three additional reaction in recycle-systems using biological treatment: biological deamination of organic compounds (waste feed and feces), endogenous respiration and cell lysis **(Kruner and Rosenthal, 1987)**.

In fish ammonia is the major nitrogenous waste product of protein catabolism and it is excreted primarily in un-ionized from through the gills **(Porath and Polluck, 1982 and Poxton, 2003)**. Ammonia is also produced through the decomposition of urea, fish feces and uneaten food. Ammonia exists in two states: un-ionized (ammonia, NH_3) and ionized (ammonium, NH_4^+). In aqueous environments, un-ionized and ionized ammonia exist in equilibrium and its speciation (NH_3/NH_4^+). The following

equation is affected by a number of environmental parameters including: pH, temperature and ionic strength **(Lawson, 1995)**.

$$NH_3 + H_2O \Leftrightarrow NH_4^+ + OH^- \quad (2.9)$$

Aqueous ammonia occurs in two molecular forms and the equilibrium between them is determined by pH, and to a lesser extent, temperature:

$$NH_3 \longleftrightarrow NH^+_4$$

and

$$NH_3 - N + NH^+_4 - N = TAN \quad (2.10)$$

The unionized form NH_3 is a gas and can freely pass the gill membrane the rate and direction of passage depends upon the NH_3 concentration gradient between the fish's blood and the adjacent water. Unionized ammonia NH_3 is toxic to fish while ionized ammonia NH_4 is relatively nontoxic. Analytical procedure dissolved oxygen not differentiates between the two forms of ammonia in solution, and only one is of consequence to the fish culturist. Thus, it is important to be readily able to determine the fraction of NH_3 in solution at any temperature and pH **(Soderberg, 1995).**

$$F = \frac{1}{10^{pKa-pH} + 1} \quad (2.11)$$

The unionized fraction, F, is the decimal fraction of NH_3 in an ammonia solution.

Thus, $NH_3 - N = TAN \times f$

Emerson *et al.*, (1975) presented the following formula to calculate the acid dissociation constant, expressed as the negative log, for ammonia, based on the values of **Bates and Pinching (1949)**:

$$\boldsymbol{pKa = 0.09018 + \frac{2729.92}{T}} \quad (2.12)$$

Where:

pKa = negative log of the acid dissociation constant for ammonia

T = temperature, ^{o}K.

Accumulation of ammonia in water is one of the major causes of functional and structural disorders in aquatic organisms **(Stickney, 1994 and Randall and Tsui, 2002)**.

Only unionized ammonia is toxic to fish because it can readily diffuse across the gill membranes into the circulation, whereas the ionized form (NH_4^+) cannot **(Randall and Tsui, 2002 and Poxton, 2003)**.

As the concentration of ammonia in water increases, the ability of aquatic organisms to excrete ammonia decrease resulting in its accumulation in blood and tissues. The effects of elevated concentrations of ammonia on aquatic life include: elevation in blood pH and reduction in the oxygen carrying capacity of the blood, gill damage and reduced membrane stability and difficulty maintaining osmotic balance **(Lawson, 1995)**.

The toxicity of ammonia has been extensively studied in freshwater fish, particularly salmonids, craps, catfish and rainbow trout **(Poxton and Allouse, 1982)**. After four months of exposure to ammonia-nitrogen (NH_3-N) concentrations above 0.04 mg L^{-1}, rainbow trout exhibited lesions in the gills and extensive tissue damage in the kidneys **(CCME, 1999)**. When exposed to NH_3-N concentrations of 0.1 mg L^{-1} for 12 h day^{-1}, Chinook salmon fingerlings (Oncorhynchus tshawytscha) exhibited reduced growth rates, stamina and disease resistance **(Poxton and Allouse, 1982)**. **Kir *et al.* (2004)** recommended maximum NH_3-N concentrations of 0.19, 0.19, 0.18 and 0.10 mg

L^{-1} at water temperatures of 14, 18, 2 and 26 ˚C for the production of juvenile shrimp (Penaeus semisulactus). **Lemarie *et al.* (2004)** reported a 42.6 % mortality rate in juvenile seabass (Dicentrarchus labrax) that were exposed to an NH_3-N concentration of 0.90 mg L^{-1} at a temperature, pH and salinity of 21.8 ˚C, 8.0 and 37.0 ppt, respectively. The researchers recommended that under the given conditions a maximum long-term NH_3-N concentration of 0.26 mg L^{-1} was acceptable for the production of juvenile seabass. **Foss *et al.* (2004)** reported reduced food intake and growth rate when Atlantic cod (Gadus morhua) were exposed to NH_3-N concentrations above 0.06 mg L^{-1} at a temperature of ˚C for 96 days.

Colt and Armstrong (1981) reviewed effects of nitrogen compounds on aquatic animals and noted sub lethal effects were often reported exclusively as the effects of unionized (NH_3). Although the effects of ammonia on growth are unknown for most cultured animals, growth reduction may be the most important sub lethal effect. They suggested that significant growth reduction occur in most aquatic animals at NH_3-N concentrations of 0.05 to 0.2 mg L^{-1}. However, many culturist regard this level as inappropriately high and consider gill damage to be the indicator of chronic ammonia poisoning.

Westers (1981) used 0.0125 mg L^{-1} NH_3-N as the maximum allowable concentration (taken at the effluent) for culture. **Burrows (1964)** reported extensive hyperplasia of gill epithelium in Chinook salmon, Oncorhynchus tshawytscha, after exposure to only 0.005 mg L^{-1} NH_3-N (reported as 0.006 mg l^{-1} NH_3) for 6 weeks, and recalculation of Burrows NH_3-N values based on **Emerson *et al.* (1975)** indicates that the actual concentration was less 0.003 mg L^{-1} NH_3-N. The European

Inland Fisheries Advisory Committee **(EIFAC)** stated that adverse effects of prolonged exposure are lacking only at concentration lower than 0.021 mg L^{-1} NH_3-N (stated as 0.025 mg L^{-1}) **(EIFAC, 1970 and Smith and Piper, 1975)**.

Criterion for ammonia is based on the unionized form (NH_3) and should be expressed in terms of nitrogen. The unionized ammonia criterion varies from 10 to 21 µg L^{-1} NH_3-N **(USEPA, 1976; Westers and Pratt, 1977; Alabaster and Lioyd, 1982; SECL, 1983).**

There is much variation in reported production rates. **Fyock (1977)** reported for rainbow trout in a reuse system, 60.4 to 78.5 g ammonia production / day / kg of diet. Some researchers reported ammonia production rate ranged from 20 – 38 g kg^{-1} **(Westers, 1981; Speece, 1973; Gunther *et al.*, 1981; Piper *et al.*, 1982)**

According to **Haskell's** hypothesis **(1955)** the ammonia production should be proportional to the amount of food given. The hypothesis is supported by **Willoughby *et al.* (1972)** who found the average ammonia production in trout hatcheries to be 32g kg^{-1} of feed fish. While the ammonia production rate given by **Clark *et al.* (1985)** is very similar to this, they also did not find any significant difference in production rates between size classes in the range 5 – 280 g. Channel catfish excrete about 20 g of ammonia per day per kg of ration fed and salmonids fed typical dry diets excrete 25 – 35 grams of ammonia per kg of feed consumed **(Colt and Armstrong, 1981).**

However, **Speece (1973)** suggested a formula to calculate the ammonia production as related to temperature in the follows equation:

$$AP = 825.3\ T + 18242 \qquad (2.13)$$

Where:

AP = the average ammonia production, mg / kg food given during 24 h

T = water temperature, ˚C

Production of ammonia can be estimated as the product of the weight (Wt) of fish in kg, the feeding rate as percent body weight per day (R_F), the protein- nitrogen percent of the diet (N_D), the percent of metabolized (N_M), and the percent of excreted nitrogen that is excreted as ammonia (N_E), as in the example from **Meade (1974).**

$$kg\ (NH_3 + NH_4^-)/day = Wt \times R_F \times N_D \times N_M \times N_E \quad (2.14)$$

Liao (1974) reported that the ammonia production could be the oxygen consumed by the fish:

$$0.053 \times kg\ O_2 \text{ consumed per day} \quad (2.15)$$

Paulson (1980) developed models of ammonia excretion that showed good agreement between actual and predicted values. He found that nitrogen consumption was by far the most important factor influencing ammonia excretion, followed by fish weight and temperature.

Boyd (1990) reported that the ammonia excreted by fish can be estimated from the net protein utilization and the percentage in the feed:

$$TAN = (1.0 - NPU)\ (P_f / 6.25)\ (1{,}000) \quad (2.16)$$

Where:

TAN = total ammonia-nitrogen, g/kg feed

NPU = net protein utilization

P_f = decimal fraction of protein in feed

Where protein is in g protein / g feed and 6.25 is the average value of g protein nitrogen. **Garling and Wilson (1976)**

reported an average NPU value of 4.0 for fish fed high protein diets.

Soderberg (1995) reported that the ammonia production rate (AP) may be expressed as:

$$AP = 56\ P_f \quad (2.17)$$

Where:

P_f = decimal fraction of protein in the diet

Generally, ammonia nitrogen production is assumed to be equal to 3 % of the daily feeding rate **(Huguenin and Colt, 1989; Tucker and Robinson, 1990)** as shown the following equation:

$$TAN = 0.03\ R \quad (2.18)$$

Where:

R = total ration, kg/day

The relationship between ammonia production, fish weight and temperature was given by **Ali (1999)** as follows:

$$AP=26.52- 0.97W + 1.31T + 0.004W^2 – 0.0026WT \quad (2.19)$$

Where: AP = ammonia production rate, mg/kg fish.hour.

2.4.3.2. Nitrite:

Nitrite (No_2–N) is the ionized from of nitrous acid (HNo_2), and it can be as lethal as NH_3-N. nitrite levels in fish ponds typically ranges from 0.5 to 5 mg L^{-1}, probably due the reduction of nitrate in anaerobic mud or water **(Boyd, 1982).**

The toxicity of nitrite (No_2–N) is due principally to its effects on oxygen transport and tissue damage. When nitrite is absorbed by fish the hem iron in blood hemoglobin is oxidized from the ferrous to the ferric state. The resulting product is called methemoglobin (blood brown) or ferri hemoglobin and is not capable of combining with oxygen **(Tuker and Boyd, 1985).**

Representative acute toxicity values for nitrite for some species of fish are ranged from 0.2-190 mg L^{-1} **(Russo and Thurston, 1991).**

In flow- through systems, ammonia is the principle toxic metabolite water generally does not have along enough residence time in flow–through system for nitrite to become a problem. However, nitrite often is a serious problem in recirculating systems where the water is continually reused. In recirculating systems, nitrite is controlled with biological filters, but can accumulate to toxic levels if the biological filters are not functioning properly or if the system temperature is below the functional range for Nitrobacter bacteria **(Lawson, 1995).**

In natural waters, ammonia is converted rather rapidly to nitrite (NO_2^-) and futher to nitrate (NO_3^-) by aerobic bacteria from the genera Nitrosomonas and Nitrobacter, respectively **(Poxton and Allouse, 1982 and Ackerfors, 1994)**.

Nitrite is considerably less toxic than ammonia; however, it may be more important than ammonia toxicity in intensive, recirculating aquaculture systems because it tends to accumulate in the recirculated water as a result of incomplete bacterial oxidation **(Poxton and Allouse, 1982 and Jo *et al.*, 2002)**.

Nitrite toxicity is associated with its ability to diffuse across the gills and into the blood circulation. When nitrite is absorbed by aquatic animals, the iron (or copper) in haemoglobin (haemocyanin) is oxidized from the ferrous (or cuprous) to the ferric (or cupic) state. The resulting product is called methaemoglobin (methaemocyanin) and it is unable to bind and transport oxygen **(Lawson, 1995)**.

Chronic toxicity symptoms caused by a decrease in the oxygen carrying capacity of the blood include: haemolytic

anemia, tissue damage in the live and gills, impediment of respiration and reduction in thermal tolerance because of the low capacity of blood to deliver oxygen to tissues **(Stickney, 1994 and Poxton, 2003)**. **Koo *et al.* (2005)** investigated the effects of nitrite-nitrogenNO_2-N) exposure (0, 50, 150, 200 and 250mg L^{-1}) on the survival, growth rate an moulting of juvenile tiger crabs (Orithyia sinica). The researchers reported that the survival rates of crabs exposed to 100, 150, 200 and 250 mg L^{-1} NO_2-N were below 50% and the 20 day and 30 day LC_{50} values were 143.1 and 82.5 mg L^{-1}, respectively. The growth rates of crabs exposed to 150, 200 and 250 mg L^{-1} NO_2-N were significantly less than that of the control group and the intermoult period and number of moulting crabs was significantly higher than that of control crabs.

Das *et al.* (2004) reported a progressive reduction in the total erythrocyte count, haemoglobin and serum protein content of mrigal fingerlings (Cirrhinus mrigala) upon exposure to increasing concentrations of nitrite-nitrogen (0, 1, 2, 4, 8 and 10.4 mg L^{-1}) and **Ferreira da Costa *et al.* (2004)** reported a 96-h LC_{50} of 1.82 ± 0.98 mg L^{-1} NO_2^- for the Amazonian fish, Colossama macropomum indicating a high sensitivity of this species to nitrite.

Wang *et al.* (2004) reported that at a pH of 8.0 the 24, 48 and 96-h LC_{50} for nitrite to the crustacean, Macrobrachium nipponense were 46, 26 and 13.3 mg L^{-1}, respectively. **Espey (2001)** reported a nitrite-nitrogen acute toxicity value (96-h LC_{50}) of 61 mg L^{-1} for juvenile yellow perch (Perca flavenscens) and **Fuller *et al.* (2003)** reported a 96-h LC_{50} of 10 mg L^{-1} $NO_2^—$ N for Gila trout (O. gilae).

2.4.3.3. Nitrate:

Nitrates are the least toxic of the inorganic nitrogen compounds **(Wickins, 1976; Colt and Tchobanoglous, 1976).**

Nitrate building occurs most in the fall in pond systems when water temperatures are cooler **(Lawson, 1995).** Representative acute toxicity values for nitrate for some species of fish are ranged from 180-1400 mg/L **(Russo and Thurston, 1991).**

A drawback of ammonia removal by means of nitrification if the subsequent increase of nitrate in the culture system. Nitrate concentrations of up to 800 mg/L No_3 – N have been recorded in semi – closed aquaculture facilities where aerobic biological filtration was employed **(Rijn and Rivera, 1990).** High nitrate concentration ought to be prevented for mainly two reasons. Firstly, nitrate at high concentrations have a toxic effect on several fish species **(Muir, 1982),** and secondly the discharge of nitrate rich effluent water is prohibited in many countries due to environmental and public health considerations **(Rijn and Rivera, 1990).** The maximum levels of nitrate allowed in the effluent water differ from country and are as low as 11.6 mg / L No_3-N in Europe according to the European community directive.

Nitrate is relatively harmless to fish and other cultured aquatic organisms and for this reason relative little attention has been paid to nitrate removal in intensive fish culture systems **(Russo and Thnston, 1991).**

Otto and Rosenthal (1979) reported that, the very high nitrate concentrations encountered in the intensive aquaculture systems (Sometimes more than 1 g/L) should be avoided, mainly for two reasons:

Nitrate accumulation**:** Nitrate is either an intermediate or an end product of nitrate respiration, a process conducted by a wide array of assimilatory and dissimulator nitrate reducing microorganisms **(Payne, 1973).** Although it is assumed that nitrate respiration is a strict anoxic process, differences exit as to the inhibitory effect of oxygen on the different enzymes involved in nitrate respiration form studies concerned with oxygen inhibition on nitrogen oxide reducing enzymes it is apparent that among these enzymes, nitrate reeducates (reducing nitrate to nitrite) is least sensitive to oxygen **(Hochstein *et al.*, 1984).** Therefore intensive fish culture systems in which nitrate is allowed to accumulate will experience high background levels of nitrite due to the fact that oxygen – poor microsites (e.g. organic matter at the bottom of the culture system or within the aerobic, nitrifying filters) will harbor bacteria capable of reducing nitrate to nitrite only.

Environmental considerations: High nitrate levels in surface and ground waters might give rise to environment problems such as eutrophication and contamination of drinking water. Nitrate – rich drinking water has been coupled to methamoglobinemia in infants and gastric cancer **(Taylor, 1975; Jensen, 1982).** It is anticipated that the growing awareness of nitrate pollution will lead to more stringent environmental restriction in regard to discharge of nitrate – rich water.

Nitrate is not acutely toxic to fish; however, it should not be allowed to accumulate in aquaculture systems because chronic toxicity symptoms and algae and phytoplankton blooms may eventually develop **(Jo *et al.*, 2002 and Poxton, 2003)**. Chronic toxicity symptoms associated with exposure to nitrate include: reduction in the oxygen carrying capacity of the blood,

inability of organisms to maintain proper balance of salts, stunted growth and lethargy **(CCME, 1999)**. The 96-h LC_{50} values for Chinook salmon and fingerling rainbow trout are 5.8 and 6.0 g L^{-1}, respectively **(CCME, 1987)**. The 96-h LC_{50} values of NO_3-N to many fish and invertebrates lies between 1000 and 3000 mg L^{-1} **(Lawson, 1995)**.

Nitrogen containing compounds are a concern in many wastewaters because when excessive amounts of these compounds are discharged into receiving waters, eutrophication may occur **(EPA, 2000)**. Eutrophication refers to the over-growth of certain plant and algae species as a result of enrichment of the water body with nutrients (hypernutrification). The overgrowth of these leads to a depletion in the oxygen content of receiving environments resulting in water quality degradation and decreased biodiversity **(EPA, 1999)**.

2.4.4. Total Solids:

Total solids (TS) are defined as all matter in a water or wastewater sample that remains as residue upon evaporation and drying at 103 – 105 ˚C. Matter that has a significant vapor pressure at this temperature is lost during evaporation and is not defined as solid **(Tchobanoglous and Burton, 1991)**.

Total solids may be differentiated according to size into total dissolved solids (TDS) and total suspended solids (TSS). Total dissolved solids (TDS) is defined as all matter in a water or wastewater sample that will pass through filter paper of a certain pore size (1.5 µm, Whatman #934AH) and typically consists of mineral salts and small amounts of organic and inorganic substances. The principal constituents are usually the cations calcium, magnesium, sodium and potassium and the anions carbonate, bicarbonate, chloride and sulphate. Total suspended

solids (TSS) is defined as all organic and inorganic matter in a water or wastewater sample that is operationally greater than 1.5 microns and is removed from the water column by filtration or sedimentation.

Each of the classes of solids may be further categorized on the basis of their volatility at 550 ± 50 ˚C. Volatile solids is defined as all matter in a water or wastewater sample that remains as a residue after evaporation at 103 – 105 ˚C, but which is oxidized and lost as a gas after ignition at 550 ˚C and includes most forms of organic matter. Fixed solids is defined as the suspended or dissolved solids in a water or wastewater sample that remains sfter ignition at 550 ˚C and includes inorganic matter **(Tchobanoglous and Burton, 1991 and Tchobanoglous and Schroeder, 1985)**.

Fecal mater and feed wastage are the two main sources of solids in aquaculture effluent **(Pillay, 1992)**. Levels of total solids in aquaculture wastewaters must be limited for several reasons. Effluents containing high concentrations of suspended solids may form a plume of discolored water in the discharge area reducing light penetration, phytoplankton productivity and feed uptake by visual feeders **(Cripps and Kumar, 2003)**. **Sigler *et al.* (1984)** reported that concentrations of suspended solids greater than 25 mg L^{-1} adversely affected growth rates in steelheads (Oncorhynchus mykiss) and Colo salmon (O. kisutch) because the suspended particles reduced light penetration and impaired the organisms ability to see and secure food. Excessive sedimentation can abrade or cover respiratory surfaces (gills) of aquatic organisms, smother eggs and larvae and bury and smother communities of benthic organisms reducing the biodiversity of the ecosystem **(Pillay, 1992 and Cripps and**

Bergheim, 2000). **Au *et al.* (2004)** evaluated the effects of exposing green grouper (Epinephelus coioides), an important marine aquaculture species to various concentrations of suspended solids (0, 50, 100, 200, 1000, and 2000 mg L^{-1}) over a 6 week period. The researchers concluded that exposure was not lethal and no changes in food intake or growth were observed. However, damage to gill structure, including epithelium lifting, hyperplasia in the pillar system and reduction of epithelial volume were clearly evident and strongly correlated with suspended solids concentration. Suspended matter which settles on the seabed may lead to the development of anoxic and reducing conditions in the sediment and enhance the activity of sulfate reducing and methanogenic bacteria resulting in the production of toxic gases such as ammonium, hydrogen sulfide and methane **(Gowen *et al.*, 1990; Wu, 1995 and Holmer *et al.*, 2003)**. Sedimentation in shallow water bodies may also render the water unfit for recreational, industrial and domestic use.

Aquatic organisms are affected by solids in suspension and by settleable solids as they are deposited by sedimentation. The effect of the solids on fish is dependent on the species, age and stage of the reproductive cycle **(Muncy *et al.*, 1979)**. The lowest concentration of suspended solids that showed lethal effects on adult fish in a study of over 16 species of fish did not occur until a concentration on average greater than 69000 mg/L was reached **(Wallen, 1951)**. Adult mortality through reduced resistance to disease **(EIFAC, 1965)** may be attributed concentrations of 207 mg L^{-1} of diatomaceous earth **(Herbert and Merkens, 1961)**.

Suspended solids is a term usually associated with plankton, fish wastes, uneaten fish feeds, or clay particles

suspended in the water. Suspended solids are large particles which usually settle out of standing water through time. Large clay particles are an exception. Clay particles (which will be discussed again) are kept in suspension because of the negative electrical charges associated with them **(Swann, 2009)**.

2.4.4.1. Solid removal in recirculation systems:

Management and removal of solids is one key process in an RAS. In recirculating finfish systems the main particulate waste materials are feces, uneaten feed, decaying fish, and tank and pipe biofilm slough **(Chen *et al.*, 1993; Patterson and Watts, 2003)**.Since the adverse effects of solids on recirculating systems were recognized, research on solids removal has been recommended by many investigators **(Brinker *et al*, 2005; Summerfelt and Penne, 2005; Davidson and Summerfelt, 2005; Steicke *et al.*, 2007; Merino *et al.*, 2007; Bai, 2007; Timmons and Ebeling, 2007; Sandu *et al.*, 2008; Pfeiffer *et al.*, 2008; Couturier *et al.*, 2009; d'Orbcastel *et al.*, 2009)**. Solids that are not removed from the RAS have numerous consequences for the fish in the system and system components. The presence of suspended solids in recirculating finfish aquaculture systems can cause damage to fish gills, increase biochemical oxygen demand, reduce biofilter nitrification, and increase ammonia in the system **(Chapman *et al.*, 1987; Bergheim *et al.*, 1998; Wong, 2001; Zhu and Chen, 2001).** The solids found in RAS operations vary in size and settling properties and have an effect in the design and operation of the solid removal mechanisms **(Merino *et al.*, 2007)**. All recirculating aquaculture systems utilize processes to remove waste solids, oxidize ammonia and nitrite-N, and aerate and/or oxygenate the water. Methods or processes that improve solids

removal also improve water quality, which can potentially enhance production and certain operating costs. However, selection of the best treatment system for a particular aquaculture operation is difficult, given the variety of processes available, and the lack of uniform methodology for evaluation of water treatment effectiveness and economic accounting and other practical considerations **(Bai, 2007** and **Timmons and Ebeling, 2007)**.

One of the key problems in RAS relates to the load of suspended solids and in particular to very fine particles. The presence and accumulation of particulate wastes in RAS (faeces, uneaten feed, and bacteria flocs) will impact negatively the water quality by affecting the performance efficiency of the water treatment units. High suspended solids load has many disadvantages:

- Particulate matter consumes oxygen during biological degradation which will decrease the availability of oxygen for fish in culture **(Rosenthal, 1997; Davidson and Summerfelt, 2005)**.
- The brake down of organic wastes will increase the TAN concentration in the water affecting nitrification **(Liao and Mayo, 1974; Spotte, 1979; Davidson and Summerfelt, 2005; Chen *et al.*, 2006)**. Small quantities of unionized ammonia can be toxic for epithelial tissues and disturb the elimination of protein metabolites across gills **(Peters *et al.*, 1984)**.
- Solids support the growth of heterotrophic bacteria which can outgrow and compete with nitrifyers. The nitrification process is strongly inhibited by heterotrophic processes

when high amounts of organic carbon are present **(Zhu and Chen, 2001)**.

- Suspended solids offer an ideal temporary substrate for facultative pathogens while they try to find a final host. **Bullock *et al.* (1994)** inferred that suspended solids may be involved in bacteria gill disease (BGD) outbreak. **Noble and Summerfelt (1996)** described that beside opportunistic microorganisms, non-infectious problems prevail as high levels of suspended solids have caused mortalities in RAS.
- Particles can potentially clog biofilters and reduce their efficiency **(Chen *et al.*, 1993; Rosenthal, 1997)**.
- Excessive solid loads can cause plugging within aeration columns, screens, and spray nozzles orifices, which could ultimately result in system failure **(Davidson and Summerfelt, 2005)**.
- The organic C/N ratios in the water will negatively affect the efficiency of nitrifyers **(Rosenthal, 1997; Ebeling *et al.*, 2006)**.
- The accumulation of solids can create anoxic conditions favourable for bacteria responsible for the production of geosmin and 2- ethylisoborneol causing offflavours in cultured fish (Tucker and Martin, 1991).
- Gill tissue can be damaged by particles **(Rosenthal, 1997)** during feeding, drinking, and breathing. **Bullock *et al.* (1994)** suspected that small suspended solids could irritate gill tissue and provide an injured surface for attachment of any bacteria (BGD) present in the water. **Peters *et al.* (1984)** found out that fin and gill lesions in rainbow trout

were induced partly by the accumulation of excretory and decomposition products.

- Fish vision can be affected by high suspended solids load, disturbing the recognition of feed.

The proper management of suspended solids is one of the key factors determining the successful operation of recirculating systems because of the elucidated potential impacts. The design of a RAS to achieve the desired solid elimination has to take the following aspects into consideration:

- The more quickly solids are removed from the water the less time they have to break down and consequently less oxygen will be consumed by attached bacteria **(Bullock *et al.*, 1994, 1997; Rosenthal, 1997; Davidson and Summerfelt, 2005)**. Long residence times for particles in the system will affect their size due to share forces and microbial degradation. Substances are leaching faster from smaller particles than from big ones. Small particles, however, are more difficult to remove from the culture water because of size and the proximity to water density.
- The methods to remove solids (sedimentation, filtration, and/or flotation) have to be able to eliminate particles over a wide range of sizes. Normally a combination of removal techniques are needed **(Waller *et al.*, 2003; Orellana *et al.*, 2005)** specially for the elimination of fine solids fraction (<20 μm) that do not settle in conventional treatment processes such as gravity settling and microscreen, and accumulate in the culture medium over time **(Chen *et al.*, 1993; Chen *et al.*, 1994; Rosenthal, 1997; Waller, 2001; Viadero and Noblet, 2002; Orellana *et al.*, 2005)**.

- The size of fish and the water flow rates seem to be two closely related factors that determine the characteristic of solid waste and because fish size and feed size are known, these characteristics can largely be predicted. Small fish produce small particles and need high quantities of feed per unit weight in order to satisfy their energy requirements, while big fish produce larger particles and need less feed per unit of biomass, compensated for by a relatively lower growth rate **(Franco-Nava *et al.*, 2004)**. The amount, characteristics, and size of solids indirectly determine the choice of methods for efficient removal.
- High stocking densities are often aimed for (depending on the species) to boost the profitability of a RAS. High stocking densities allow more fish biomass to be produced per unit of culture. However, increasing stocking densities require a better management of solid removal and highly reliable removal techniques. Solid loads will increase rapidly. Waste removal from the system has to be efficient and becomes costly if mechanical means are no longer sufficient.

The removal of suspended solids from RAS is a solid-liquid separation process. Such processes can be classified as sedimentation, filtration and flotation, according to the removal techniques. Sedimentation will depend on the difference in density between particles and water. The greater the density difference the faster will occur the settling of solid matter **(Timmons *et al.*, 2001)**. Common sedimentation methods include clarifiers (settling tanks), settling tubes and hydrocyclones (swirl separators). Filtration processes can be

accomplished with screens, granular media or porous filter media **(Chen *et al.*, 1994)**. The separation of the solids from the water is controlled by the way particles are transported from the suspension onto the filter medium **(Chen *et al.*, 1994; Timmons, *et al.*, 2001)**. In a flotation process, particles attach onto air bubbles and are separated from the water. This last technique has being described as foam fractionation and is repeatedly reported by several authors **(Rosenthal, 1981; Rosenthal and Krüner, 1985; Chen *et al.*, 1993)**.

2.5. Energy in Recirculating Aquaculture Systems:

Singh and Marsh (1996) mention that the most significant components of the energy requirements of recirculating systems are due to heating (42%) and pumping (35%) the system water.

The degassing tower is another source of energy loss. Stripping the CO_2 from the water requires a large amount of air **(Summerfelt, *et al.*, 2000)**. This air is rarely at the same temperature as the system water and the degassing tower therefore acts as a cooling tower in winter and as a heating tower in summer. Furthermore, wintertime outside air humidity is often lower than the saturation air humidity at the system temperature. Air coming from outside therefore reaches saturated humidity conditions in the degassing tower and the energy to evaporate the corresponding amount of water is taken from the system water itself, which further cools down the water. In the same way, air moisture condensation occurs in summer and the condensation energy absorbed by the water participates to the heat gain **(Summerfelt, *et al.*, 2000)**.

Energy losses into the ground also contribute to the total thermal energy load of the system. In cold climate countries, it is

estimated that these losses can account for more than one third of the total heat loss of a building **(Claesson and Hagentoft, 1991)**.

In aquaculture, tanks are often buried into the ground without insulation. It is also not uncommon to use the building foundations as part of a reservoir or tank walls. This configuration exposes the water to wide soil temperature variations generated by the seasonal outside air temperature fluctuations. It therefore contributes to increase the total energy budget **(Renaud, 2003)**.

Regulating the makeup water temperature also requires a significant amount of energy. The temperature of the water source (well, river or sea) is often subjected to seasonal variations and can be either cooler or warmer than the system water temperature. According to **Singh and Marsh (1996)**, around 27% of the total energy requirements of the recirculating system studies are lost due to water replacement. This energy load depends on the water exchange rate of the system and it is estimated that the total energy cost could drop by 57% when decreasing the water exchange rate from 15 to 0% (closed system).

Since the water is recycled within the system, pumping requirements are of primary importance in recirculating aquaculture. Indeed, the recirculated flow rate and thus the pumping costs depends on the water quality required and the efficiency of the treatment processes. High water quality criteria impose a relatively high turnover in the tanks to remove the pollutants, which requires pumping a large flow rate to the treatment units. Furthermore, oddly shaped piping arrangements contribute to incease the frictional head losses into the system, which has a direct impact on the pumping energy required. The

pumping power is also a function of the overall elevation of the system and special care must therefore be given to optimize the system flow configuration **(Renaud, 2003)**.

2.6. Aquacultural Models:

Aquaculture is complex ecosystem. Computer modeling is a valuable tool for the analysis of complex systems and is becoming an important component of research efforts that are directed toward improving our understanding of aquaculture ecosystems and developing management practices that optimize resource utilization **(Piedrahita, 1988).**

Cuenco (1989) reported that modeling aquaculture systems is relatively new and is not yet practiced extensively. It has not matured to the point where a common, consistent terminology and a well-defined methodology are in use. Approaches to aquaculture modeling reflect adaption of developed for and used in other disciplines.

Most mechanistic describing water quality in aquaculture ponds have focused on prediction of diurnal variation in dissolved oxygen concentration. Models describing annual variation in pond water quality are rare. Although dissolved oxygen is undoubtedly the most important water quality parameter affecting fish growth and production in ponds, other water quality variables, particulary sub-lethal consentrations of nitrogenous compounds, such as ammonia and nitrite, may effect fish growth and production **(Hargreaves, 1997).**

Empirical **(Boyd, 1985)** and theoretical **(Piedrahita, 1991)** evidence indicates that fish respiration has a relatively small effect on pond dissolved oxygen budgets and that fish nitrogenous excretion has a much more important effec on water quality.

A conceptual model of a nitrogen bio-geochemistry of aquaculture ponds has been developed **(Shilo and Rimon, 1982)**, although mathematical description of the process described in that model has not neen accomplished.

Prediction of biological filter performance by using either theoretical or empirically derived models has been presented by several author: e.g., **Liao and Mayo (1974), Weatherley (1984), Bovendeur *et al.* (1987) and Paller (1992).** In some studies **(Bovendeur *et al.*, 1987; Heinsbroek and Kamstra, 1990; Nijhof and Bovendeur, 1990)** evaluation were made in which trickling filters were assumed to be completely mixed, whereas plug-flow characteristics are more likely to occur in percolated filter columns **(Weatherley, 1975 and Rittman, 1982).** Discrepancies in predicted results between plug-flow and complete mixed model depend largely on the quantitative properties of the processed modeled and under certain circumstances (small filter, high hydraulic loading) completely mixed models might indeed be justified. However, for trickling filters with dimensions and management used in practice, these models often suggest ammonia removal rates exceeding the ammonia loading rates. In general, models are most powerful if the mathematical formulation incorporated reflect the fundamental mechanisms behind the process.

Research in the aquaculture industry has been dramatic in recent years, especially in advancements made in recirculation technology. However, one area of research that has progressed slowly is the development of computer simulation models that can be used by a fish farmer to better understand his system. One aquacultural model currently under development is the "Aquafarm" model by Oregon State University **(Ernst *et al.*,**

2000). Such models could potentially be used to predict the potential of a system and assist in the planning process, Cuenco explains this lack of progress due to both a duplication of efforts and studies where important interactions were not considered or understood and studies where important factors were not measured in a useful form or were not considered at all **(Cuenco, 1989).** Tomer and Wheaton reinforce this idea when they comment that the aquaculture industry has lagged behind the fisheries science industry in embracing computer models as a useful tool for management, design and marketing **(Tomer and Wheaton, 1996).** As aquacultural modelling is still in its infancy, the models that have been developed have been user-specific. This means, that in the past, aquaculture models have been produced for a specific use and are not easily adapted to a different farm. Models that have been designed include growth models, water temperature models, bio-econmic models, etc.

Piedrahita has made significant contributions in the area of aquacultural modelling, but more specifically in non-intensive facilities. He proposed that aquaculture models are limited by:

1- More accurate quantification of metabolic rates of the fish under intensive production conditions.
2- Quantification of the relationship between water quality and fish growth and health, and
3- Improvement and refinement of water reuse technology **(Brinkop and Piedrahita, 1996).**

Predicted water quality regimes and fertilizer and feed requirements were comparable to reported values for tilapia production under similar site and management conditions. As expected, total lime application rates were in the low range of reported rates **(Boyd, 1990; Boyd and Bowman, 1997)**, for

which pond source water had low alkalinity but soils were assumed to already be neutralized with respect to exchange acidity (base unsaturation). The nitrogen and phosphorous application rates used were within reported ranges for tilapia production in fertilized ponds, which range 2.0 – 4.0 kg N ha^{-1} day^{-1} at N:P ratios that range 1:1 – 8:1 **(Lin *et al.*, 1997).** For fertilized and fertilized-fed ponds, simulated fish growth rates and total production per hectare, fish density level at the onset of feeding, and required feed application rates were comparable to reported results **(Diana *et al.*, 1996; Diana, 1997; Lin *et al.*, 1997).** Fish production and application of fertilizer and feed were adequately estimated using a daily time step with no consideration of water stratification. However, as generally found for solar-algae ponds, diurnal simulations and consideration of stratification were required to estimate extremes in water quality regimes. Typical diurnal profiles of temperature and dissolved oxygen for mid summer, were comparable to reported profiles for stratified tropical ponds **(Losordo and Piedrahita, 1991; Piedrahita *et al.*, 1993; Culberson and Piedrahita, 1994).** The maximum divergence in water quality between the top and bottom layers was controlled by the specified regime of daily-minimum layer mixing rates.

Ellner *et al.* (1996) and Kochba *et al.* (1994) showed that simulation was useful for investigating the production, transfer, and loss of inorganic nitrogen in pond systems. **Jamu and Piedrahita (2002)** developed simulation models for organic matter and nitrogen in integrated aquaculture systems. **Singh *et al.* (1996)** simulated the discharge of wastewater heat from an RAS facility to determine optimum greenhouse size. **Weatherley *et al.* (1993)** compared a continuous-time

simulation language designed for solving time-dependent, nonlinear differential equations with analytical solutions of the unsteady-state mass-balance equations for the transfer and removal of ammonia; they concluded that simulation is a powerful tool for describing the dynamic behavior of ammonia concentration. A general discussion for the use of models in aquaculture science was presented by **Ernst *et al.* (2000)**, who developed decision support software for design and management planning that simulates physical, chemical and biological unit processes. However, no one has yet developed a complete stochastic simulation model of the entire system, including both discrete and continuous processes and incorporating animation for use as a practical tool for optimizing design and management of a specific RAS.

Halachmi *et al.* (2005) studied that model combines simulation and optimization to overcome the difficulties that characterize the RAS system. Simulation experiments allow fish behavior, equipment, and layouts to be evaluated jointly. Hence, an initial design can be fine-tuned to produce a balanced system, i.e., an optimal layout specific to a given RAS, within a reasonable time. By implementing the suggested methodology, step-by-step, we designed an optimal RAS that met both economic and stocking density needs. Application of the new methodology and rigid specifications for 20–25 raceways in a specific RAS in the simulation led to the following findings: (1) The farm will build five more raceways in addition to the existing 20. (2) The batch size will be 6500 fish arriving every 6, 5, or 4 days depending on the growth rate achieved. (3) To support its peak loading, a small raceway should have a capacity of 1625 kg, and a large one should carry up to 3250 kg. (4) The

existing RAS design, with improved management, can achieve the desired production. (5) The animation allowed a range of personnel unfamiliar with RASs to appreciate how the new RAS would operate.

Additional data relevant to different species, water quality, feed components, cultivation units, stocking density, etc., would make the model applicable in a wider range of cases. The model is a 'discrete-event' as well as 'continuous-process' simulation. Clearly, the programming of combined continuous and discrete event processes is a challenge **(Kleijnen and van Groenendaal, 1992)** programmed in order to illustrate the capability to deal with both in parallel. In the future, as needed, environmental impacts and other continuous processes can be modeled in the same way. The economic part of the model is a crucial part of the simulation. It is advised, in further research, to elaborate the ecumenical aspects in the direction of developing an economical risk analysis model.

2.5.1. Water Temperature Models:

Cuenco (1989) reported that water temperature models may be (1) theoretical (based on heat energy balance) or (2) empirical (based on historical air or water temperature records and regression analysis). Temperature varies temporary with diurnal and seasonal components. This temporal variability approximates a sine or cosine curve. To control water temperature in ponds several strategies can be followed. Proper selection of the site is the most obvious one and sets the ambient temperature range. Pond depth can also be designed to stabilize water temperature fluctuations compared to air temperature fluctuations. Mixing of two or more source of water of different temperatures is another technique. Circulation of water in the

pond is important to prevent temperature gradients reduce spatial variability. Processes affecting water temperature in the pond are:

1- The amount of solar radiation falling on the pond surface, which depends on the radiation for the particular time of the year and the amount of cloud cover.
2- Connective heat transfer, that may add or remove heat from the pond depending on the difference between air and water temperature and the wind speed.
3- Evaporative heat loss, which depends on wind speed, water temperature and relative humidity.
4- Precipitation and runoff, that usually decrease the pond temperature as rainfall is colder than the pond water.
5- Seepage/infiltration, but these can be considered negligible for ponds with appropriate soils for water retention.

Caissie *et al.* (2001) developed a stochastic model based on the autocorrelation function of the water temperature time series to link the air and water temperatures in Catamaran Brook, in New Brunswick. They used Fourier and sine functions, and their combinations, in developing **(Caissie *et al.*, 2001). Nelson and Palmer (2007)** in an attempt to assess potential impacts of climate change on stream temperatures, developed empirical relationships to complement a simple model of in-stream temperature. They included the impact on water temperature of increased watershed imperviousness, destruction of the riparian vegetation, and increased siltation **(Nelson and Palmer, 2007).**

One example of the application of stochastic models is given by **Lu and Piedrahita (1996)** based on research in which they stochastically generated weather parameters applied to

aquaculture. Their model was similar to the model used by **Sadeh *et al.* (1986)** to study the economic profitability of shrimp growth rate. The water temperature was determined from air temperature using a linear regression equation. However, statistical models are based on observations in specific situations and cannot, or at least should not, be applied beyond a limited range of observed values.

A more recent advancement in statistically based temperature models occurred when Geographical Information Systems (GIS) were introduced in water in water temperature models. The Geographical Information Systems-Stream Temperature model (GIS-STRTEMP) is a water temperature simulation model created for prediction of maximum stream temperature during the critical summer low-flow period in forested watersheds **(Sridhar *et al.*, 2004)**. The GIS-STRTEMP model was intended for estimation of worst case or maximum annual temperature and is therefore applied on an event basis to low-flow conditions using maximum annul solar radiation and air temperature as input. For the research conducted in Cascades mountains, the low-flow conditions were defined as the 7-day 10-day low-flow (7Q10), which was estimated by a regional regression equation **(Sridhar *et al.*, 2004)**.

Ali (2006) predicted that aquaculture pond temperatures throughout the year is essential to the design and evaluation of potential aquaculture sites. An energy balance was developed for earthen aquaculture ponds to 1) determine the relative importance of energy transfer mechanisms affecting pond temperature; 2) predict pond temperatures, and 3) estimate the energy required to control pond temperatures. A computer program was developed to solve the energy balance using

weather and pond temperature data. Initial simulations for aquaculture pond validated the model's ability to predict pond temperature changes. The dominant energy transfer mechanisms for ponds were solar radiation, pond radiation and longwave sky radiation. Finally, management and design questions about the warm water aquaculture ponds, such as the pond temperature throughout an average weather year, the amount of energy needed to maintain the pond temperature constant and the amount of energy required to warm a pond from 10 to 28°C, were answered by additional simulations.

2.6.2. Dissolved Oxygen Models:

Cuenco (1989) reported that two basic types of these models occur: theoretical models, based on mass balance and empirical models, based on regression analysis of historical data.

Dissolved oxygen generally increases during the daytime due to photosynthesis and declines during the nighttime due to the absence of photosynthesis and continuing respiration. Models can break down the diurnal fluctuation into two: the nighttime decrease and the daytime increase.

The processes that add oxygen to the pond are: (1) photosynthesis by phytoplankton, the major source of oxygen; (2) oxygen diffusion from the air governed by the difference in oxygen concentration between the pond water and the air and the wind speed.

The amount of oxygen that the water will hold is determined by the temperature and the salinity of the water.

McWhiter and Hutter (1989) studied that developed a model for oxygen mass transfer in sub-surface aeration systems. This model evaluate the mass transfer process taking into account both the liquid and gas phases. It is comprised of a

system of partial differential equations which can be simplified to a system of ordinary differential equations.

Oliveira and Franca (1998) studied that a simulation of oxygen mass transfer in subsurface aeration system was presents. There was good agreement between simulation and experimental results. It was observed that the equilibrium DO level decreased with increase in temperature and that the oxygen transfer efficiency is higher for smaller values of gas flow rate. The application of the aeration system to aquaculture resulted in a decrease in the equilibrium DO level due to the oxygen consumption by the fish.

2.6.3. Ammonia Models:

Both the diurnal and the seasonal fluctuations of ammonia in the pond were considered. Fish feed and added manures are the major sources of nitrogen in fishponds. The major sinks for ammonia are the photo-oxidation of algae and bacteria and bacterial nitrification of ammonia to nitrate **(Shilo and Rimon, 1982).**

Ammonia is produced by bacterial decomposition of organic matter (uneaten feeds, feces) and ammonia excretion by the fish. Ammonia is removed from the water through uptake by algae and bacteria. The pond sediment acts as a storage medium for ammonia. However, ammonia may also be released from the sediment into the water column. The level of unionized ammonia in the pond water increases with pH and temperature. The toxicity of ammonia increases at low dissolved oxygen concentrations. Periodic drying of ponds an established practice for many aquaculturists, was found to remove ammonia from the ponds and renew the ability of the pond to reach high levels of production.

2.6.4. Fish Growth Models:

The relationships among fish growth, water quality and feeding are of major concern in predicting fish weight. It is difficult to conduct experiments to examine the effects of one factor only because various biotic factors, such as fish size, species and behavior influence fish growth. Most fish growth models have been developed based on the concept of bioenergetics **(Cuenco *et al*., 1985c; Liu and Chang, 1992; Bolte *et al*., 1995; Nath, 1996)**. The basic principle of bioenergetics is that all energy intacke through food consumption is lost as waste (feces or excretion), used in metabolic processes or stored as new body tissue **(Jobling, 1994)**. Since food consumption is a function of fish size, the energy balance within a fish body is usually described based on fish biomass.

Variables affecting food intake include fish size, food availability, photoperiod, temperature, DO and un-ionized ammonia concentrations **(Cuenco *et al*., 1985a).** Water temperature is the factor that affects the fish growth rate the most. A sensitivity analysis performed by **Cuenco *et al.* (1985b)** showed that parameters for food consumption are more sensitive than parameters related to the metabolic terms. **Liu and Chang (1992)** developed a bioenergetics model to examine the effects of pond fertilization, stocking density and spawning on the growth of Nile tilapia. A non-linear regression method was used to estimate the parameters in the growth model. The model provided fairly accurate results of the estimated parameters from PD/A CRSP Thailand data **(Liu and Chang, 1992).**

A more complete bioenergetics model was developed for Nile tilapia **(Bolte *et al*., 1995; Nath, 1996)**. The model

accounted for the effects of water temperature, DO, un-ionzed ammonia, photoperiod, fish size and food availability. The model can be used to predict fish growth under different pond management strategies. Three different food sources (two types of phytoplankton and one of zooplankton) were included in the model. The different types of food sources were described based on their carbon content. The coefficients of food intake rate for each food source were determined by model calibration. The model was used to simulate fish growth at different stocking densities and different fertilization rates at several locations. The simulation results indicated that the model could not describe the effects of fertilization on fish growth because the nutrient content of food sources was not included.

Nile tilapia is one of the most popular cultured species in many tropical countries such as Thailand. Various growth models have been developed for this species **(Liu and Chang, 1992; Nath *et al*., 1994; Bolte *et al*., 1995; Yi, 1998),** however, these models are for Nile tilapia cultured primarily in fertilized ponds with or without supplemental feeding. Modeling techniques have yet to be applied to integrated aquaculture such as a cage-cum-pond system, in which large Nile tilapia are fattened in cages and small Nile tilapia are nursed in open water to utilize wastes derived from cages **(Yi *et al*., 1996; Yi, 1997).**

3. MODEL DEVELOPMENT

Heat and mass balances were performed on the recirculating aquaculture system (RAS). Heat balance of the system include: sortwave radiation (solar radiation and solar reflected), longwave radiation (pond back radiation and sky radiation), heat transfer through conduction, heat transfer through convection and latent heat loss. Mass balance include: oxygen, nitrogen and solids.

3.1. Heat Balance:

The theory used to develop an energy balance for recirculating aquaculture systems is presented as follows. Figure (3.1) represents the energy balance described by the following mathematical expression:

$$(dq / dt) = q_{solar} + q_{sky} - q_{evap} \pm q_{conv} \pm q_{cond} + q_{in} - q_{drain} + q_{rain} \pm q_{other} \quad (3.1)$$

$$q_{solar} = q_D - q_{reflected} - q_{back} \quad (3.2)$$

Where:-

q is the total energy (kJ) at any given time (t) in the pond per m^2

q_{solar} is the rate of energy gained by radiation, kW m^{-2}

q_D is the rate of energy gained by direct radiation, kW m^{-2}

$q_{reflected}$ is the rate of solar energy reflected a way from the system, kW m^{-2}

q_{back} is the rate of heat loss due to back radiation, kW m^{-2}

q_{sky} is the rate of energy gained by long wave radiation from the sky, kW m^{-2}

q_{evap} is the rate of heat lost through the evaporation of water, kW m^{-2}

q_{conv} is the rate of heat exchange with the air by convection, kW m^{-2}

q_{cond} is the rate of heat exchange with the wall, kW m^{-2}

q_{in} is the rate of bulk energy gain from makeup water, kW m^{-2}

q_{drain} is the rate of bulk energy lost to the overflow of water, kW m^{-2}

q_{rain} is the rate f bulk energy gain due to rainfall, kW m^{-2}

q_{other} is the rate of energy transfer from or to other sources, kW m^{-2}

The temperature of the water at time t can be calculated as:

$$T_t = T_o + \frac{\left(q_{t-1} + \left(\frac{dq}{dt} \right)_{\text{pond}} \times dt \; x \; A \right)}{\rho \times c_p \times v} \qquad (3.3)$$

Where:

T_t is the temperature of water volume v at time t (K)

T_o is the temperature of water volume v at time t=0 (K)

q_{t-1} is the heat stored in water volume v at time t-1 (kJ)

ρ is the density of water (kg m^{-3})

c_p is the specific heat of water at constant pressure (kJ kg^{-1} K^{-1})

v is the volume of water (m^3)

A is the tank area (m^2)

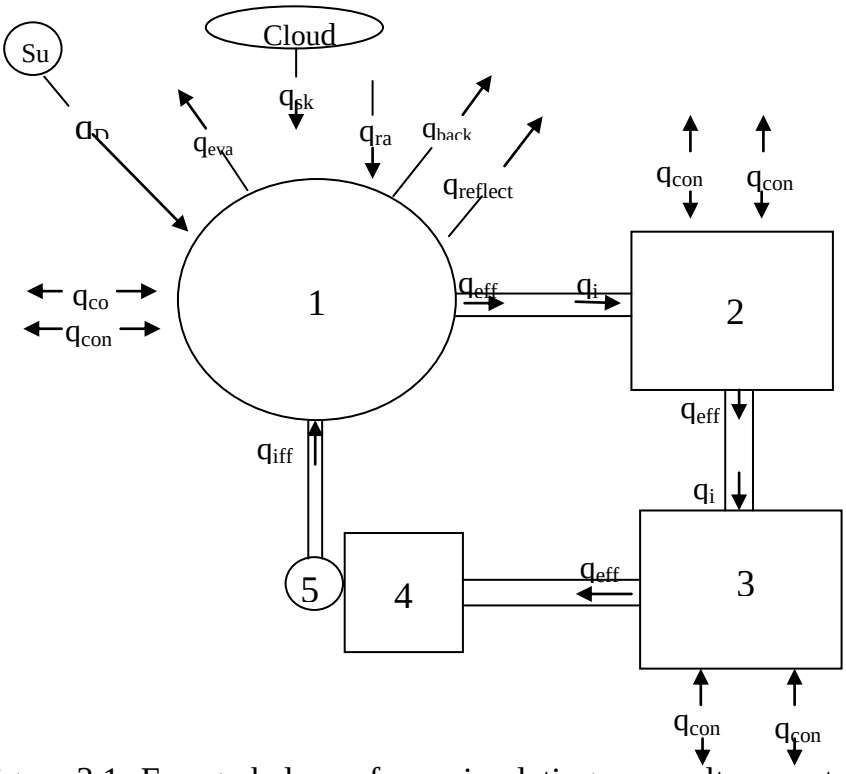

Figure 3.1: Energy balance for recirculating aquaculture systems, (1) culture tank, (2) screen filter, (3) biofilter, (4) collector tank, (5) pump

3.1.1. Heat Transfer through Radiation:

Heat transfer through radiation for recirculating aquaculture systems incidence in ponds. For outdoor aquaculture ponds, two types of radiation must be considered: short wave and long wave radiation.

3.1.1.1. Shortwave Radiation:

1. Solar Radiation:

Radiation emitted by the Sun travels through the vacuum of space unaltered. The percentage of energy associated with certain bandwidths of solar radiation emitted from a blackbody at 5800K (**Holman, 1997**).

To determine the amount of incoming extraterrestrial radiation, the following equations can be used:

$$q_D = \Psi S_c \left(\frac{D}{D_o}\right)^2 \cos\theta_z \tag{3.4}$$

$$\left(\frac{D}{D_o}\right)^2 = 1.000110 + 0.034221\cos\tau + 0.001280\sin\tau + 0.000719\cos(2\tau) + 0.000077\sin(2\tau) \tag{3.5}$$

$$\tau = \frac{2\pi(n-1)}{365} \tag{3.6}$$

Where: τ is the day angle (radians)

n is the day of the year (on January 1st , n = 1)

S_c is the solar constant (1353 W m^{-2})

D is the distance from the Earth to the sun (km)

D_0 is the mean distance from the Earth to the sun, 1.496 x 10^8 km

ψ is a "clearness" factor (1 on clear days, 0.2 on cloudy days)

The solar zenith (θ_z) is the angle formed by the pond normal and direct incident beam radiation (the angle of incidence in Figure 3.2), and this angle varies with the time of day, the time of year and the geographical position of the pond. The solar zenith is given by the following equations **(Anderson, 1983 and ASHRAE, 1998)**:

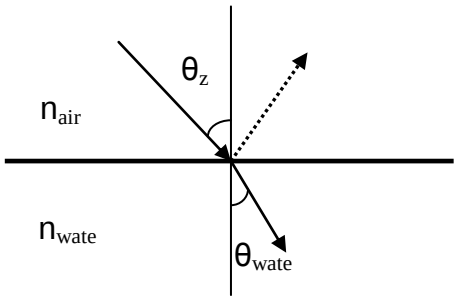

Figure (3.2): When light goes from one medium (n_{air}) to another (n_{water}).

$$\cos\theta_z = \sin\Phi\sin\delta + \cos\Phi\cos\delta\cos\omega \quad (3.7)$$

$$\delta = 23.45\sin\left[\frac{360}{365}(284+n)\right] \quad (3.8)$$

$$\omega = (12 - \omega_{time})x15^{\circ} \quad (3.9)$$

$$\omega_{time} = LST + (Lnt - Lng) \div 15 \quad (3.10)$$

Where: Φ is the pond's latitude (positive for North) (degrees),

δ is the solar declination (the angle formed by the line from the center of the Earth to the center of the Sun and the Earth's equator) (degrees)

ω is the hour angle (degrees)

ω_{time} is the solar time (degrees)

LST is local standard time

Lnt is the longitude of the standard time meridian (degrees)

Lng is the longitude of the pond (degrees)

2. Solar 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 **(Laska, 1981; Wetzel, 1983)**.

$$q_{reflected} = q_D \text{ x R} \quad (3.11)$$

where: $q_{reflected}$ is the rate of energy loss by the pond by radiation (kW m^{-2})

R is the fraction of reflected radiation.

Using Fresnel's Law, and assuming the water surface is smooth, the fraction of reflected radiation R is:

$$R = \frac{I_{reflected}}{I_{incident}} = \frac{1}{2}\left(\frac{\sin^2(\theta_{water} - \theta_z)}{\sin^2(\theta_{water} + \theta_z)} + \frac{\tan^2(\theta_{water} - \theta_z)}{\tan^2(\theta_{water} + \theta_z)} \right) \quad (3.12)$$

Where: θz is the zenith angle and

θ_{water} is the refracted angle of the beam

Using Snell's Law, one can determine refraction angle.

$$n_{air} \sin\theta_z = n_{water} \sin\theta_{water} \quad (3.13)$$

Where: n_{air} is the index of refraction of air (1) and

n_{water} is the index of refraction of water (1.33 in the visible spectrum).

Once radiation penetrates the water surface, it is either absorbed or scattered.

3.1.1.2. Longwave Radiation:

1. Pond Backradiation:

The range of wavelengths emitted from a pond at 27°C spans from about 4.8 to 74 μm. This leads to three conclusions:

- There is no exchange of radiation within the body of water **(Rabl and Nielsen, 1975)**.
- Pond backradiation is a surface phenomenon.
- The pond can be treated as a grey body.

Noting that the emissivity of water is 0.96 **(Siegel and Howell, 1981; Kondratyev, 1969)**, the rate of heat loss due to pond backradiation is:

$$q_{back} = 0.96\sigma(T_{pond})^4 \quad (3.14)$$

Where:-

q_{back} is the backradiation of the pond (kW m^{-2})

σ is the Stefen-Boltzmann constant (5.67×10^{-11} kW m^{-2} K^{-4})

T_{pond} is the temperature of the pond (K)

2. Longwave Sky Radiation:

Longwave sky radiation can be seen as the emission of radiation from two atmospheric gases: water vapour and carbon dioxide, both of which are generally opaque to the longwave radiation emitted by the Earth **(Bliss, 1961, Kondratyev, 1969)**. The apparent emissivity of these gases from the Earth's surface is strongly related to the total precipitable water in the atmosphere (i.e. the more water vapour in the air, the greater the absorbance and emittance power of this gas).

$$q_{sky} = 0.97e\sigma(T_{air})^4 \quad (3.15)$$

Where:-

q_{sky} is the long wave radiation from the sky (kW m^{-2})

T_{air} is absolute air temperature 2 m above the water surface (K)

e is average emittance of the atmosphere (dimensionless)

3.1.1.3. Heat Transfer by Conduction:

The conduction of heat across the bottom and walls of ponds, filters and pipes been considered of minor importance to the heat balance and has been largely ignored by modelers. However, **(Cathcart, 1987)** suggested the magnitude of the measured temperature gradient between the inner surface and outer surface in an experimental ponds, filters and pipes indicated the material may act as a heat sink during the spring monitoring period.

An equation to simulate the heat exchange with the system was included in the temperature model because of the findings of the studies mentioned above. The conduction of heat between the inner surface and the outer surface was calculated as:

$$q_{cond} = k(T_i - T_o)/z \quad (3.16)$$

Where:-

q_{cond} is the rate of heat transfer through conduction (kW m^{-2})

k is thermal conductivity coefficient (kW m^{-1} K^{-1})

Ti is temperature of the inner surface (K)

T_o is temperature of the outer surface (K)

Z is thickness of material (m)

For ponds, conduction occurs in two places, the bottom of pond and the walls of pond. For filters, conduction occurs in two places, the bottom of filter and the walls of filter. For pipes, the conduction of heat occurs between the inner surface and the outer surface.

3.1.1.4. Heat Transfer by Convection:

Convection can be viewed as the combining heat transfer effects of conduction and advection in fluids. Heat transferred through convection can be calculated using Newton's Law of cooling:

$$q_{conv} = h\left(T_{surface} - T_{fluid}\right) \tag{3.17}$$

Where

q_{conv} is the heat transferred by convection (kW m^{-2})

h is the heat transfer coefficient (kW m^{-2} K^{-1})

$T_{surface}$ is the temperature of the surface (K)

T_{fluid} is the temperature of the cooling (or heating) fluid (K).

For ponds, convection occurs in two places, the wall-water interface and the water-air interface. For filters, convection occurs in one place, the wall-water interface. For pipes, convection occurs in one place, the wall-water interface.

3.1.1.4.1. Determination of a Heat Transfer Coefficient- Nusselt Number Correlations:

Nusselt number (Nu) correlations are traditionally used to predict a heat transfer coefficient, depending on:

- the geometry of the surface
- the properties of the cooling fluid
- the velocity at which the cooling fluid is moving

However, there seems to be no Nusselt number correlations in the literature for bodies of water cooled or heated by the ambient air.

For the case when there is no wind (i.e. free convection), the flat plate Nusselt number correlations might be valid. This is because there are no waves on the water surface, and therefore, the approximation that the water surface is a flat plate might sufficiently precise.

The Nusselt number, a dimensionless number, is the ratio between the rate of convection to the rate of conduction in a fluid. Numerically, the Nusselt number (Nu) is related to the heat transfer coefficient by:

$$N_u = \frac{hL_c}{k_{air}} \tag{3.18}$$

Where

L_c is the characteristic length of the surface (m)

h is the heat transfer coefficient (kW m^{-2} K^{-1})

k_{air} is the thermal conductivity of the air (kW m^{-1} K^{-1})

$$k_{air} = \left(1.52E-11xT_{air}^3 - 4.86E-08xT_{air}^2 + 1.02E-04xT_{air} - 3.93E-04\right)/1000 \tag{3.19}$$

$$L_c = \frac{Area}{Perimeter}$$

For the case of free convective surfaces, the Nusselt number is related to another dimensionless number, the Rayleigh number (Ra), through empirical correlations. The Rayleigh number is:

$$R_a = \frac{g\beta(T_{water} - T_{air})L_c^3}{\alpha_{air} v_{air}} \quad (3.20)$$

$$\alpha_{air} = k_{air} / \rho.Cp \quad (3.21)$$

Where

g is the gravitational acceleration (9.81 m s^{-2})

β is the coefficient of thermal expansion (K^{-1})

T_{water} is the temperature of water (K)

α_{air} is the thermal diffusivity of the air (m^2 s^{-1})

v_{air} is the kinematic viscosity of the air (m^2 s^{-1})

ρ is the density of air (kg m^{-3})

Cp is the specific heat of air at constant pressure (kJ kg^{-1} K^{-1})

$$\rho = 360.77819 x T_{air}^{-1.00336} \quad (3.22)$$

$$Cp = 1.63E-10 x T_{air}^4 - 7.99E-07 x T_{air}^3 + 1014E-03 x T_{air}^2 - 4049E-01 x T_{air} + 1.06E+03 \quad (3.23)$$

Estimates for the case of a flat horizontal plate where the plate (in this case, the water) is warmer than the cooling fluid (in this case, the air), the following empirical correlations apply **(Holman, 1997)**:

$Nu = 0.54\ Ra^{0.25}$ if Ra is between 10^4 and 10^7.

$Nu = 0.15\ Ra^{1/3}$ if Ra is between 10^7 and 10^{11}

If the plate is cooler than the fluid, and Ra is between 10^5 and 10^{10}, then

$$Nu = 0.54\ Ra^{1/4} \quad (3.24)$$

For cases where wind is present (i.e. forced convection), different flat plate correlations could be used but run the risk of

not being appropriate. Under windy conditions, the pond surface is no longer flat because of waves. However, in the absence of any other relationship, the following Nusselt number correlation for mixed laminar and turbulent flow regions (for $5 \times 10^5 < Re < 10^8$) can be used **(Holman, 1997)**:

$$Nu = \left(0.037\,\mathrm{Re}^{4/5} - 871\right)\mathrm{Pr}^{1/3} \tag{3.25}$$

Where

Re is the Reynold's number

Pr is the Prandtl number

The previous equation is valid for Prandtl numbers between 0.6 to 60. The Reynold's number, Re, is a dimensionless number representing the ratio of inertial to viscous forces in the boundary layer of the fluid. It can be calculated as follows:

$$\mathrm{Re} = \frac{V_{air} \cdot \mathrm{x}}{\mathrm{v_{air}}} \tag{3.26}$$

Where

V_{air} is the velocity of the air (m s^{-1})

x is the length in the direction of wind flow

The Prandtl number, Pr, is a dimensionless number representing the ratio of the ability of a fluid to diffuse momentum to that of heat. It can be calculated as follows:

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{3.27}$$

Where

v is the kinematic viscosity of the fluid (m^2 s^{-1}).

α is the thermal diffusivity of the fluid (m^2 s^{-1})

Alternately, the heat transfer coefficient can be assumed constant, as was done by **Singh *et al.* (1994)**. The heat transfer coefficient was fixed at 17.5 W m^{-2} K^{-1}.

3.1.1.5. Energy Associated with Movements of Water:

3.1.1.5.1. Bulk Energy Transport in Liquid Water:

Because the liquid water entering or leaving the control volume also has internal energy, movements of liquid water across the system boundary represent gains or losses of energy. The rate of bulk energy moved across the system boundary can be calculated with the following equation:

$$q = \dot{m}CpT_{water} \tag{3.28}$$

Where

$\dot{m}$ is the mass flow rate of water into (or out of) the system,

Cp is the specific heat of water and

T_{water} is the temperature of the water.

3.1.1.5.2. Latent heat of evaporartion:

The process of evaporation requires a lot of energy. Evaporation heat losses (q_{evap}) are calculated with the following set of equations **(Anonymous, 1992)**:

$$q_{evap} = m^{\bullet}_{evap} h_{fg} = Q_e \rho_w h_{fg} \tag{3.29}$$

$$h_{fg} = \left(2502535.259 - 212.56384\left(T_{water} - 273\right)\right)/1000 \tag{3.30}$$

Where

$m^{\bullet}_{evap}$ is the rate of evaporation (kg s^{-1})

h_{fg} is the latent heat of vaporization (kJ kg^{-1})

Q_e is the water lost to evaporation (m^3 s^{-1})

Alternately, the following equation can be used to estimate the rate of evaporation **(Piedrahita, 1991)**:

$$Q_e = 2.241x10^{-3} xV_2 x(e_s - e_a) \quad (3.31)$$

Where

Q_e is the rate of evaporation ($m^3\ s^{-1}$)

V_2 is the wind velocity 2 meters above the pond surface ($m\ h^{-1}$)

e_s is the saturated vapor pressure (Pa)

e_a is the air vapor pressure (Pa)

$$e_s = 25.374xExp\left(17.62 - \frac{5271}{T_{water}}\right)x\left(\frac{760mmHg}{101300Pa}\right) \quad (3.32)$$

$$e_a = RHx25.374xExp\left(17.62 - \frac{5271}{T_{air}}\right)x\left(\frac{760mmHg}{101300Pa}\right) \quad (3.33)$$

Where

RH is the Relative Humidity (%)

3.2. Mass Balance:

3.2.1. Dissolved Oxygen Balance (DO):

The DO in this model had a number of interactions to consider. Firstly, the fish consume oxygen through the process of respiration. Secondly, the process of nitrificationin the biofilter consumes oxygen, as the process is aerobic. On the other hand, the water receives oxygen through water agitation as it is pumped through the system and from the blower.

The model considered the dissolved oxygen consumed through fish metabolism and biofilteration and the aeration through the water pumping cycle from the fish tank (figure 3.3).

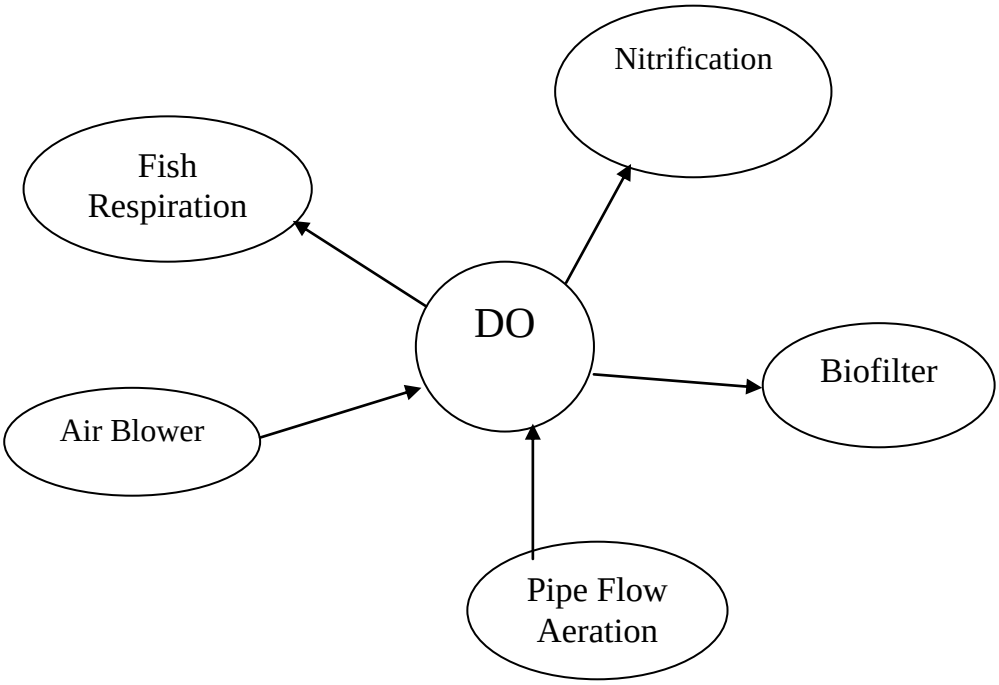

Figure (3.3): Dissolved oxygen model

The required oxygen supplementation is a sum of these four values. Equation – summarizes the terms included in the model.

$$DO_{FR} + DO_B + DO_N = DO_{\sup} + DO_{PF} \quad (3.34)$$

Where

DO_{FR} is dissolved oxygen consumption through fish respiration

DO_B is dissolved oxygen consumption through the biofilter

DO_N is dissolved oxygen consumption through nitrification

DO_{PF} is dissolved oxygen addition through pipe flow

DO_{sup} is required oxygen supplementation (air blower)

The rate of oxygen consumption through fish respiration can be calculated on water temperature and average fish weight. This calculation is shown in the following equation **(Ali, 1999)**

$$DO_{FR} = 2014.45 + 2.75W - 165.2T_{water} + 0.007W^2 + 3.93T_{water}^2 - 0.21WT_{water} \quad (3.35)$$

Where

DO_{FR} is dissolved oxygen consumption through fish respiration, mgO_2/kg fish. hour

W is average of individual fish mass, g

T is water temperature, ˚C

The correlation coefficient for the equation was 0.99. Data used in preparing the equation ranged from 20 to 200 g for fish weight and from 24 to 32°C.

The rate of oxygen consumption through nitrification is calculated in terms of Total Ammonia Nitrogen (TAN) that is converted from ammonia to nitrate. The rate found in the literature is 4.57 g-O_2/g-TAN **(Lawson, 1995).** The bacteria in the biofilter are a second source of oxygen consumption. Lawson explains that the biofilter oxygen demand is approximated 2.3 times the BOD_5 production rate of fish **(Lawson, 1995).** He further provides BOD_5 excretion rate of 2160 mg-O_2/kg fish.day for channel catfish, another warm water species. The oxygen consumption of the biofilter is calculated using Equation

$$DO_N = \frac{(2.3)(BOD_5)(BM)}{(24)} \quad (3.36)$$

Where

DO_N is dissolved oxygen consumption through nitrification, mgO_2/ hour

BOD_5 is average unfiltered BOD_5 excretion rate, 2160 mg-O_2/kg fish. day

BM is biomass, kg-fish

The water pumping cycle was a source of oxygen addition to the system. The amount of oxygen addition through the water pumping cycle was calculated on an hourly basis. The method of calculating aeration from a pipe is detailed by Moore and Boyed **(Moore and Boyd, 1984).** For this model the device type chosen was a straight pipe discharge. A straight pipe discharge with a flow rate of approximately 50 gpm has an aeration efficiency of 25.1% and an oxygen transfer rate of 36.8 g-O_2/hr **(Moore and Boyed, 1984).**

$$DO_{PF} = \frac{PC \times f \times E \times OTR}{W} \times 10^6 \qquad (3.37)$$

Where

DO_{PF} is required oxygen supplementation, mgO_2/kg fish.hour

PC is pump cycle length, hr

f is pumping frequency, l hr^{-1}

E is efficiency, %

OTR is oxygen transfer rate, kg-O_2/hr

This model sums the DO_{FR}, DO_B**,** DO_N, and DO_{PF} to determine the supplemental dissolved oxygen demand in kilogram per hour. This number can be used to estimate the oxygen consumption if pure oxygen transfers system is used. However, if the farmer is using an air blower, then the model further calculates the required blower size as follows. This method assumes the farmer will use fine diffusers or airstones to aerate. The potential oxygen generation using a blower is calculated using standard

aeration efficiency method (SAE). The SAE using fine diffusers is approximately 2 kg O_2/kW.hr was used **(Lawson, 1995)**. An air blower efficiency of 80% is assumed as the actual efficiency is difficult to determine experimentally. Therefore, the size of the required air blower is calculated using Equation

$$AB = \frac{DO_{\sup}(24)}{(SAE)(E)(HPC)} \tag{3.38}$$

Where:-

AB is size of airblower, hp

SAE is standard aeration efficiency, kg-O_2/kW-hr

DO_{sup} is total dissolved oxygen demand, kg-O_2/day

E is efficiency, %

HPC is horsepower to watts conversion factor, 0.7467 kW/hp

3.2.2. Nitrogen Balance:

The production of nitrogenous waste products through metabolism and nitrification are biological in nature because they are caused by living organisms. The addition of nitrogenous waste products through replacement with new water is controlled by the farmer. In an aquaculture setting the total ammonia nitrogen (TAN) is the most important form of nitrogen as it is the most toxic. The two components of TAN unionized ammonia and the ammonium ion exist in a balance based on the pH and water temperature of the system. As the pH rises the unionized ammonia becomes the predominate species which is very dangerous as unionized ammonia is much more toxic than ammonia. However, at this point it is only possible to measure the TAN rather than the individual ions. The mole fraction of ammonia production can be calculated using Equation **(Ali, 1999):**

$$AP = 16.38 - 0.49W + 1.23T + 0.0019W^2 - 0.00251WT \quad (3.39)$$

Where:-

AP is ammonia production, mg NH_3/kg fish.hr

The correlation coefficient for the equation was 0.98. Data used in preparing the equation ranged from 20 to 200 g for fish weight and from 24 to 32°C.

In the model the production of TAN is a function of the temperature and individual weight of fish. This value is important to know for two reasons. Firstly, the production of nitrate as a function of TAN can be calculated to determine the nitrate production capacity of the system. Secondly the size of the required biofilter can be calculated.

The production of nitrate from TAN is part of the nitrification process. The model assumes that the biofilter will convert all of the TAN to nitrate. Lawson reported a value of 4.34 grams of nitrate-nitrogen for every gram of TAN production **(Lawson, 1995).**

The size of required biofilter can be easily calculated once the type of biofilter has been selected. In this model uses rotating biological contactors.

The first calculation is to determine required surface area. Required surface area depends on ammonia production (mg TAN/kg fish. hour) and the maximum ammonia loading rate (ammonia removal per unit of media specific surface area per hour). The ammonia loading rate, which of 11.25 mg TAN m^{-2} $hour^{-1}$, was used in the model **(Rijn and Rivera, 1990)**

$$R.S.A. = AP / A.L.R. \quad (3.40)$$

Where

R.S.A. is required surface area, m^2/kg fish

Ap is ammonia production, mg TAN/kg fish. hour

A.L.R. is ammonia loading rate, mg TAN/m^2 of surface area/hour

$$T.S.A. = R.S.A. \times W_t \quad (3.41)$$

Where

T.S.A. is total surface area, m^2

W_t is total weight of fish, kg

Next, the volume of biofilter media can be calculated knowing the specific surface area of the biofilter media

$$V_b = T.S.A. / S_b \quad (3.42)$$

Where

V_b is required volume of biofilter media, m^3

S_b is specific surface area, m^2 m^{-3}

3.2.3. Solids Balance:

The effectiveness of the double drain at concentrating solids within the bottom center drain discharge can be illustrated by a steady state solids balance written over the culture tank **(Tommons *et al.*, 2002)**.

$$\{Q.TS_{in}\} + \{TS_P\} = \{Q_{out1}.TS_{out1}\} + \{Q_{out2}.TS_{out2}\} \quad (3.43)$$

Where:

Q is the water flow rate, m^3/day

Q_{out1} is the flow rate leaving the lateral drain, m^3/day

Q_{out2} is the flow rate leaving the main drain, m^3/day

TS_{in} is the TS concentration entering unit, kg m^{-3}

TS_{out1} is the TS concentration leaving the lateral drain, kg m^{-3}

TS_{out2} is the TS concentration leaving the main drain, kg m^{-3}

TS_P is the TS production rate, kg TS produced per day

TS resulted from feeding can be determined by using the following equation:

$$TS_P = A_{TS}.R_{feed}.\rho_{fish}.V_{\tan k} \quad (3.44)$$

Where:

A_{TS} is the TS produced as a proportion of feed fed, (25% of feed fed) as according to **Hopkins and Manci (1989)** and **Losordo and Hobbs (2000)**

R_{feed} is the feeding rate, kg feed per kg fish per day

ρ_{fish} is the density of fish in the culture tank, kg fish per m^3

V_{tank} is the volume of water contained within culture tank, m^3

A simplified approach to solids sedimentation is used here, where solid removal rate by sedimentation (TS_{out1}, kg m^{-3}) is:

$$TS_{out1} = TS_{in} \text{ (fraction removed) (exchange rate, l/day)}$$

$$TS_{out1} = TS_{in} (v_s / HLR) (Q/V) \quad (3.45)$$

It could be rewritten as:-

$$TS_{out1} = TS_{in} (v_s / d) \quad (3.46)$$

Where:

v_s is the particle mean settling velocity (m h^{-1})

d is the water depth (m)

HLR is the hydraulic loading rate (m^3 m^{-2} h^{-1})

This derivation represents solid sedimentation in terms of first order, exponential decay kinetics, a simplification that has been used exponential decay kinetics, a simplification that has been used by others **(Fritz *et al.*, 1979; Fritz, 1985; James, 1984; Piedrahita and Giovannini, 1989)**. The sedimentation term represents one term in the differential equation for TS_{in}, with additional sources and sink added as needed. If the water body is stratified, then solids settle from the top layer to the bottom layer and from the bottom layer and from the bottom layer to the bottom surface of the facility unit. Any upward vertical mixing of solids is considered by the use of reduced settling velocities. Typical particle settling velocity used in model is given by **(Chesness *et al.*, 1975; Chen *et al.*, 1994)** mention that solids of

fish in basin designed for sedimentation 0.83 to 5 m h^{-1} for 65 to 90% of total particulate solids.

3.3. Energy Consumption:

Energy is consumed by air and water pumps, aerators and water heaters. Power (PW) is expresses as kilowatts (kW) or kilowatt-hours (kW hr day^{-1}). Conversion of joules (J), watts (W) and work (N-m s^{-1}) is based on the equivalency: W=J s^{-1} = N-m s^{-1}. Energy can be provided as electrical or fuel energy, where kilowatt-hours are used as internal calculation units are converted to equivalent fuel volumes when energy resources are reported. The conversion is based on reported heats of combustion **(Jensen, 1983)**: diesel (3 J l^{-1}), gasoline (2.67 J l^{-1}), methanol (1.44 J l^{-1}), propane (1.97 J l^{-1}) and methane (natural gas, 2.86 J m^{-3}).

For electrical power, current (I, amperes), voltage (V, volts), motor power factor (PF, 0-1, e.g. 0.9) and electrical power consumption (PW, kW) of single and three phase (Φ) motors are related by **(Jensen, 1983)**:

$$PW = PF\ I\ V\ /(1000\ W/kW) \quad (3.47)$$

$$PW = PF\ I\ V\ 3^{0.5}\ /(1000\ W/kW) \quad (3.48)$$

These relationships hold for other uses of electrical power (e.g. resistive heaters) where PF is dropped from the equations. Power and amperage values are calculated over the course of facility simulations and used in resource accounting and sizing of electrical supplies, thermal protection, and motors. Voltage and phase values are user specified and default values are based on power levels (1Φ 120V AC for ≤ 1.0 kW; 1Φ 220V AC for 1.0 – 4.0 kW; 3Φ 220V AC for ≥ 4.0 kW). Motor power input (PW; electrical or fuel energy) and output power (PW_{bp}; brake power, mechanical energy) are related by the motor efficiency rating (e; 0.8) where PW_{bp} = e PW.

3.4. Fish Growth Model:

Fish growth is affected by environmental and physical factors, such as water temperature, dissolved oxygen, unionized ammonia, photoperiod, fish stocking density, food availability, and food quality.

In order to calculate the fish growth rate (g day^{-1}) for individual fish, the following model was used **(Yang Yi, 1998)** as it includes the main environmental factors influencing fish growth. Those factors are temperature, dissolved oxygen and unionized ammonia.

$$FGR = \left(0.2919\,\tau\,\kappa\,\delta\,\varphi\,h\,f\,W^{m}\right) - kW^{n} \qquad (3.49)$$

Where:

τ is the temperature factor ($0 < \tau > 1$, dimensionless).

κ is the photoperiod factor ($0 < \kappa > 1$, dimensionless).

δ is the dissolved oxygen factor ($0 < \delta > 1$, dimensionless).

φ is the unionized ammonia factor ($0<\varphi>1$, dimensionless).

h is the coefficient of food consumption (g^{1-m} day^{-1}).

f is the relative feeding level ($0 < f > 1$, dimensionless).

k is the coefficient of catabolism.

h, m, n are constants

3.4.1. Water Temperature Effects:

Water temperature affects the food intake **(Brett, 1979)**. **Caulton (1978)** described the relationship between temperature and feed intake for tilapias. Food intake rate reaches the maximum value when the temperature is in an optimal range. If the temperature is outside the optimal range, the food intake rate decreases. Food intake stops when the temperature is the limit range. The temperature factor (from 0 to 1) can be described as **(Svirezhev *et al.*, 1984 and Bolte *et al.*, 1995)**.

$$\tau = EXP\left\{-4.6\left[\frac{T_{opti} - T}{T_{opti} - T_{\max}}\right]^4\right\} \qquad \text{if} \quad T \prec T_{opti} \qquad (3.50)$$

$$\tau = EXP\left\{-4.6\left[\frac{T - T_{opti}}{T_{\max} - T_{opti}}\right]^4\right\} \qquad \text{if} \quad T \geq T_{opti} \qquad (3.51)$$

Where:

T_{min} is the below this temperature fish stop eating, ºC

T_{max} is the above this temperature fish stop eating, ºC

T_{opti} is the optimum temperature for fish taking food, ºC

The values of the optimal and limit temperatures vary with species. **Lawson (1995) and Nath (1996)** suggested that T_{min} = 15 ºC**,** T_{max} = 40 ºC**,** and T_{opti} = 28 ºC, for tilapia. The catabolism term is also affected by temperature. The effect is described as **(Nath, 1996)**:

$$\kappa = \kappa_{min}\ \exp\left[s(T - T_{min})\right] \qquad (3.52)$$

Where:

K_{min} is the coefficient of fasting catabolism at T_{min}, $g^{1-n}\ hr^{-1}$

s is a constant

The κ_{min} and s can be determined through model calibration and κ_{min} = 0.025 and s = 0.015 were found suitable for tilapia in the model developed by **Nath (1996)**. The range of κ was 0.0319 to 0.0468 from an earlier published model **(Liu and Chang, 1992)**. In early models, fish growth was simulated on a daily basis **(Nath, 1996; Liu and Chang, 1992)**.

3.4.2. Dissolved Oxygen Effects:

The effect of DO on fish growth is described in three stages. When DO is below the minimum limits level, DO_{min} fish feeding stops. When DO is above a critical level, DO_{crit}, DO has

no effect on feeding. When DO is between DO_{min} and DO_{crit} feeding is affected by DO **(Nath, 1996)**.

$$\delta = 1.0 \qquad \text{if } DO \succ DO_{crit} \tag{3.53}$$

$$\delta = \frac{DO - DO_{min}}{DO_{crit} - DO_{min}} \qquad \text{if } DO_{min} \le DO \le DO_{crit} \tag{3.54}$$

$$\delta = 0.0 \qquad \text{if } DO \prec DO_{crit} \tag{3.55}$$

The DO_{crit} and DO_{min} used in the present model were 3.0 and 0.3 mg L^{-1}, respectively **(Yang Yi, 1998)**.

3.4.3. Unionized Ammonia Effects:

Unionized ammonia, NH_3, is toxic to fish **(Boyd, 1979)**. The effects of unionized ammonia can be simulated using an equation similar to that for DO **(Nath, 1996)**. When NH_3 is higher than NH_{3max}, then the fish stop feeding. When NH_3 is lower than the critical value, NH_{3crit}, then there is no effect on feeding. When the concentration of NH_3 is higher than the critical value, NH_{3crit} and lower than a maximum value, NH_{3max}, then food intake will decrease as the concentration of NH_3 increases. The function can be decreased as **(Nath, 1996).**

$$\varphi = 1.0 \qquad \text{if } NH_3 \prec NH_{3crit} \tag{3.56}$$

$$\varphi = \frac{NH_{3max} - NH_3}{NH_{3max} - NH_{3crit}} \qquad \text{if } NH_{3crit} \le NH_3 \le NH_{3max} \tag{3.57}$$

$$\varphi = 0.0 \qquad \text{if } NH_3 \succ NH_{3crit} \tag{3.58}$$

Abdalla (1989) determined that NH_{3max} = 1.4 mg L^{-1} and NH_{3crit} = 0.06 mg L^{-1} for Nile tilapia.

3.4.4. Photoperiod Effects:

Caulton (1982) indicates that many cultured fish species including tilapias tended to feed only during daylight hours.

Photoperiod factor (κ), based on 12:12 h of light-dark cycle and used for adjusting daily food consumption, is expressed as follow:

$$\kappa = \text{photoperiod} / 12 \tag{3.59}$$

Where, photoperiod is the day time between sunrise and sunset (h), which can be estimated from sunrise and sunset hour angle calculations **(Hsieh, 1986)**. The constant of 12 is the photoperiod in the 12:12 h of light dark cycle.

3.4.5. Food Effects:

The fish growth rate is dependent on the amount of food and the quality of available. To determine the value of the relative feeding level "*f*" to be used in our case, we used the model at progressive values of "*f*" starting from zero, step 0.01 up to 1.0 and compare the results with those obtained by **Racoky (1989)**, data presented in table (4.11). The reason of using **Racoky's** data to assess the value of the relative feeding level "*f*" is that the **Racoky** "*f*" data was determined from semi-intensive tilapia culture. This similar to our target. The determined value of "*f*" was 0.37. This value was used in the model.

The value of parameters "h", "n" and "m" were assumed to be 0.80 **(Bolte *et al.*, 1995)**, 0.81 **(Nath *et al.*, 1994)** and 0.67 **(Ursin, 1967)**.

Equation is used to calculate the accumulate growth starting by one gram of individual fish to the marketable weight of 250 gram.

$$\mathrm{W_n} = W_{n-1} + DGR_n \tag{3.60}$$

$$\mathrm{FR} = 17.02 \times \mathrm{e}^{\left((\mathrm{L_n} W_n + 1.14)^2 / -19.52 \right)} \tag{3.61}$$

$$\text{Amount of feeding } (\mathrm{kg}/\ day) = FR \times W_n \times No. \text{ of fish}/100000$$

Where:

DGR is the daily growth rate, g

W is the average fish weight, g

n is the number of day from the start

FR is the feeding ratio, % of body fish

All computational procedures of the simulation model were carried out using Excel spreadsheet. The computer program consisted of three parts in addition to the input parts. The first part was devoted to heat balance for predicting the water temperature. The second part was devoted to mass balance for predicting the oxygen consumption, ammonia production, nitrate production and solids generation. Finally, the third part was used to predict the fish growth rate under different condition.

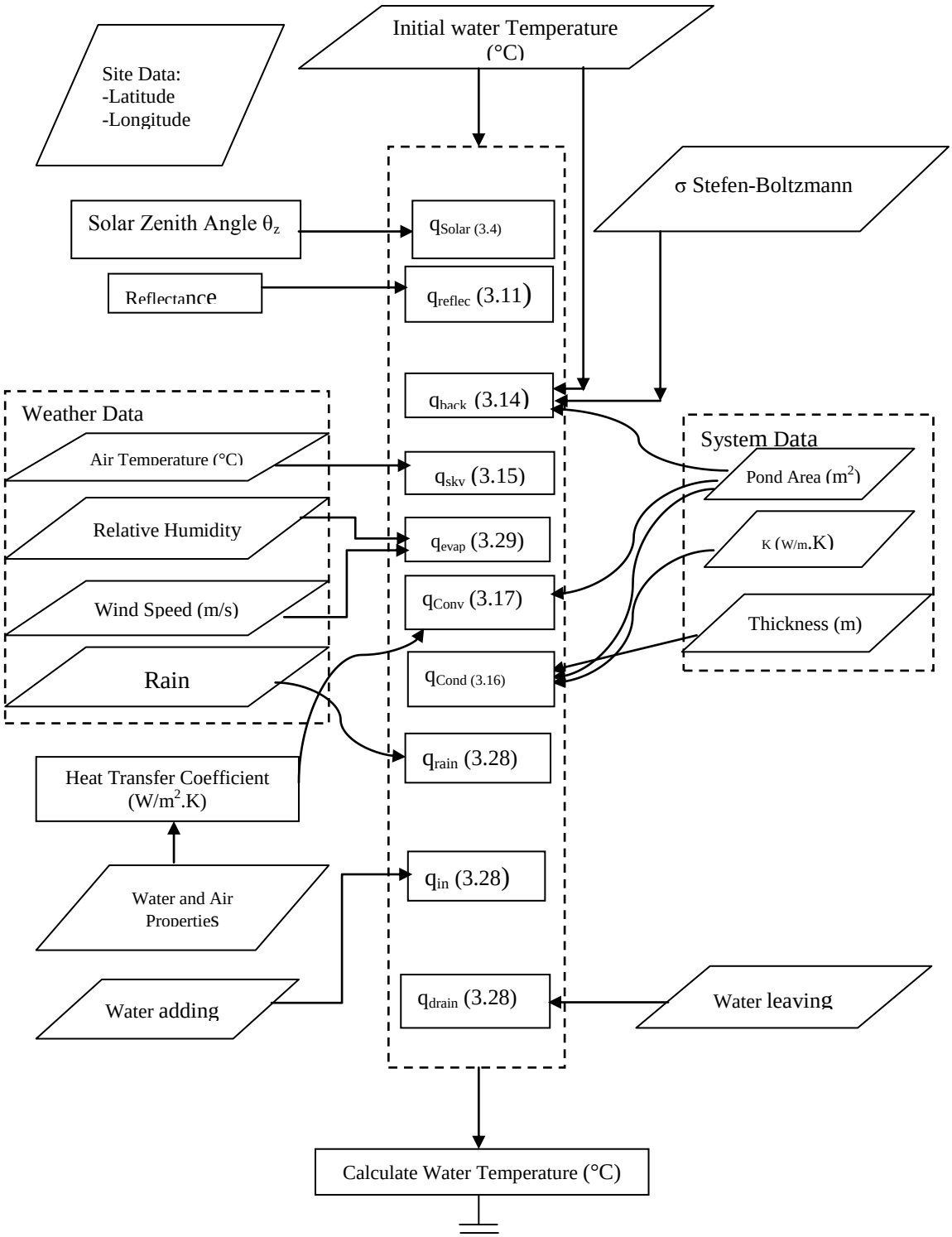

Figure (3.4): Flowchart of the model

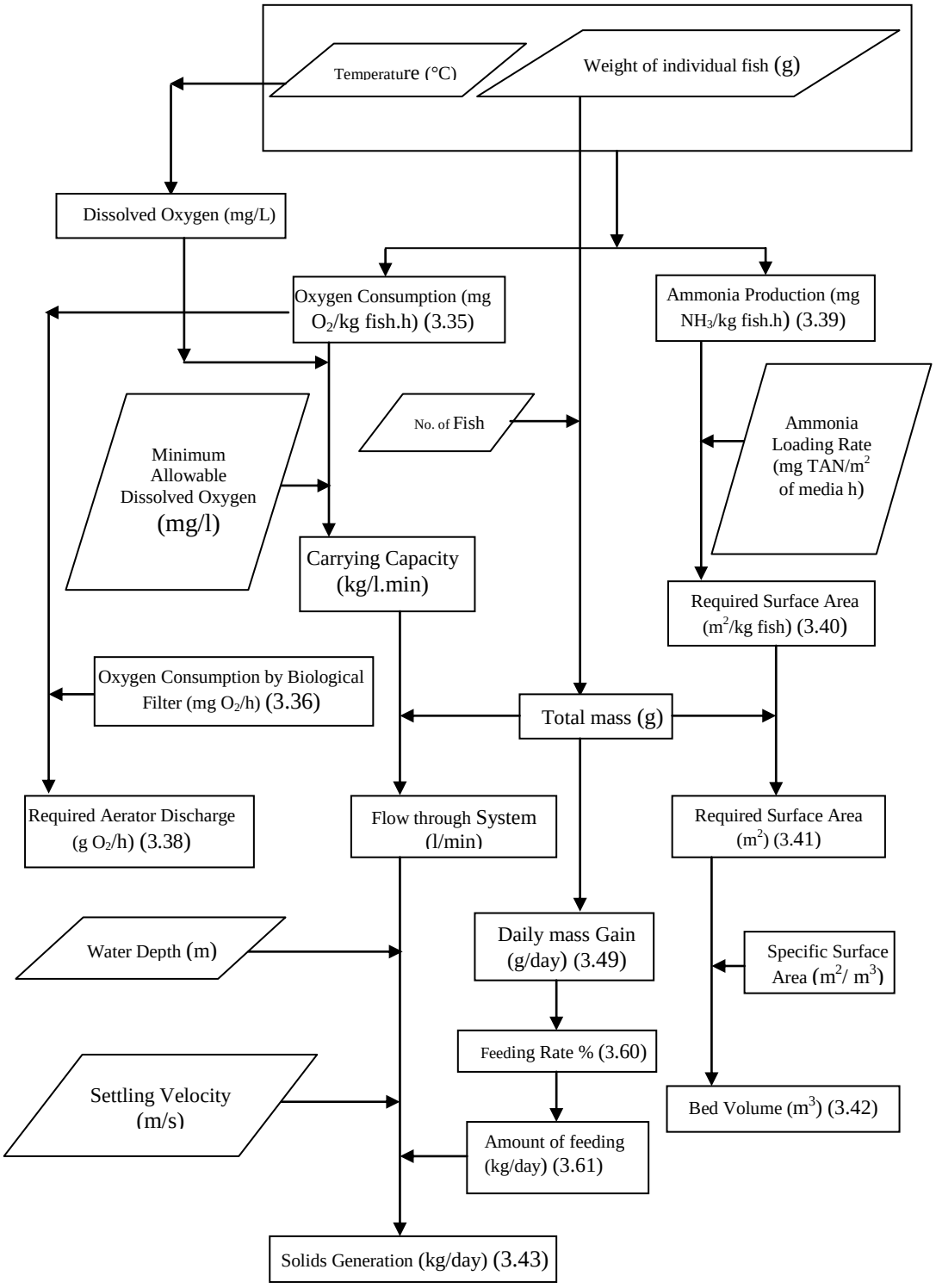

Figure (3.4): Continued flowchart of the model

4. MATERIALS AND METHODS

The experiment was carried out at Agricultural Engineering Department, Faculty of Agriculture, Moshtohor, Benha University. During the period of March to July, 2011. Table (4.1) shows the input parameters of the experiment. The fish was brought from the General Authority for Fish Resources Development of A.R.E. in El-Knater El-Khiria, Kalubia, Eygpt.

Table (4.1): The experimental inputs of the experiment.

Date of start	6/ 3/ 2006
Initial average mass of individual fish (g)	4
Number of total fish	1000
Water volume in fish tank (m^3)	5.65
Initial density (kg m^{-3})	0.8

4.1. Materials:

4.1.1. System Description:

Figure (4.1) illustrates the experimental setup. It shows the recirculating aquaculture system (RAS) which consists of fish tank, hydrocyclone, screen filter, biological filter and aeration tank.

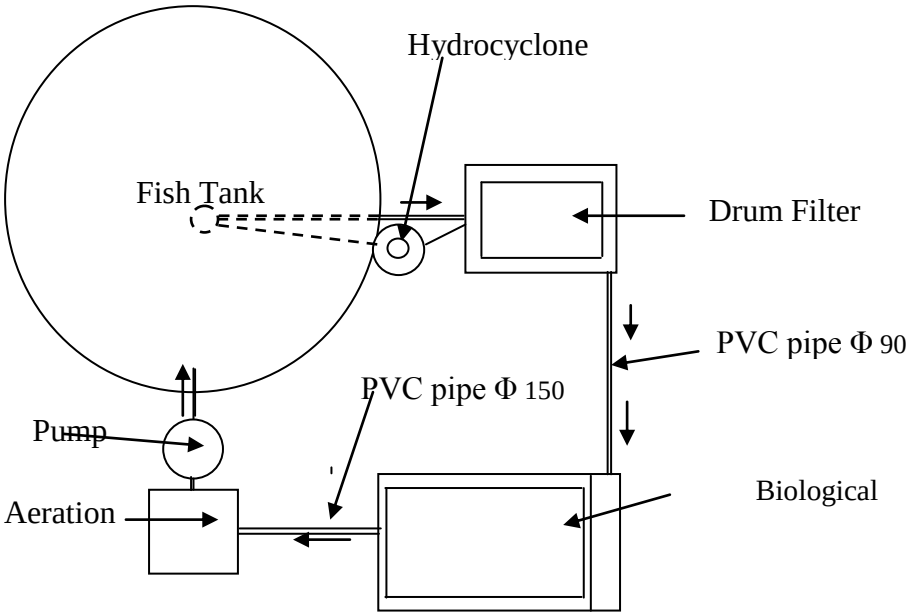

Figure (4.1): Schematic diagram of the recirculating aquaculture system (RAS).

4.1.1.1. Fish Tank:

The tank is a circular in shape made of fiberglass which was used for fish culture. Its volume is 7 m^3 and has a diameter of 3 m. The tank was provided with double drainage openings in the center. One of them for the settleable solids and the other for the suspended solids. The first opening allows for 1 – 10 % of the total flow leaving the tank. The second opening allows of 90 - 99 % of the total flow to leave the tank. The waste particles settle and are retained in the sludge collector and the clarified water exits the sludge collector at the top and flows by gravity for further treatment. The level of water was controlled by standpipe.

4.1.1.2. Hydrocyclone:

The hydrocyclone is used to remove the settleable solids. It is made of stainless steel and has inlet diameter of 30 mm, overflow diameter of 50 mm, height of 350 mm, top diameter of 335 mm, underflow diameter of 50 mm and cone angle of 68^{o}. Figure (4.2) shows the dimensions of the hydrocyclone.

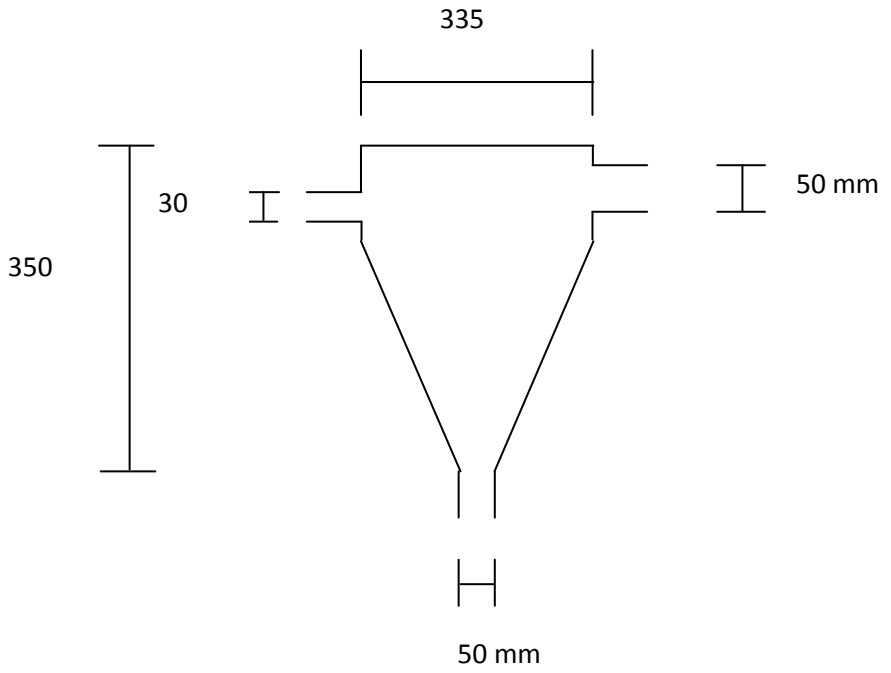

Fig (4.2): The dimensions of the hydrocyclone.

4.1.1.3. Screen Filter:

The drum screen filter is used to remove the suspended solids and has dimensions of 0.7 m in diameter and 0.8 m long. The water enters the open end of a drum filter and passes through a screen attached to the outer surface of the filter. The filter was made from stainless steel manufactured at a private

company for steel industry. The fine mesh (silk 60 micron) was used as a media of screening. The filter was driven by one motor of 0.5 hp power and 1500 rpm and controlled by a gearbox to reduce the rotation speed 500 times to give the recommended rotation speed (3 rpm) **(Libey, 1993)**. Figure (4.3) shows elevation, plan and side view for the drum screen filter.

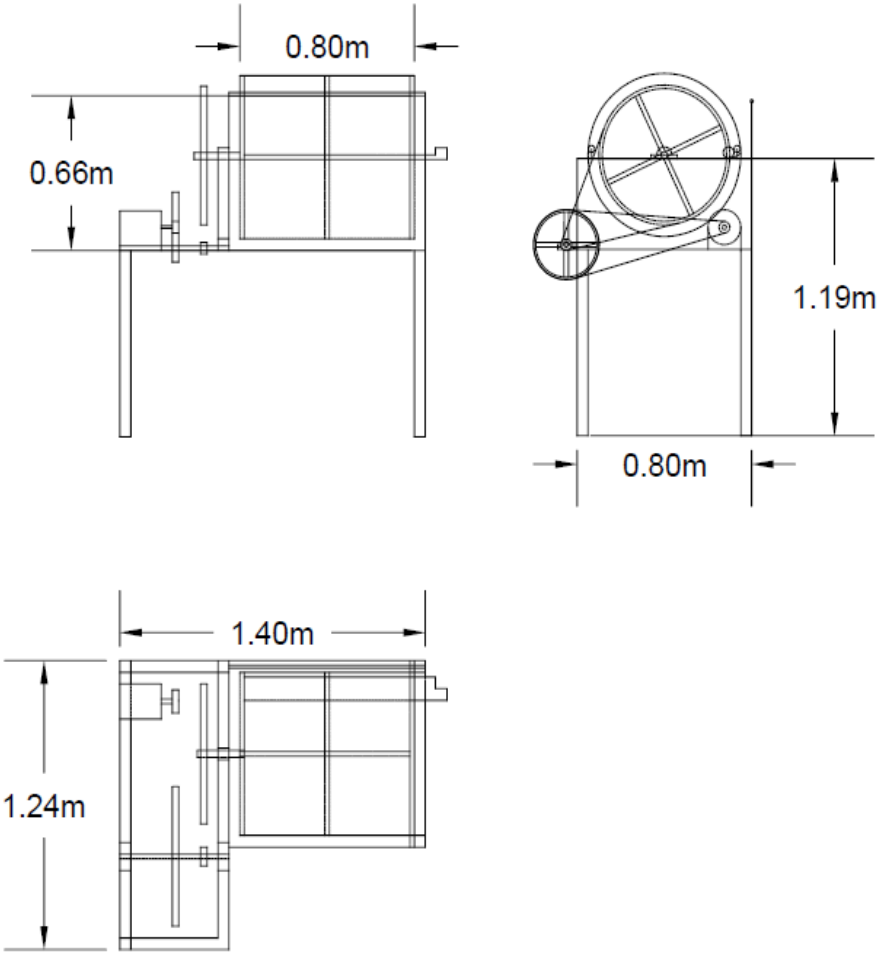

Figure (4.3) Elevation, plan and side view for the drum screen filter.

4.1.1.4. Biological Filter:

Rotating Biological Contactor (RBC) was used in this system, approximately 40 percent of the substrate is submerged in the recycle water. The filter dimensions were 1.2 m in diameter and 1.5 m long. The filter was made from stainless steel. Plastic sheets were used as a media. The filter was driven by one motor of 1.5 hp power and 1500 rpm and controlled by a gearbox of reduction ratio of 500 to give the recommended rotation speed (3 rpm) **(Ali *et al.*, 2006)**. Figure (4.4) shows elevation, plan and side view for the rotating biological contactor.

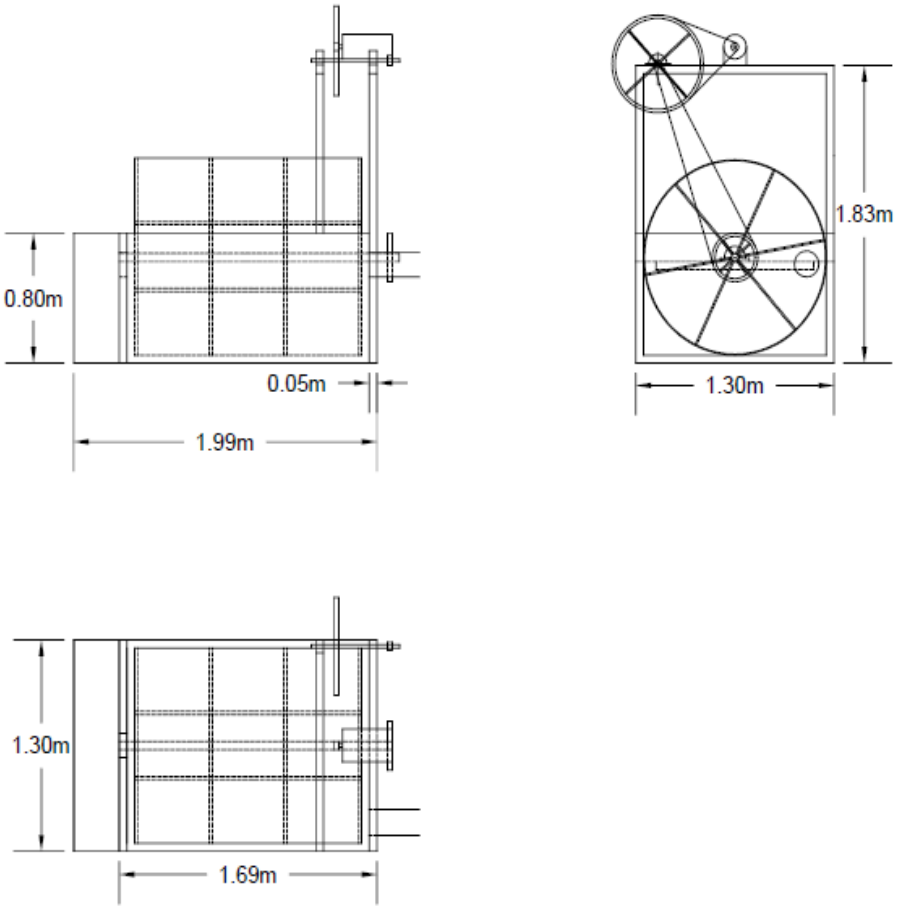

Figure (4.4) Elevation, plan and side view for the rotating biological contactor.

4.1.1.5. Aeration:

Air-contact aeration system was used to transfer all gases present in atmospheric air into water. This system can only increase dissolved oxygen concentrations to saturation, and the efficiency of oxygen transfer declines as the dissolved oxygen concentration in water increase **(Boyd, 1982).** The air was

pumped to the aeration tank by an air blower, under various pressures through leaky pipes of 16 mm in diameter of different lengths. The tank has a dimensions of 1 x 1x 1 m^3 and was fully filled with water.

4.1.1.6. Accessories:

1. Pumps:

The pumps specifications which are used in the experiment are listed in table (4.2).

Table (4.2): Specifications of pump.

Origin of manufacture	China
Type	Mero
Flow Rate	Maximum 36 m^3/h
Head	Maximum 18 m
Power	2 hp

2. Air blower:

The air blower specifications which are used in the experiment are listed in table (4.3).

Table (4.3): Specifications of air blower.

Origin of manufacture	Italy
Model	C.C.P. Parma
Flow Rate	Maximum 125 m^3/h
RPM	2800
Power	2.5 hp 380V 50Hz

3. Biological filter motor:

The motor drives of biological filter specifications which are used in the experiment are listed in table (4.4).

Table (4.4) Specifications of Motor drives of biological filter.

Origin of manufacture	Egypt
Model	Military factory 127
Rpm	1500
Power	1.5 hp 380V 50Hz

4. Screen filter motor:

The motor drives of screen filter specifications which are used in the experiment are listed in table (4.5).

Table (4.5): Specifications of Motor drives of screen filter.

Origin of manufacture	China
Model	TY 144
RPM	1500
Power	0.5 hp 220V 50Hz

3.1.2. Flow Pattern:

Figure (4.1) illustrates the water recycle system. The effluent water of the rearing tank was treated through a screen filter and a biological filter before it was returned to the fish tank. The water drains from the fish tank to the filter tank, which was trapping feces and uneaten feed. then, water passes through the screen filter, then, the water inters the biological filter. The water leaves the biological filter to the aeration tank, and then the pumps return it to fish tank. The air was pumped to the aeration tank by air blower through leaky pipes of 16 mm in diameter.

The use of fresh water by the system was low. Daily partial a replacement of water with average of 1-2% was carried out to reduce the accumulation of nitrate, and supplement the water losses due to the evaporation.

4.1.3. Instruments:

Scanning thermometer was used to measure temperature (figure 4.5). Dissolved oxygen was measured by a dissolved

oxygen meter as show (figure 4.6). Ammonia (NH_3) as nitrite (NO_2) and nitrate (NO_3) was measured by Speckol 11(figure 4.7). The pH was measured by the pH meter (and figure 4.8). Voltage (volt) and current (ampere) were measure by the Avometer (figure 4.9). The specifications of these devises are listed in tables (4.6 to 4.10).

Table (4.6): Specifications of scanning thermometer.

Origin of manufacture	USA
Model	Digi-Sense 69202-30
Range	-250 to 1800°C (-418 to 3272°F)
Resolution	0.1°/1° selectable to 999.9°; 1° above 1000°
Accuracy	J, K, T, E, N: ±0.1% of reading, ±0.5°C (±0.8°F) above -150°C; ±0.25% of reading, ±1°C (±2°F) below -150°C; R, S, B: ±0.1% of reading, ±2°C (±4°F)
Memory	up to 4680 sets of readings
Sampling Rate	from 4 seconds/12 channels to 99 minutes 59 seconds/12 channels
Software	Included
Display	12-character alphanumeric LCD
Dimensions	L×W×H : 265×215×90 mm
Shipping Weight	700 g

Figure (4.5): Image of thermocouple.

Table (4.7): Specifications of dissolved oxygen meter.

Origin of manufacture	Italy
Model	HI 9143
Range	0.0 to 45.00 mg L^{-1} O_2 0.0 to 300 % O_2 0.0 to 50.0 ◌̊c
Resolution	0.01 mg L^{-1} O_2 0.1 % O_2 0.1 ◌̊C
Accuracy	± 1.5% full scale mg L^{-1} O_2 ± 1.5% full scale % O_2 ± 0.5 ◌̊C
EMC Typical Deviation	± 0.3 mg L^{-1} O_2 ± 3.5 % O_2 ± 0.5 ◌̊C
Calibration	Automatic in saturated air
Temperature Compensation	Automatic from 0 to 50 ◌̊C
Altitude compensation	0 to 1900 m 100 m resolution
Salinity Compensation	0 to 40 g L^{-1} 1 g L^{-1} resolution
Operation Conditions	From 0 to 50 ◌̊C Humidity 100% maximum
Battery	4×1.5 V AA, 200 hour continuous use. Auto shut-off after 4 hours. Power plug for 12 VDC supply
Dimensions	L×W×H : 196×80×60 mm
Shipping Weight	425 g

Figure (4.6): Image of the dissolved oxygen meter.

Table (4.8): the Specifications of Spekol 11.

Origin of manufacture	UK
Model	11
Wavelength	349-850nm
Bandwidth	5nm
Ranges	0 to 100.0% T. 0 to1.999Abs 0.1 to 1000 Concentration
Resolution	0.1% T. 0.001Abs. 0.1to1.0 Concentration ± 1 nm λ
Wavelength Accuracy	± 2 nm
Photometric Accuracy	±1% or±0.005A whichever is greater
Photometric Noise levels	< 0.001A
Photometric Stability	0.004A/Hr after warm-up
Stray Radiant Energy	< 0.5% at 340nm
Readouts	3 digit LED, %T, Abs, Conc. (20nm) 3 digit LED, λ
Outputs	Analogue (0–IV for 0–1A) Centronics parallel port RS232 serial port
Light Source	Tungsten Halogen
Power	100/115/200/230 Vac ±10% 50/60Hz
Size	340 x 460 x 350mm
Weight	11Kg

Figure (4.7): Image of the spekol 11.

Table (4.9): The specifications of pH Meter.

Origin of manufacture	USA
Model	JENCO 1671
pH Range	-2 to 16.00
Resolution	0.01 pH
Relative Accuracy	0.1 1 digit
Slope	80 to 120%
Auto-Buffer-Recognition	1.68, 4.01, 7.00, 10.01, 12.46
Temperature Range	0 to 100 ºC
Temperature Resolution	0.1 ºC
Display	Custom LCD
Inputs	1 BNC, 1 pin tip, ATC, Power, RS232
Power Requirements	AC line, 110 V, 220 V or 240 V
Dimensions	250 (L) x 250 (W) x 10(H) mm

Figure (4.8): Image of the pH Meter.

Table (4.10). The specifications of avometer.

Origin of manufacture	China
Model	DT266 clamp meter
Ac clamp on Current ranges	200, 1000A
Dc voltage range	1000 V
AC Voltage Range	750Vac
Resistance full scale	20K ohms
Overload protection	250V rms ac
Diode test	forward diode voltage drop
Continuity test	Audible sound when below 50 ohms
Weight	approx 310g including battery
Battery	12VX1 or GP23A
Fuse	250mA@250V
Measuring method	Dual-slope integration A/D Converter
Over-range indication	only digit "1" displayed
Display	LCD 3/12 digits 1999 counts updates 2-3 sec
Polarity indication	prefix "-"
Operation temperature	0 - 40 degrees C
Size	23cm x 7 cm x 3.7cm

Figure (4.9): Image of the avometer.

4.2. Methods:

Tilapia nilotica fingerlings, which were used in the experiment, were brought from the General Authority for Fish Resources Development of A.R.E. in El-Knater El-Khiria, Kalubia, Eygpt. The fish was weighed initially and every week and the flow rate was adjusted according to the growth rate. The weekly fish weight was used to adjust both of water flow rate and length of leaky pipe and air pressure of the aerator.

4.2.1. Feed Management:

Fish feeding was carried out according to the recommendations of **Rakocy (1989)** as shown in table (4.11). The feed pellet diameter was prepared according to the recommendation of **Jauncey and Ross (1982)** as shown in table (4.12).

Table (4.11): The recommended feeding rates for different size of tilapia in tanks and estimated growth rates at 28 ºC.

Weight (g)		Growth Rate (g/day)	Growth Period (day)	Feeding Rate (%) of fish mass
Initial	Final			
0.02	0.5 – 1	-	30	15 – 20
0.5 – 1	5	-	30	10 – 15
5	20	0.5	30	7 -10
20	50	1.0	30	4 – 7
50	100	1.5	30	3.5 – 4
100	250	2.5	50	1.5 – 3.5
250	450	3.0	70	1.0 – 1.5

Table (4.12): The recommended pellet size for tilapia.

Fish size (g)	Pellet diameter (mm)
Fry: first 24 hr	Liquefy
Fry: 2^{nd} – 10^{th} day	0.5
Fry: 10^{th} – 30^{th} day	0.5 – 1.0
1 -30	1 – 2
20 – 120	2
100 – 250	2
> 250	4

4.2.2. Sampling and Measurements:

Water samples were taken, at inlet and outlet of the biological filter for measuring ammonia (NH_3), nitrite (NO_2), and nitrate (NO_3), at inlet and outlet of the screen filter for measuring suspended solids, at inlet and outlet of the hydrocyclone for measuring settleable solids, and inlet and outlet of fish tank for measuring alkalinity. Dissolved oxygen, temperature, pH and current and voltage were measured directly in the field. The samples were stored in refrigeration for analysis.

4.2.2.1. Heat transfer in system:

The model makes predictions regarding the heat transfer in the system. These predictions of are water temperature and supplemental heat required.

Weather data was obtained from the weather station at the Agriculture College of Moshtohor, Tokh, Kalubia, Eygpt.

4.2.3.2. Dissolved Oxygen:

The model predicts the hourly dissolved oxygen demand as a function of the temperature and the individual average weight of fish (fish and biofilter respiration). The amount of oxygen added to the system through the aeration of the pipe nozzle. However, the model averages the daily oxygen demand by the fish and biofilter throughout 24 hours.

In reality, the dissolved oxygen concentration is a function of many factors, rather than being a constant value. For example, the dissolved oxygen demand of the fish increases shortly after feeding as fish metabolism increases. Likewise, the

breakdown of uneaten feed begins to demand oxygen shortly after a feeding session. Another varying factor in the experimental date was the water pumping cycle. The oxygen added through the pipe nozzle was calculated on an hourly basis.

The last factor to consider in testing the model's ability to predict dissolved oxygen demand is the "shared" nature of the oxygen supply in the aeration tank. The aeration tank receives its aeration through leaky pipe that are supplied by a common air blower. This air blower is oversized to supply air to all of the tanks in the facility. Due to the oversized nature a bleed valve exists on the supply line to bleed off excess air as to not much back pressure on the air blower and thereby increase the operating costs. As a result of this, the model's ability to predict the computed size of blower. Instead, the dissolved oxygen concentration in the tank was monitored to show that the blower was suitability sized to maintain the DO at a suitable level.

The dissolved oxygen concentration was monitored using a DO meter.

4.2.3.3. Nitrogen:

The model predictes the daily ammonia levels (TAN). This prediction was validated experimentally by measuring the ammonia levels on a daily basis using Phnate methods.

4.2.3.4. Solids:

The model predictes the daily total solids (settleable solids and suspended solids). This experimental data collection was measured according to **(APHA, 1998)**. Processes that may

be used to remove particulate solids including sedimentation and mechanical filtration.

4.2.4. Calculations:

Fish sample were taken weekly to determine the biological parameters of the fish as following:

$$WG = W_f - W_i \tag{4.1}$$

$$SGR = \frac{\ln W_f - \ln W_i}{t} \times 100 \tag{4.2}$$

$$FCR = \frac{FI}{WG.Nt} \tag{4.3}$$

Where:

WG is the mass gained, g

W_f is the mean final fish mass, g

W_i is the mean initial fish mass, g

SGR is the specific growth rate, (% or g day^{-1})

t is the time, day

FCR is the feed conversion rate, g feed g^{-1} fish mass

FI is the feed intake, g

Nt is the final number of fish in the tank

Oxygen consumption was calculated based on the differences between the dissolved oxygen at inlet and outlet of the fish tank by the following formula:

$$OC = \frac{(DO_{in} - DO_{out}) \times Q}{W_t} \times 1000 \quad (4.4)$$

Where:

OC is the oxygen consumption, mg O_2/kg fish.h

DO_{in} is the dissolved oxygen at inlet the fish tank, mg L^{-1}

DO_{out} is the dissolved oxygen at outlet the fish tank, mg L^{-1}

Q is the flow rate, m^3 h^{-1}

W_t is the total mass, kg

Ammonia production and the biological filter efficiencies were calculated as follows:

$$AP = \frac{(NH_{3in} - NH_{3out}) \times Q}{W_t} \times 1000 \quad (4.5)$$

$$\eta_{bf} = \frac{(NH_{3in} - NH_{3out})}{NH_{3in}} \times 100 \quad (4.6)$$

Where

AP is the ammonia production, mg NH_3/kg fish.h

NH_{3in} is the ammonia concentration at inlet the biological filter, mg L^{-1}

NH_{3out} is the ammonia concentration at outlet the biological filter, mg L^{-1}

η_{bf} is the efficiency of biological filter (%)

Settleable solids removal and hydrocyclone efficiencies were calculated as follows:

$$SSR_h = \frac{SS_{h\,in} - SS_{h\,\mathrm{out}}}{1000} \tag{4.7}$$

$$\eta_h = \frac{\left(SS_{h\,in} - SS_{h\,out}\right)}{SS_{h\,in}} \times 100 \tag{4.8}$$

Where:

SSR_h is the settleable solids removed, kg m^{-3}

$SS_{h\,in}$ is the settleable solids at the inlet the hydrocyclone, mg L^{-1}

$SS_{h\,out}$ is the settleable solids at the outlet the hydrocyclone, mg L^{-1}

η_h is the removal efficiency for settleable solids (%)

Suspended solids removal and screen filter efficiencies were calculated as follows:

$$SSR_f = \frac{SS_{f\,in} - SS_{f\,\mathrm{out}}}{1000} \tag{4.9}$$

$$\eta_f = \frac{\left(SS_{f\ in} - SS_{f\ out}\right)}{SS_{f\ in}} \times 100 \quad (4.10)$$

Where

SSR_f is the suspended solids removed, kg m^{-3}

$SS_{f\ in}$ is the suspended solids at the inlet the screen filter, mg L^{-1}

$SS_{f\ out}$ is the suspended solids at the outlet the screen filter, mg L^{-1}

η_f is the screen filter efficiency for suspended solids (%)

The power required for the system was calculated by the following equation:

$$PW = PF \times I \times V \quad (4.11)$$

The energy required for the system was calculated by the following equation:

$$ER = PW \times time \quad (4.12)$$

Where:

PW is the power required, W

PF is the power factor, dimensionless

I is the current, amperes

V is the voltage, volts

5. RESULTS AND DISCUSSION

A simulation model on the recirculating aquaculture system (RAS) was developed to optimize the factors affecting the system. Water temperature, oxygen consumption, ammonia production, nitrate production, biological filter volume, solids generation and fish growth rate, were the most variables influenced by those factors. These factors such as ambient air temperature, water temperature, water depths and flow rates.

Experiment was carried out to validate the model results which include: water temperature, dissolved oxygen, ammonia, nitrite, nitrate, solids, pH, alkalinity and fish weight.

5.1. Model Validation:

5.1.1. Water Temperature:

Figure (5.1) and appendix (A) show the predicted and the measured water temperature from the recirculating aquaculture system (RAS). It could be noticed that, the average hourly temperature predicted by the model was in a good agreement with those measured by the system, where, it ranged 25.00 to 30.90˚C experimental while it was from 24.20 to 29.86˚C theoretically during the whole period of fish growth. The stratification of water temperature has been predicted well for the system.

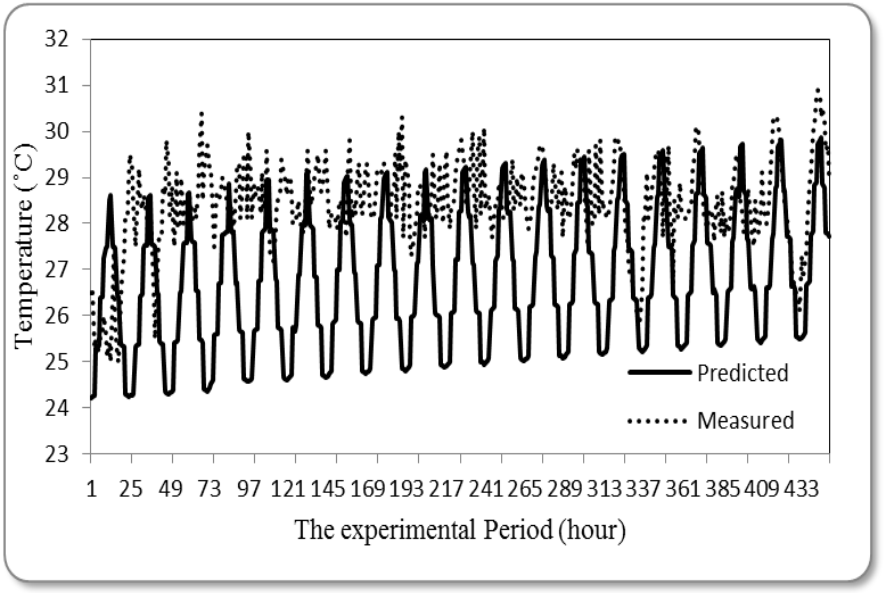

Figure (5.1): The predicted and the measured water temperature from the recirculating aquaculture system (RAS) during the long period of fish growth.

Figure (5.2) shows the predicted and the measured hourly average water temperature for the recirculating aquaculture system (RAS) during the whole growth period. The average hourly temperature predicted by the model was in a good agreement with those measured by the system, where, it ranged 28.00 to28.86˚C experimentally, while, it was from 24.66 to 28.96˚C theoretically.

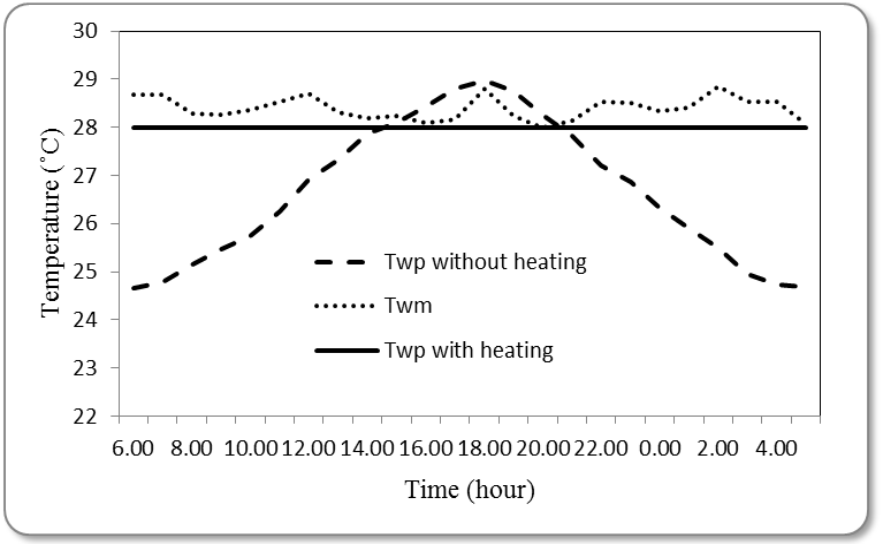

Figure (5.2): The comparison between the predicted and the measured hourly average water temperatures for the RAS.

The variations between the predicted and measured water temperatures are shown in figure (5.3). The best fit for the relationship between the predicted and the measured value was as follows:

$$T_{wp} = 7 \times 10^{-12}\, T_{wm} + 28 \qquad R^2 = 0.999 \qquad (5.1)$$

Where:

T_{wp} is the predicted water temperature, ˚C

T_{wm} is the measured water temperature, ˚C

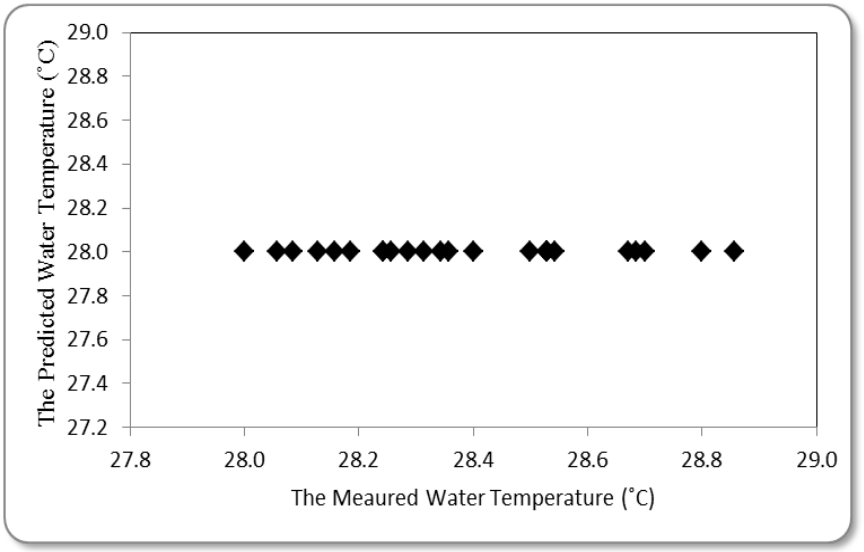

Figure (5.3): The comparison between the predicted and the measured water temperatures for the RAS

5.1.2. Oxygen Consumption:

Table (5.1) and figure (5.4a and b) show the comparison between the predicted and the measured dissolved oxygen consumption of fish for the recirculating aquaculture system (RAS). It could be seen that the predicted oxygen consumption values were between 189.13 to 457.56 mg O_2/kg fish per hour and the measured oxygen consumption values are from 197.42 to 467.61 mg O_2/kg fish per hour. The predicted oxygen consumption showed a similar pattern to that of the measured oxygen consumption, but the predicted values were much lower.

Table (5.1): The comparison between the daily average the predicted and the measured oxygen consumption by fish.

Growth period, day	The measured OC mg O_2/kg.hour	The predicted OC mg O_2/kg.hour	Growth period, day	The measured OC mg O_2/kg.hour	The predicted OC mg O_2/kg.hour	Growth period, day	The measured OC mg O_2/kg.hour	The predicted OC mg O_2/kg.hour
1	459.19	457.56	23	421.18	433.30	45	390.04	387.13
2	467.61	456.76	24	427.92	431.55	46	393.60	384.65
3	452.82	455.97	25	430.18	429.81	47	388.36	382.23
4	457.04	455.17	26	426.14	428.08	48	371.40	379.77
5	466.55	454.37	27	419.38	426.35	49	372.18	377.33
6	484.97	453.58	28	425.86	424.62	50	367.85	375.10
7	464.27	452.78	29	431.22	422.99	51	381.71	372.73
8	442.11	451.99	30	423.23	420.90	52	372.03	370.37
9	443.92	450.92	31	416.95	418.81	53	367.85	368.02
10	445.96	449.86	32	419.88	416.73	54	381.71	365.68
11	439.25	448.80	33	420.98	414.66	55	373.21	363.35
12	435.61	447.74	34	413.84	412.60	56	363.82	361.03
13	466.45	446.68	35	411.21	410.54	57	367.04	358.73
14	428.24	445.62	36	408.77	408.49	58	366.64	353.69
15	430.18	444.56	37	405.44	406.17	59	363.13	351.19
16	423.01	443.21	38	399.42	403.85	60	361.34	348.70
17	421.05	441.86	39	401.12	401.54	61	360.64	346.23
18	440.61	440.51	40	404.71	399.25	62	357.97	343.77
19	425.11	439.16	41	408.06	396.96	63	349.88	341.32
20	426.27	437.82	42	407.36	394.68	64	347.12	338.79
21	421.82	436.48	43	400.60	392.41	65	339.01	336.28
22	428.95	435.05	44	396.39	389.63	66	344.57	333.77

Table (5.1): Continued.

Growth period, day	The measured OC mg O2/kg.hour	The predicted OC mg O2/kg.hour	Growth period, day	The measured OC mg O2/kg.hour	The predicted OC mg O2/kg.hour	Growth period, day	The measured OC mg O2/kg.hour	The predicted OC mg O2/kg.hour
67	349.53	331.29	88	286.54	280.07	109	219.27	231.94
68	337.59	328.81	89	283.70	277.92	110	226.45	229.55
69	335.56	326.35	90	279.87	275.93	111	221.02	227.18
70	328.40	323.91	91	281.75	274.62	112	217.37	224.84
71	324.92	321.29	92	284.32	273.04	113	213.25	222.35
72	328.80	318.69	93	285.05	270.57	114	208.73	219.98
73	327.49	316.10	94	275.24	268.11	115	207.89	217.63
74	331.03	313.53	95	262.16	265.68	116	204.77	215.32
75	324.12	310.98	96	269.28	263.27	117	203.70	213.03
76	319.10	308.45	97	261.40	260.87	118	204.73	210.77
77	316.13	305.93	98	263.06	258.50	119	202.90	208.54
78	312.02	303.57	99	265.47	256.15	120	201.94	206.33
79	310.66	301.22	100	266.02	253.64	121	199.72	204.08
80	307.88	298.88	101	249.02	251.16	122	198.65	201.85
81	306.37	296.56	102	253.79	248.70	123	197.42	199.66
82	308.23	294.26	103	254.39	246.26	124	204.80	197.49
83	301.92	291.97	104	253.06	243.85	125	199.02	195.36
84	295.03	289.69	105	250.31	241.46	126	201.15	193.25
85	296.05	287.26	106	247.32	239.09	127	198.31	191.18
86	294.48	284.85	107	246.59	236.62			
87	299.52	282.45	108	230.89	234.36			

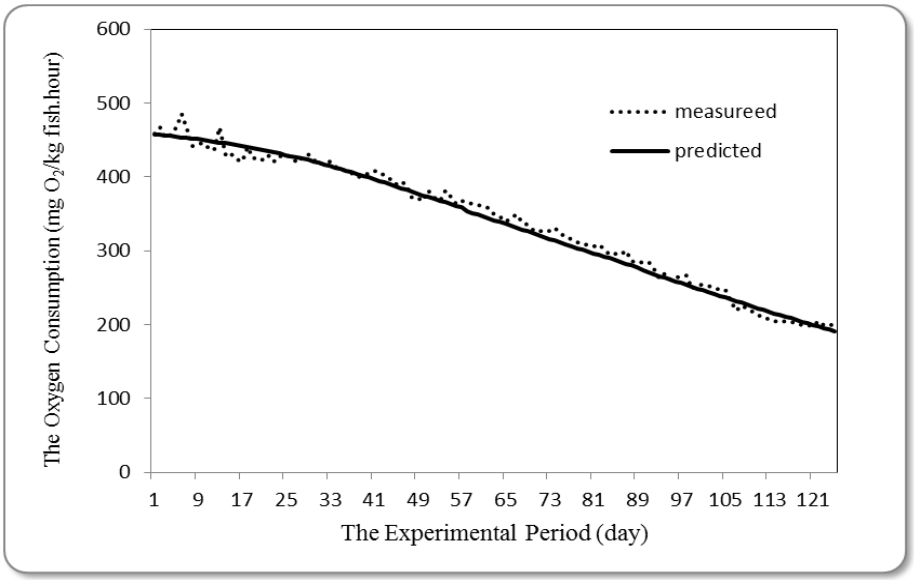

Figure (5.4a): The predicted and the measured oxygen consumption during the whole period of fish growth under the recirculating aquaculture system.

The best fit for the relationship between the predicted and the measured values was in followed form:

$$OC_p = 1.0004\ OC_m - 2.9975 \qquad R^2 = 0.988 \qquad (5.2)$$

Where:

OC_p is the predicted oxygen consumption, mgO_2/kg fish.h

OC_m is the measured oxygen consumption, mg O_2/kg fish.hour

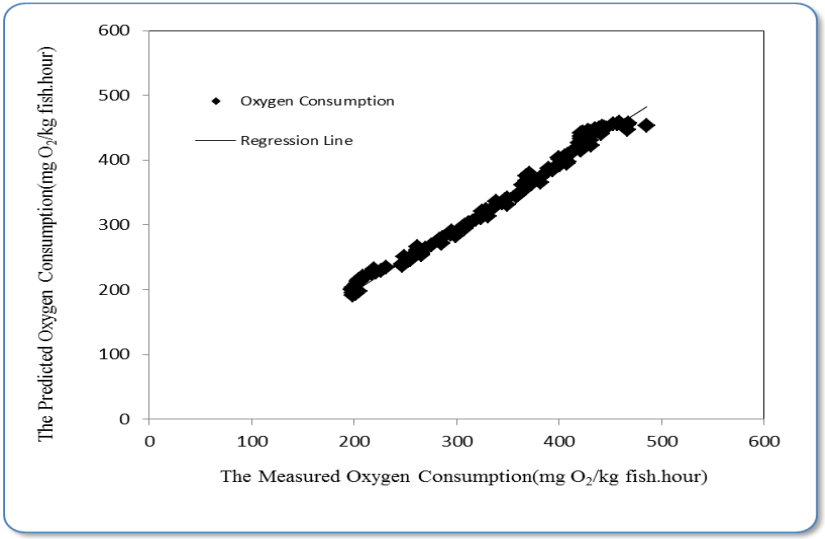

Figure (5.4b): The comparison between the predicted and the measured oxygen consumption by fish.

The oxygen consumption rate of fish on a per unit mass basis decreases as fish size increases **(Berg *et al.*, 1993; Jobling, 1993; Forsberg, 1994; Fivelstad *et al.*, 1999)**. This was also evident in this study. Therefore, an increase in system biomass does not mean that there is an equal increase in feeding rate. In fact, suggested feeding rate (% body weight per day) decreases as fish size increases and as water temperature decreases.

- **Effect of fish weight on oxygen consumption:**

Table (5.2) and figures (5.5a and b) show the comparison between the predicted and measured oxygen consumption of fish for the recirculating aquaculture system (RAS). It could be seen that the oxygen consumption decreases with increasing fish weight, where, it decreased from 459.19 to 198.31 mg O_2/kg fish per hour experimentally, while, it decreased from 457.56 to 201.40 mg O_2/kg fish per hour theoretically. The predicted oxygen consumption showed a similar pattern to that of the measured oxygen consumption.

Table (5.2): The comparison between the predicted and the measured oxygen consumption of fish for the recirculating aquaculture system (RAS).

Fish mass (g)	The measured OC mg O_2/kg.hour	The predicted OC mg O_2/kg.hour
4	459.19	457.56
5.82	442.11	451.99
8.27	430.18	444.56
11.42	428.95	435.14
15.55	431.22	422.99
20.59	408.77	408.49
26.33	400.60	392.41
31.7	367.85	377.78
38.93	367.04	358.73
45.79	347.12	341.32
50.93	324.92	328.72
60.63	312.02	305.93
69.91	296.05	285.36
77.75	284.32	268.93
80.15	265.47	264.07
94.18	247.32	237.28
100.7	213.25	225.76
105.57	201.94	217.55
115.79	198.31	201.40

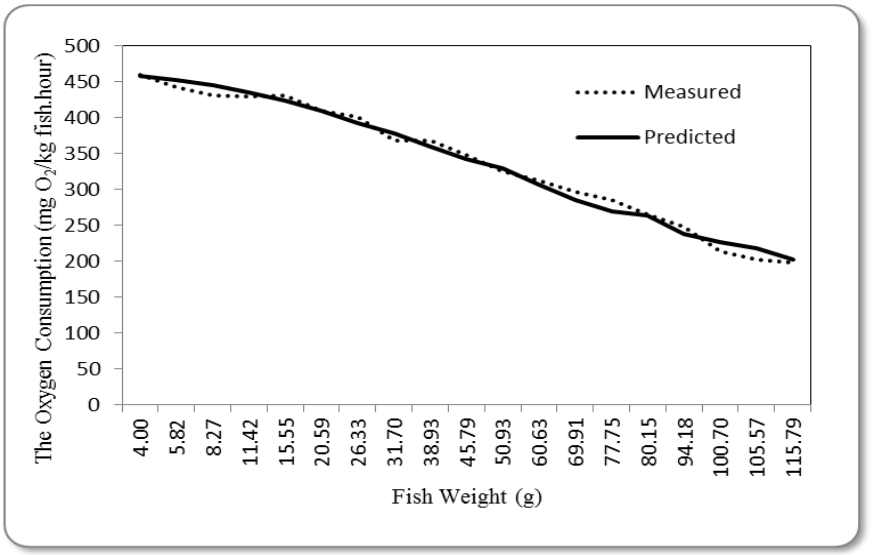

Figure (5.5a): The predicted and the measured oxygen consumption of fish for the recirculating aquaculture system (RAS) during the whole growth period.

The best fit for the relationship between the predicted and the measured values was in the following form:

$$OC_p = 0.9978\ OC_m + 0.7164 \qquad R^2 = 0.988 \qquad (5.3)$$

Where:

OC_p is the predicted oxygen consumption, mg O_2/kg fish.hour

OC_m is the measured oxygen consumption, mg O_2/kg fish.hour

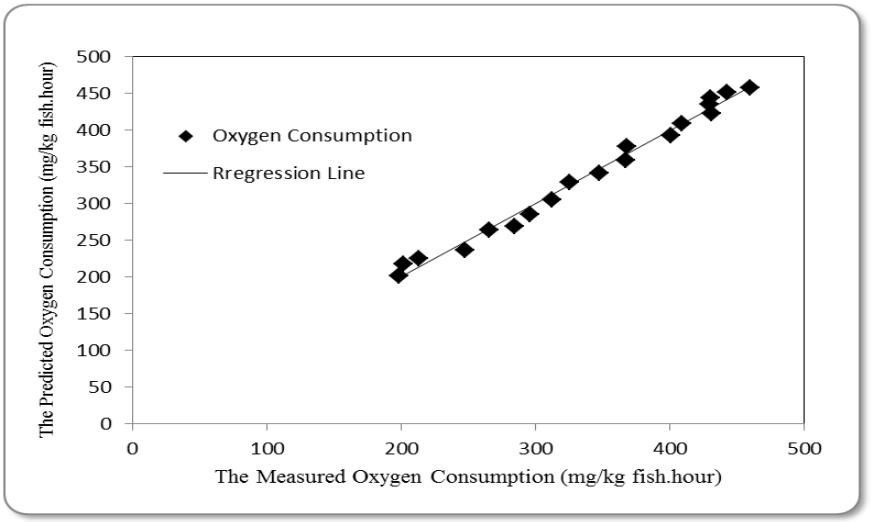

Figure (5.5b): The comparison between the predicted and the measured oxygen consumption of fish for the recirculating aquaculture system (RAS).

5.1.3. Ammonia Production

The model was able to predict variation in water column ammonia concentration in recirculation aquaculture system. Table (5.3) and figure (5.6) show the predicted and the measured ammonia production from the recirculating aquaculture system (RAS). It could be seen that the ammonia production decreased with growth time experimentally and theoretically, the average ammonia production from the system ranged from 10.56 to 55.99 mg NH_3/kg fish.hour experimentally, while, it was from 10.45 to 48.61 mg NH_3/kg fish.hour theoretically.

Table (5.3): The comparison between the predicted and the measure ammonia production.

Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour	Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour	Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour
1	48.34	48.61	23	55.99	44.35	45	35.88	36.52
2	47.46	48.47	24	55.72	44.05	46	35.70	36.11
3	48.37	48.33	25	50.62	43.75	47	36.64	35.71
4	40.07	48.19	26	49.75	43.45	48	40.88	35.30
5	52.96	48.05	27	45.69	43.15	49	45.51	34.90
6	54.53	47.91	28	43.39	42.85	50	42.62	34.54
7	45.37	47.77	29	41.70	42.57	51	36.76	34.15
8	46.30	47.63	30	43.69	42.21	52	34.22	33.77
9	48.43	47.44	31	50.57	41.85	53	32.95	33.39
10	41.47	47.25	32	48.52	41.50	54	42.07	33.01
11	44.17	47.06	33	44.30	41.14	55	33.58	32.64
12	42.30	46.88	34	46.06	40.79	56	31.41	32.27
13	46.54	46.69	35	45.68	40.44	57	32.14	31.90
14	42.86	46.50	36	40.11	40.10	58	34.34	31.10
15	51.67	46.32	37	48.83	39.70	59	33.68	30.70
16	40.20	46.08	38	40.46	39.31	60	34.87	30.31
17	41.87	45.84	39	42.42	38.92	61	36.95	29.93
18	44.72	45.61	40	44.80	38.54	62	31.29	29.54
19	48.72	45.37	41	45.68	38.15	63	31.90	29.16
20	49.13	45.14	42	39.77	37.77	64	38.39	28.77
21	43.47	44.91	43	41.66	37.39	65	32.32	28.38
22	51.02	44.66	44	38.69	36.93	66	28.20	28.00

Table (5.3): Continued.

Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour	Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour	Growth period, day	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour
67	31.37	27.62	88	27.95	20.24	109	15.33	13.84
68	31.89	27.24	89	24.23	19.95	110	17.37	13.60
69	31.10	26.87	90	26.41	19.30	111	20.17	13.35
70	26.85	26.50	91	18.71	18.98	112	19.46	13.11
71	23.76	26.11	92	17.55	18.66	113	19.03	12.88
72	28.05	25.72	93	25.72	18.35	114	12.43	12.66
73	30.11	25.34	94	18.11	18.04	115	14.10	12.45
74	33.37	24.96	95	22.13	17.74	116	13.32	12.25
75	25.21	24.59	96	17.28	17.44	117	14.90	12.05
76	31.16	24.22	97	20.78	17.15	118	12.97	11.86
77	27.97	23.85	98	17.96	16.84	119	15.10	11.67
78	29.06	23.51	99	18.05	16.54	120	10.56	11.49
79	22.21	23.17	100	22.23	16.25	121	16.72	11.31
80	29.37	22.84	101	21.08	15.96	122	12.96	11.15
81	24.82	22.51	102	22.54	15.68	123	10.98	10.99
82	22.41	22.19	103	16.48	15.40	124	14.92	10.85
83	30.82	21.87	104	17.71	15.14	125	15.58	10.70
84	22.22	21.55	105	21.94	14.86	126	15.02	10.57
85	26.25	21.22	106	18.66	14.61	127	13.84	10.45
86	26.10	20.89	107	15.28	14.35			
87	20.79	20.56	108	17.84	14.09			

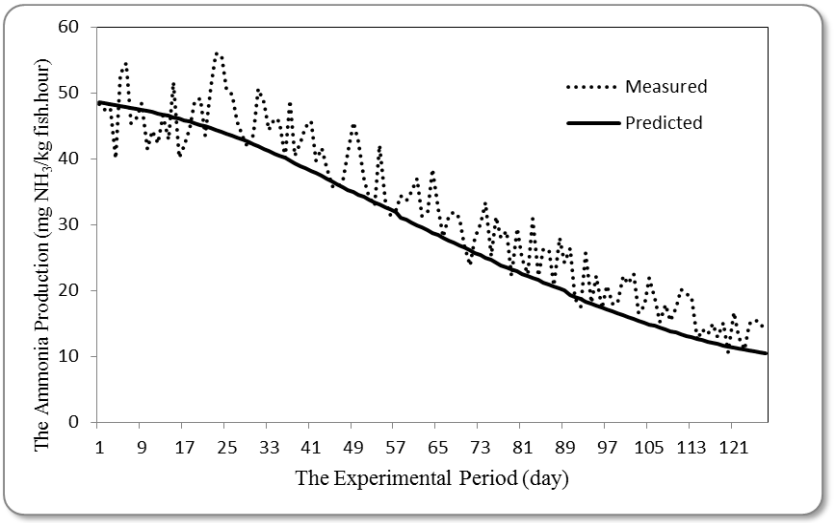

Figure (5.6): The predicted and the measured ammonia production by fish grown under the recirculating aquaculture system (RAS) during the whole growth period.

The variations between the predicted and the measured are shown in figure (5.7). It shows the predicted and the measured ammonia production is in a reasonable agreement. The best fit for the relationship between the predicted and the measured values was as follows:

$$AP_p = 0.966\ AP_m - 1.0803 \qquad R^2 = 0.915 \qquad (5.4)$$

Where:

AP_p is the predicted ammonia production, mg NH_3/kg fish.hour

AP_m is the measured ammonia production, mg NH_3/kg fish.hour

The ammonia production decreased with the increasing fish weight, the highest value of ammonia production was recorded 55.99 mg NH_3/kg fish.hour after 23 days of the growth period, but the lowest value of ammonia production was10.56 mg NH_3/kg fish.hour after 120 days of the growth period experimentally, while, the highest value of ammonia production was 48.61mg NH_3/kg fish.hour but the lowest value of ammonia production was 10.45 mg NH_3/kg fish.hour theoretically.

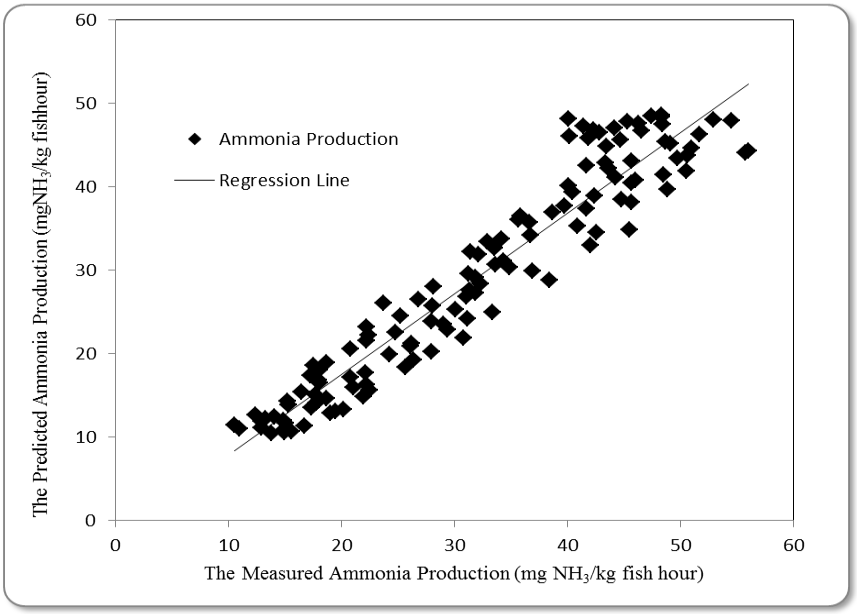

Figure (5.7): The comparison between the predicted and the measured ammonia production in RAS.

- **Effect of fish weight on Ammonia Production:**

Table (5.4) and figures (5.8a and b) show the comparison between the predicted and the measured ammonia production of fish for the recirculating aquaculture system (RAS). It could be seen that the ammonia production decreases with increasing fish weight, where, it decreased from 48.34 to 13.84 mg NH_3/kg fish per hour experimentally, while, it decreased from 48.61 to 11.45 mg NH_3/kg fish per hour theoretically. The predicted ammonia production showed a similar pattern to that of the measured ammonia production. The best fit for the relationship between the predicted and the measured values was in the following form:

$$AP_p = 0.9212\ AP_m + 0.1371 \qquad R^2 = 0.925 \qquad (5.5)$$

Where:

AP_p is the predicted ammonia production, mg NH_3/kg fish.hour

AP_m is the measured ammonia production, mg NH_3/kg fish.hour

Table (5.4): The comparison between the predicted and measured ammonia production of fish for the recirculating aquaculture system (RAS)

Fish mass (g)	The measured AP mg NH_3/kg.hour	The predicted AP mg NH_3/kg.hour
4	48.34	48.61
5.82	46.30	47.625
8.27	51.67	46.31
11.42	51.02	44.67
15.55	41.70	42.57
20.59	40.11	40.09
26.33	41.66	37.39
31.7	42.62	34.98
38.93	32.14	31.90
45.79	38.39	29.16
50.93	23.76	27.23
60.63	29.06	23.85
69.91	26.25	20.96
77.75	17.55	18.77
80.15	18.05	18.14
94.18	18.66	14.93
100.7	19.03	13.69
105.57	10.56	12.88
115.79	13.84	11.45

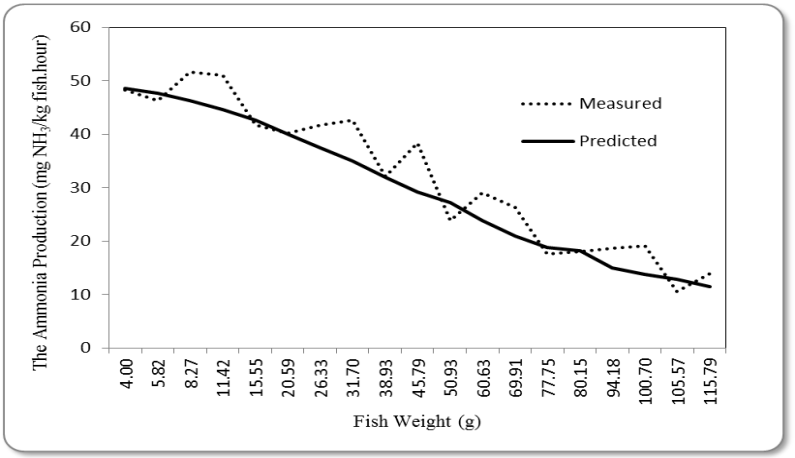

Figure (5.8a): The predicted and the measured ammonia production of fish for the recirculating aquaculture system (RAS) during the whole growth period.

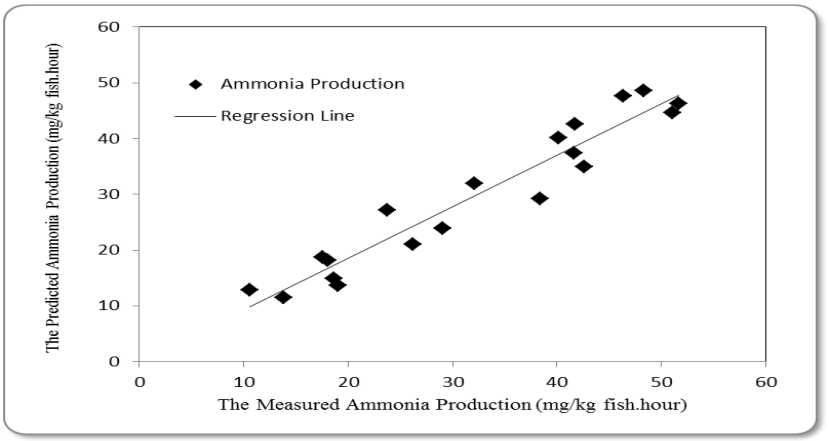

Figure (5.8b): The comparison between the predicted and the measured ammonia production of fish for the recirculating aquaculture system (RAS).

5.1.3.1. The relationship between the ammonia conversion and ammonia concentration:

The relationship between the ammonia conversion rate and ammonia concentration is shown figure (5.9). The ammonia conversion rate ranged from 12.24 to 611.61 mg NH_3/m^3.day. These results were agreed with those obtained by **Greiner and Timmons (1998), Brazil (2006)** and **Guerdat *et al.* (2010).**

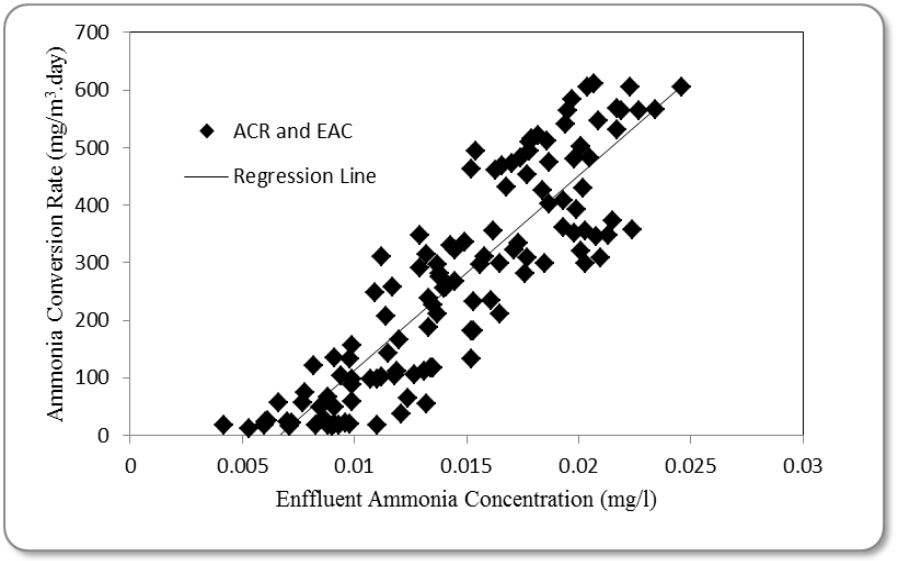

Figure (5.9): The relationship between the effluent ammonia concentration and ammonia conversion rate.

The regression between the ammonia conversion rate and ammonia concentration for the system is show in the following equation:-

$$ACR = 33873NH_{3in} - 225.38 \qquad R^2 = 0.779 \qquad (5.6)$$

Where:

ACR is the ammonia conversion rate, mg l^{-1}

NH_{3in} is the influent ammonia concentration, mg/kg.day

5.1.3.2. The relationship between the ammonia loading rate and ammonia conversion:

The relationship between the ammonia loading rate and the ammonia conversion rate is shown figure (5.10). It could be seen that the ammonia loading rate ranged from 65.79 to 22044.53 mg/m^3.day. These results were agreed with those obtained by **Brazil (2006)** and **Guerdat *et al.* (2010).**

The regression between the ammonia conversion rate and ammonia loading rate for the system is show the following equation:-

$$LR_{NH3} = 28.59\ ACR - 1219.3 \qquad R^2 = 0.942 \qquad (5.7)$$

Where:

LR_{NH3} is the ammonia loading rate, mg/m^3.day

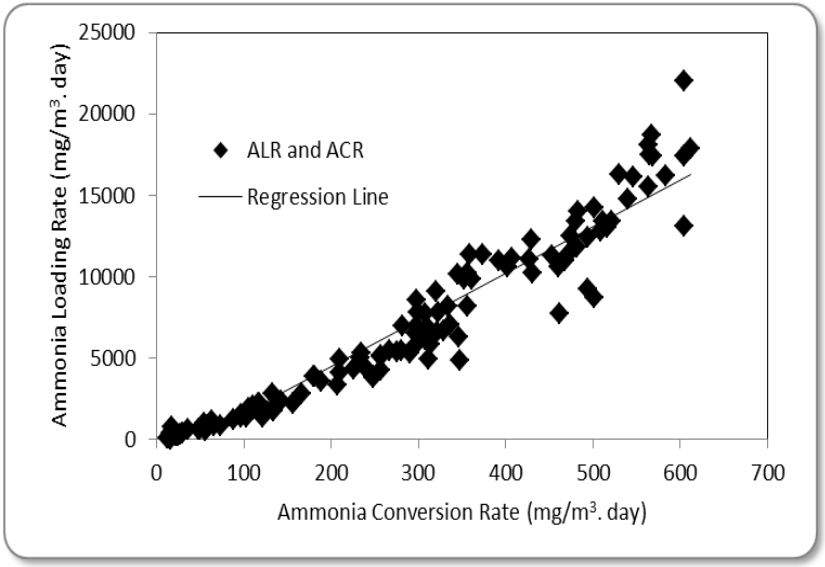

Figure (5.10): The relationship between ammonia conversion rate and ammonia loading rate

5.1.4. Nitrate Production:

The model was able to predict the variations in water column nitrate Production in recirculation aquaculture system. Table (5.5) and figure (5.11) show the predicted and the measured nitrate production from the recirculating aquaculture system (RAS) during the whole period of fish growth. It could be seen that the average nitrate production from the system ranged from 41.61 to 222.31 mg NO_3/kg fish.hour experimentally, while, it was from 45.34 to 210.97 mg NO_3/kg fish.hour theoretically.

The variations between the predicted and the measured are shown in figure (5.12). It shows the predicted and measured are in a reasonable agreement. The best fit for the relationship between the predicted and measured value was in the following form:

$$NP_p = 0.9862\ NP_m - 0.4778 \qquad R^2 = 0.993 \qquad (5.8)$$

Where:

NP_p is the predicted nitrate production, mg NO_3/kg fish.hour

NP_m is the measured nitrate production, mg NO_3/kg fish.hour

The nitrate production decreased with the increasing fish weight, the highest value of nitrate production was 222.31 mg NO_3/kg fish.hour after 3 days of growth period, but the lowest value of nitrate production was 41.61 mg NO_3/kg fish.hour after 127 days of growth period experimentally, while, the highest value of nitrate accumulation was 210.97mg NO_3/kg fish.hour but the lowest value of nitrate accumulation was 45.31 mg NO_3/kg fish.hour theoretically.

Table (5.5): The comparison between the measured and predicted nitrate production Rate.

Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour	Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour	Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour
1	215.06	210.97	23	200.95	192.49	45	153.10	158.48
2	206.16	210.35	24	186.43	191.18	46	159.54	156.70
3	222.31	209.74	25	196.89	189.87	47	155.93	154.97
4	216.04	209.13	26	190.46	188.57	48	158.80	153.22
5	202.19	208.52	27	192.40	187.27	49	160.93	151.48
6	206.22	207.91	28	190.35	185.98	50	156.48	149.90
7	215.84	207.30	29	180.28	184.76	51	147.51	148.23
8	202.86	206.69	30	186.04	183.20	52	153.73	146.56
9	215.22	205.88	31	181.38	181.65	53	151.83	144.91
10	206.58	205.06	32	189.53	180.10	54	143.28	143.27
11	209.66	204.25	33	185.86	178.57	55	135.67	141.65
12	207.47	203.44	34	181.42	177.04	56	133.38	140.04
13	206.54	202.63	35	180.39	175.52	57	142.41	138.44
14	202.24	201.83	36	174.84	174.01	58	138.33	134.97
15	197.75	201.02	37	162.78	172.30	59	130.14	133.25
16	210.49	199.99	38	175.55	170.61	60	133.81	131.56
17	204.16	198.97	39	172.31	168.92	61	131.56	129.88
18	197.89	197.94	40	170.01	167.24	62	131.56	128.21
19	196.00	196.92	41	166.35	165.58	63	132.17	126.56
20	201.85	195.90	42	166.35	163.93	64	128.82	124.86
21	188.09	194.89	43	163.16	162.28	65	128.13	123.18
22	206.23	193.81	44	166.52	160.28	66	125.75	121.51

Table (5.5): Continued.

Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour	Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour	Growth period, day	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour
67	113.75	119.86	88	90.12	87.83	109	66.71	60.07
68	111.23	118.23	89	86.03	86.58	110	58.75	59.02
69	113.50	116.62	90	87.94	83.77	111	61.78	57.93
70	122.03	115.02	91	84.54	82.37	112	65.80	56.91
71	118.68	113.32	92	86.92	80.98	113	57.35	55.92
72	118.83	111.63	93	84.95	79.63	114	59.39	54.96
73	111.32	109.97	94	82.00	78.29	115	48.67	54.04
74	111.89	108.33	95	71.78	76.98	116	51.39	53.15
75	113.02	106.70	96	73.67	75.70	117	55.29	52.29
76	107.46	105.10	97	76.00	74.43	118	53.90	51.46
77	108.92	103.52	98	76.63	73.10	119	45.16	50.64
78	104.04	102.04	99	70.98	71.80	120	53.01	49.86
79	107.67	100.58	100	74.41	70.52	121	49.37	49.11
80	102.48	99.13	101	69.38	69.27	122	48.66	48.39
81	92.87	97.71	102	72.38	68.05	123	43.20	47.71
82	98.82	96.30	103	73.60	66.86	124	51.97	47.07
83	90.66	94.91	104	69.43	65.69	125	54.36	46.46
84	91.31	93.54	105	66.65	64.49	126	46.00	45.88
85	91.08	92.08	106	74.33	63.41	127	41.61	45.34
86	99.93	90.64	107	66.93	62.26			
87	89.45	89.23	108	58.02	61.15			

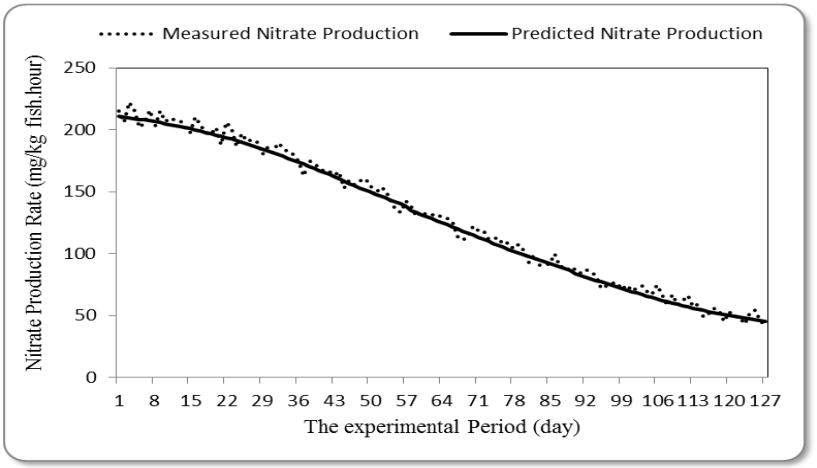

Figure (5.11): Nitrate production rate with the growth period of fish grown under recirculating aquaculture system (RAS).

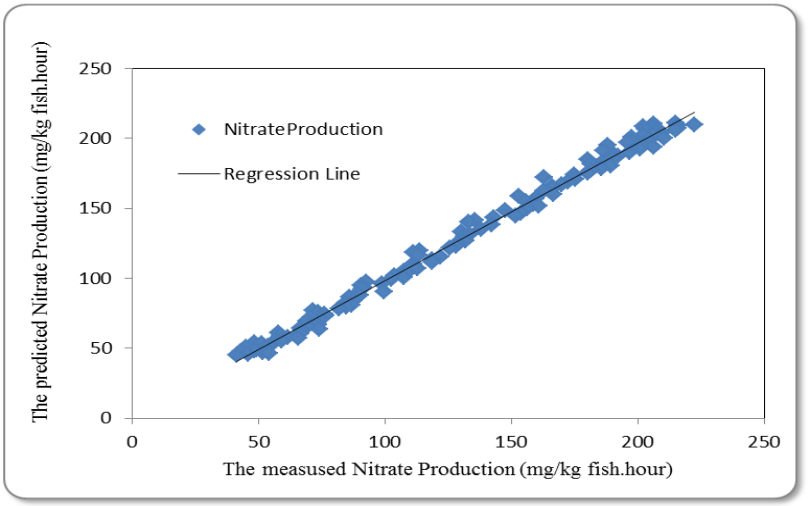

Figure (5.12): The comparison between the predicted and the measured nitrate production (mg NO_3/kg fish.hour).

The accumulation of nitrate in the system is inevitable when there is more nitrate production. The nitrate level continues to rise to the point that it can become dangerous to the fish health. However, in reality this does not occur at this system due to there are times when water exchanges have to take place for other reasons (fish health, poor performance of the biofilters resulting in elevated ammonia concentrations, etc.). Each time a water exchange, the nitrate concentration is reduced and the nitrate build-up process starts over **(Ernst *et al.*, 2000)**.

- **Effect of fish weight on Nitrate Production:**

Table (5.6) and figure (5.13a and b) show the comparison between the predicted and the measured nitrate production of fish for the recirculating aquaculture system (RAS). It could be seen that the nitrate production decreases with increasing fish weight, where, it decreased from 215.06 to 41.61 mg NO_3/kg fish per hour experimentally while it was decreased from 210.97 to 49.70 mg NO_3/kg fish per hour theoretically. The predicted nitrate production showed a similar pattern to that of the measured nitrate production. The best fit for the relationship between the predicted and the measured values was in the following form:

$$NP_p = 0.9737\ NP_m + 0.7379 \qquad R^2 = 0.992 \qquad (5.9)$$

Where:

NP_p is the predicted nitrate production, mg NO_3/kg fish.hour

Np_m is the measured nitrate production, mg NO_3/kg fish.hour

Table (5.6): The comparison between the predicted and measured nitrate production of fish for the recirculating aquaculture system (RAS).

Fish mass (g)	The measured NP mg NO_3/kg.hour	The predicted NP mg NO_3/kg.hour
4	215.06	210.97
5.82	202.86	206.69
8.27	197.75	201.02
11.42	206.23	193.88
15.55	180.28	184.76
20.59	174.84	174.01
26.33	163.16	162.28
31.7	156.48	151.80
38.93	142.41	138.44
45.79	128.82	126.56
50.93	118.68	118.17
60.63	104.04	103.52
69.91	91.08	90.95
77.75	86.92	81.44
80.15	70.98	78.73
94.18	74.33	64.80
100.7	57.35	59.44
105.57	53.01	55.88
115.79	41.61	49.70

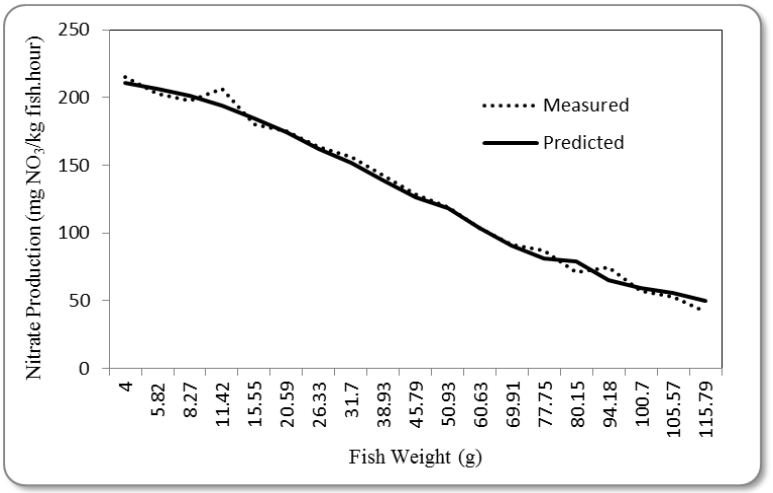

Figure (5.13a): The nitrate production of fish for the recirculating aquaculture system (RAS) during the whole growth period.

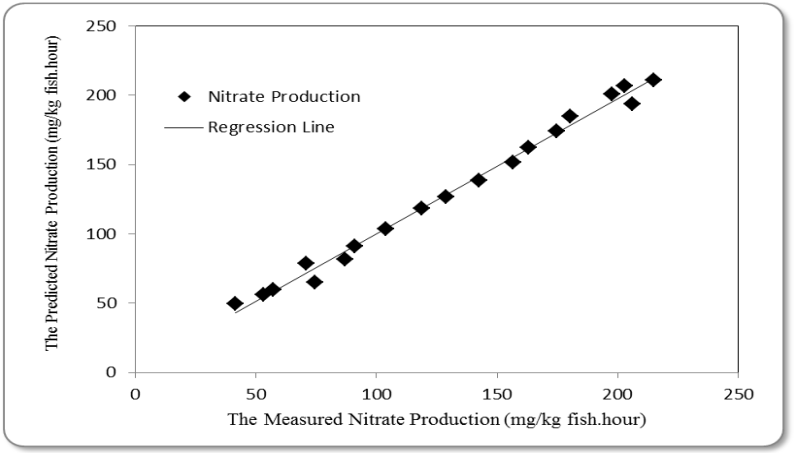

Figure (5.13b): The comparison between the predicted and the measured nitrate production of fish for the recirculating aquaculture system (RAS).

5.1.5. Biological filter performance:

5.1.5.1. Biological filter efficiency:

The efficiency of the filter was determined by measuring the ammonia concentration in the water entering the biological filter and the ammonia concentration in the water leaving the biological filter. The data presented in table (5.7) and figure (5.14) along with the calculated biological filter efficiency values shows that the efficiency of the drum filter for ammonia removal from the system ranged from 11.11 to 63.64 %.

The efficiency observed in this study was in agreement with the ranges of efficiencies reported by **Skjolstrup *et al.* (1997); Skjolstrup *et al.* (1998) and Brazil (2006).**

Filter efficiency is affected by water temperature, ammonia concentration, dissolved oxygen concentration, solids concentration, pH, alkalinity and flow rate.

Table (5.7):The efficiency of biological filter (%).

Growth period, day	Filter efficiency %	Growth period, day	Filter efficiency %	Growth period, day	Filter efficiency %
1	11.11	44	31.09	87	38.89
2	39.89	45	41.21	88	37.96
3	39.62	46	50.25	89	35.51
4	61.54	47	27.12	90	39.45
5	63.64	48	40.82	91	57.72
6	25.00	49	26.79	92	40.00
7	57.14	50	42.68	93	40.91
8	21.43	51	41.76	94	41.79
9	39.74	52	32.89	95	42.25
10	23.47	53	23.68	96	42.37
11	20.43	54	40.88	97	45.88
12	25.35	55	38.42	98	40.09
13	22.61	56	41.62	99	24.84
14	23.30	57	44.07	100	44.62
15	33.72	58	39.39	101	35.86
16	18.68	59	34.59	102	36.24
17	18.75	60	33.25	103	41.07
18	16.87	61	42.98	104	37.88
19	25.58	62	41.41	105	42.64
20	23.14	63	43.01	106	36.36
21	54.55	64	36.16	107	43.75
22	38.46	65	37.02	108	43.53
23	57.58	66	38.14	109	44.17
24	38.38	67	42.71	110	43.10
25	46.59	68	45.99	111	44.38
26	34.12	69	44.56	112	36.84
27	50.91	70	30.43	113	45.69
28	49.49	71	32.95	114	40.19
29	40.85	72	34.07	115	37.18
30	54.64	73	36.09	116	40.09
31	44.86	74	36.43	117	39.43
32	40.46	75	38.61	118	44.10
33	42.86	76	35.46	119	45.10
34	48.94	77	43.41	120	42.13
35	36.22	78	41.88	121	42.77
36	36.30	79	37.68	122	43.41
37	38.46	80	34.48	123	43.58
38	20.16	81	35.26	124	41.56
39	33.58	82	39.11	125	37.44
40	46.09	83	35.26	126	38.81
41	35.35	84	32.73	127	44.44
42	49.41	85	33.92		
43	33.81	86	41.30		

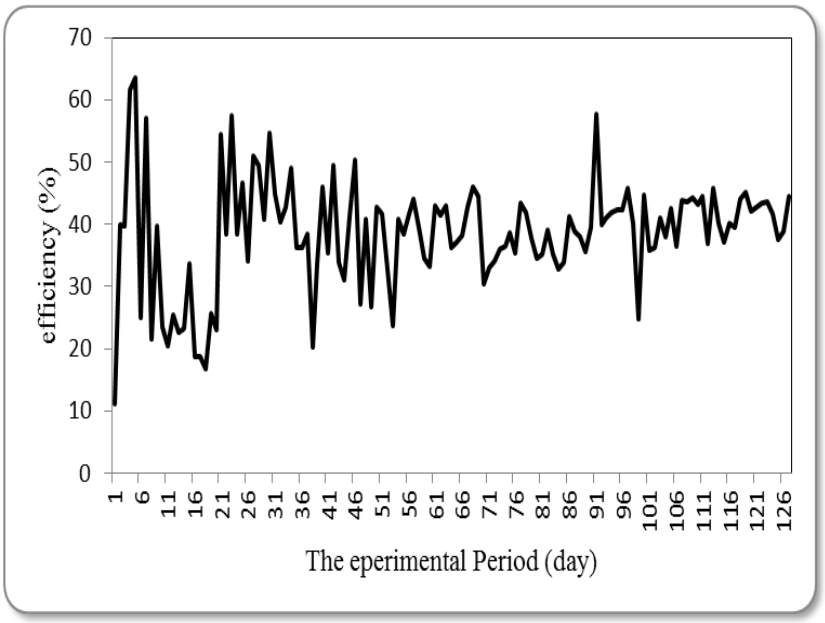

Figure (5.14): The efficiency of the biological filter (%).

5.1.5.2. Nitrite removal rate:

The nitrite removal rate varied during the experimental period (table 5.8 and figure 5.15), where, the highest value of nitrite removal rate for this system was 20.67 mg NO_2/kg fish.hour but the lowest value of nitrite removal rate was 6.25 mg NO_2/kg fish.hour. The nitrite removal rate decreased with the increasing of fish weight.

Table (5.8): Nitrite removal rate.

Growth period, day	Nitrite removal rate mg NO_2/kg.hour	Growth period, day	Nitrite removal rate mg NO_2/kg.hour	Growth period, day	Nitrite removal rate mg NO_2/kg.hour
1	18.34	44	17.18	87	8.43
2	16.61	45	10.12	88	7.80
3	18.27	46	16.17	89	8.30
4	16.38	47	14.60	90	14.03
5	16.37	48	17.61	91	13.92
6	18.18	49	16.07	92	12.28
7	15.44	50	10.52	93	11.11
8	19.06	51	11.95	94	10.49
9	18.13	52	13.36	95	9.36
10	18.11	53	14.71	96	7.73
11	17.19	54	13.19	97	11.22
12	18.97	55	15.29	98	9.61
13	11.64	56	15.92	99	10.01
14	19.82	57	17.25	100	7.93
15	12.47	58	16.72	101	11.30
16	11.55	59	13.15	102	10.22
17	18.85	60	12.38	103	11.08
18	12.36	61	13.66	104	10.02
19	11.44	62	10.86	105	10.39
20	17.02	63	10.11	106	11.23
21	15.74	64	11.37	107	9.24
22	14.46	65	9.97	108	9.63
23	13.89	66	12.54	109	8.62
24	14.70	67	12.45	110	9.43
25	20.67	68	14.31	111	8.88
26	20.30	69	11.63	112	7.07
27	16.23	70	10.90	113	8.78
28	17.02	71	12.08	114	10.35
29	11.87	72	10.10	115	10.22
30	12.65	73	11.27	116	8.01
31	13.23	74	8.70	117	6.25
32	14.19	75	7.40	118	8.67
33	12.92	76	8.56	119	8.98
34	13.23	77	11.53	120	8.88
35	12.34	78	10.25	121	8.39
36	18.01	79	12.56	122	9.96
37	15.46	80	14.25	123	9.38
38	9.71	81	8.25	124	8.97
39	19.31	82	11.11	125	8.10
40	15.20	83	9.29	126	8.41
41	12.73	84	11.52	127	8.73
42	11.07	85	12.56		
43	14.15	86	11.90		

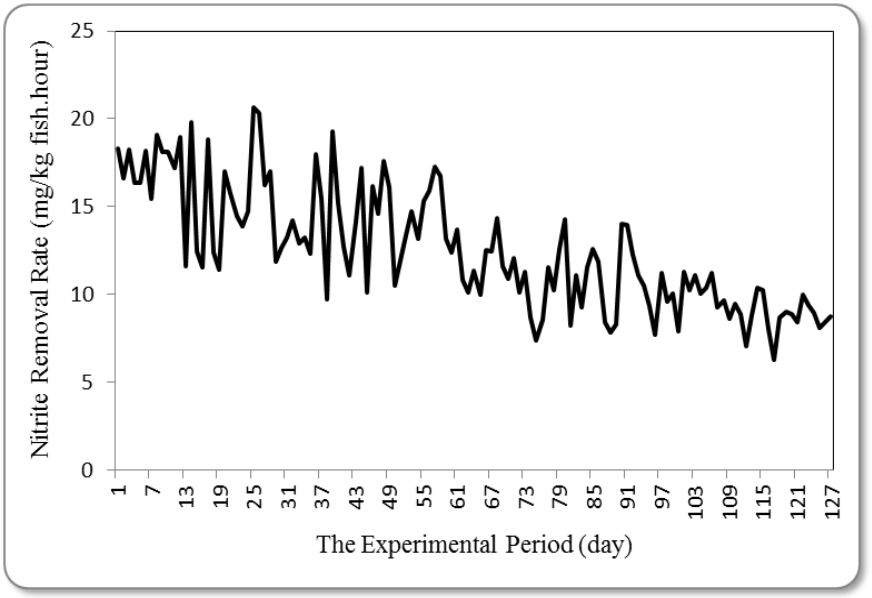

Figure (5.15): Nitrite removal rate with growth period.

5.1.6. Solids Removal:

There are two types of solids that to be removed from the recirculating aquaculture system (RAS), one is the settleable solids removal which is more dependent on the gravity rather than centrifugal force, while the second type is the suspended solids removal which is dependent on the centrifugal force. The hydrocyclone was used to remove the settleable solids from the recirculating aquaculture system (RAS). The data was recorded daily.

5.1.6.1. Settleable Solids:

Tables (5.9 and 5.10) and figures (5.16 and 5.17) show the predicted and measured settleable solids removed from the recirculating aquaculture system (RAS). It indicates that the average settleable solids removed from the system was 0.0429 ± 0.0127 kg m^{-3} (42.90 ± 12.70 mg l^{-1}). The daily average of solids removed from the system ranged from 0.33 to 6.62 kg/day experimentally while it ranged from 0.34 to 4.41 kg/day theoretically.

Regression analysis was carried out to find a relationship between the predicted and the measured settleable solids for the system with high coefficient of determination as follows:

$$SSR_{hp} = 0.039 - 9.6 \times 10^{-23} SSR_{hm} \qquad R^2 = 0.999 \qquad (5.10)$$

Where:

SSR_{hp} is the predicted settleable solids removal by hydrocyclone, kg m^{-3} of water

SSR_{hm} is the measured settleable solids removal by hydrocyclone, kg m^{-3} of water

Table (5.9): The predicted and measured settleable solids removed from the system (RAS).

Growth period, day	The measured SS_h kg m^{-3}	The predicted SS_h kg m^{-3}	Growth period, day	The measured SS_h kg m^{-3}	The predicted SS_h kg m^{-3}	Growth period, day	The measured SS_h kg m^{-3}	The predicted SS_h kg m^{-3}
1	0.03753	0.039	23	0.04014	0.039	45	0.03887	0.039
2	0.03987	0.039	24	0.03806	0.039	46	0.04045	0.039
3	0.04059	0.039	25	0.04501	0.039	47	0.04039	0.039
4	0.03855	0.039	26	0.04069	0.039	48	0.03852	0.039
5	0.03618	0.039	27	0.03923	0.039	49	0.0386	0.039
6	0.03544	0.039	28	0.04024	0.039	50	0.04084	0.039
7	0.04197	0.039	29	0.04157	0.039	51	0.03719	0.039
8	0.03915	0.039	30	0.04526	0.039	52	0.03974	0.039
9	0.03815	0.039	31	0.03905	0.039	53	0.0373	0.039
10	0.04021	0.039	32	0.04339	0.039	54	0.03894	0.039
11	0.03939	0.039	33	0.04192	0.039	55	0.03865	0.039
12	0.03962	0.039	34	0.03913	0.039	56	0.03539	0.039
13	0.04187	0.039	35	0.03921	0.039	57	0.05262	0.039
14	0.03913	0.039	36	0.04243	0.039	58	0.04874	0.039
15	0.0412	0.039	37	0.04098	0.039	59	0.04112	0.039
16	0.03769	0.039	38	0.04055	0.039	60	0.03902	0.039
17	0.04125	0.039	39	0.04093	0.039	61	0.04321	0.039
18	0.04333	0.039	40	0.03991	0.039	62	0.04795	0.039
19	0.03945	0.039	41	0.04047	0.039	63	0.04828	0.039
20	0.03993	0.039	42	0.03989	0.039	64	0.05423	0.039
21	0.04187	0.039	43	0.04004	0.039	65	0.05493	0.039
22	0.04204	0.039	44	0.03889	0.039	66	0.03939	0.039

SS_h : Settleable Solids removed by hydrocyclone

Table (5.9): Continued.

Growth period, day	The measured SS_b kg m^{-3}	The predicted SS_b kg m^{-3}	Growth period, day	The measured SS_b kg m^{-3}	The predicted SS_b kg m^{-3}	Growth period, day	The measured SS_b kg m^{-3}	The predicted SS_b kg m^{-3}
67	0.04102	0.039	88	0.04103	0.039	109	0.04739	0.039
68	0.04042	0.039	89	0.04133	0.039	110	0.04451	0.039
69	0.04176	0.039	90	0.03686	0.039	111	0.04115	0.039
70	0.04301	0.039	91	0.03896	0.039	112	0.03816	0.039
71	0.03839	0.039	92	0.04337	0.039	113	0.04241	0.039
72	0.03949	0.039	93	0.03037	0.039	114	0.03712	0.039
73	0.04502	0.039	94	0.04403	0.039	115	0.04501	0.039
74	0.0405	0.039	95	0.04057	0.039	116	0.05249	0.039
75	0.04287	0.039	96	0.04351	0.039	117	0.05455	0.039
76	0.04283	0.039	97	0.03257	0.039	118	0.04719	0.039
77	0.03767	0.039	98	0.04019	0.039	119	0.05236	0.039
78	0.04169	0.039	99	0.04446	0.039	120	0.05414	0.039
79	0.04747	0.039	100	0.05031	0.039	121	0.04916	0.039
80	0.03998	0.039	101	0.04547	0.039	122	0.0354	0.039
81	0.04126	0.039	102	0.04681	0.039	123	0.05205	0.039
82	0.04767	0.039	103	0.05053	0.039	124	0.05562	0.039
83	0.03857	0.039	104	0.05204	0.039	125	0.05316	0.039
84	0.03218	0.039	105	0.0539	0.039	126	0.05018	0.039
85	0.03917	0.039	106	0.04552	0.039	127	0.05062	0.039
86	0.04184	0.039	107	0.04364	0.039			
87	0.04214	0.039	108	0.04391	0.039			

Table (5.10): The daily average of settleable solids removed by hydrocyclone.

Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day	Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day	Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day
1	0.33	0.34	23	1.01	0.98	45	2.04	2.05
2	0.37	0.36	24	1.00	1.02	46	2.18	2.10
3	0.40	0.39	25	1.23	1.07	47	2.23	2.15
4	0.40	0.41	26	1.16	1.11	48	2.18	2.21
5	0.40	0.43	27	1.16	1.15	49	2.23	2.26
6	0.41	0.45	28	1.23	1.19	50	2.41	2.30
7	0.51	0.47	29	1.31	1.23	51	2.24	2.35
8	0.50	0.49	30	1.49	1.28	52	2.44	2.40
9	0.51	0.52	31	1.34	1.33	53	2.33	2.44
10	0.57	0.55	32	1.54	1.38	54	2.48	2.49
11	0.58	0.58	33	1.54	1.43	55	2.51	2.53
12	0.62	0.61	34	1.49	1.48	56	2.34	2.58
13	0.68	0.63	35	1.54	1.53	57	3.53	2.62
14	0.66	0.66	36	1.72	1.58	58	3.33	2.67
15	0.73	0.69	37	1.71	1.63	59	2.86	2.71
16	0.70	0.72	38	1.75	1.68	60	2.76	2.76
17	0.80	0.76	39	1.82	1.74	61	3.10	2.80
18	0.88	0.79	40	1.83	1.79	62	3.50	2.85
19	0.84	0.83	41	1.91	1.84	63	3.58	2.89
20	0.88	0.86	42	1.93	1.89	64	4.08	2.93
21	0.96	0.90	43	1.99	1.94	65	4.19	2.97
22	1.01	0.93	44	1.99	2.00	66	3.05	3.02

SS_h : Settleable Solids removed by hydrocyclone

Table (5.10): Continued.

Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day	Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day	Growth period, day	The measured SS_h kg/day	The predicted SS_h kg/day
67	3.22	3.06	88	3.97	3.78	109	5.15	4.24
68	3.21	3.10	89	4.03	3.80	110	4.86	4.26
69	3.36	3.14	90	3.62	3.83	111	4.50	4.27
70	3.50	3.18	91	3.88	3.88	112	4.19	4.28
71	3.17	3.22	92	4.34	3.90	113	4.67	4.30
72	3.30	3.26	93	3.06	3.93	114	4.10	4.31
73	3.80	3.30	94	4.46	3.95	115	4.98	4.32
74	3.46	3.33	95	4.14	3.98	116	5.83	4.33
75	3.71	3.37	96	4.46	4.00	117	6.07	4.34
76	3.74	3.41	97	3.36	4.02	118	5.26	4.35
77	3.33	3.44	98	4.17	4.04	119	5.85	4.36
78	3.72	3.48	99	4.63	4.06	120	6.06	4.36
79	4.27	3.51	100	5.27	4.09	121	5.51	4.37
80	3.63	3.54	101	4.79	4.11	122	3.98	4.38
81	3.78	3.57	102	4.95	4.13	123	5.85	4.39
82	4.40	3.60	103	5.37	4.14	124	6.26	4.39
83	3.59	3.63	104	5.55	4.16	125	5.99	4.40
84	3.02	3.66	105	5.78	4.18	126	5.67	4.40
85	3.71	3.69	106	4.90	4.20	127	5.72	4.41
86	3.99	3.72	107	4.71	4.21			
87	4.05	3.75	108	4.76	4.23			

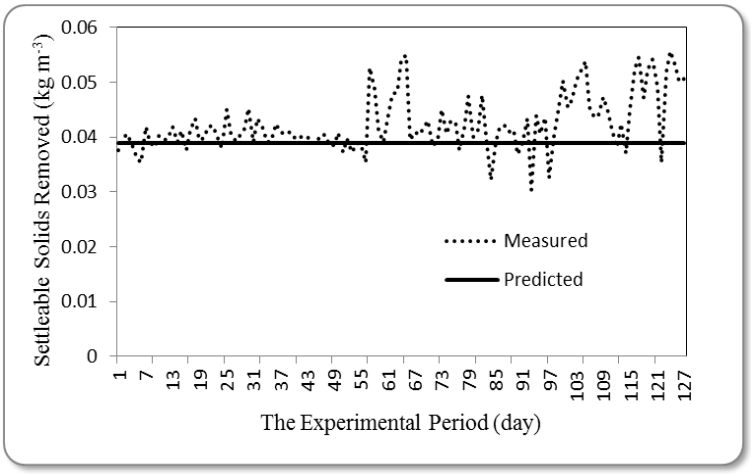

Figure (5.16): The predicted and the measured settleable solids removed from the system (RAS) during the growth period of fish.

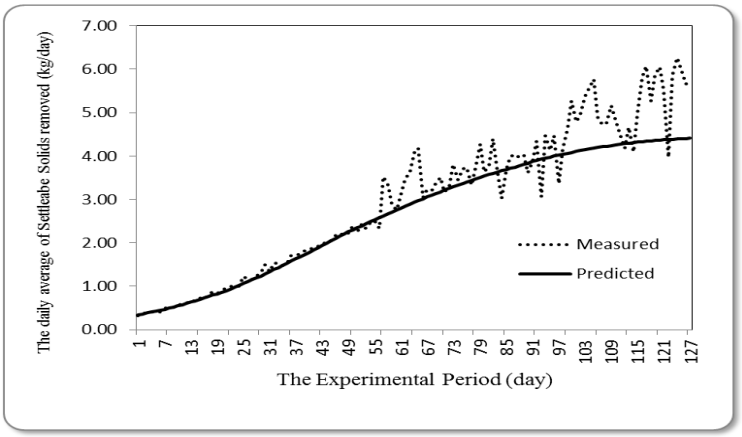

Figure (5.17): The daily average of settleable solids removed by hydrocyclone during the growth period of fish.

5.1.6.2. Suspended Solids:

Table (5.11) and figure (5.18) show the predicted and the measured suspended solids removal from the recirculating aquaculture system (RAS). It could be seen that the suspended solids removed by the system increased with growth period, where it was 0.0123 kg m^{-3} (12.30 mg l^{-1}) at the beginning and increased rapidly to reach 0.0806 kg m^{-3} (80.60 mg l^{-1}) after 3 months. Also, the results in table (5.12) and figure (5.19) show that the daily average solids removed from the system ranged from 0.11 to 11.34 kg/day experimentally while it was from 0.11 to 15.70 kg/day theoretically.

The variations between the predicted and the measured suspended solids removal are shown in figure (5.20). It shows the predicted and measured are in a reasonable agreement. The best fit for the relationship between the predicted and measured values was as follows:

$$SSR_{fp} = 1.59 SSR_{fm} - 0.015 \qquad R^2 = 0.915 \qquad (5.11)$$

Where:

SSR_{fp} is the predicted suspended solids removal, kg m^{-3} of water

SSR_{fm} is the measured suspended solids, kg m^{-3} of water

These results are in agreement with those obtained by **Steicke *et al.* (2007)** whose found that the suspended solids removed from the recirculating aquaculture system (RAS) ranged 0.0104 to 0.0400 kg m^{-3} (10.40 to 40.00 mg l^{-1}).

Table (5.11): The predicted and the measured suspended solids removal from the system (RAS).

Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}	Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}	Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}
1	0.0129	0.0124	23	0.0154	0.0128	45	0.0191	0.0155
2	0.0140	0.0124	24	0.0195	0.0129	46	0.0176	0.0157
3	0.0123	0.0124	25	0.0179	0.0130	47	0.0187	0.0160
4	0.0170	0.0124	26	0.0189	0.0130	48	0.0180	0.0162
5	0.0155	0.0124	27	0.0178	0.0131	49	0.0193	0.0165
6	0.0143	0.0124	28	0.0198	0.0131	50	0.0216	0.0167
7	0.0191	0.0124	29	0.0188	0.0132	51	0.0195	0.0170
8	0.0161	0.0124	30	0.0176	0.0133	52	0.0189	0.0173
9	0.0176	0.0125	31	0.0173	0.0134	53	0.0188	0.0176
10	0.0145	0.0125	32	0.0185	0.0135	54	0.0220	0.0179
11	0.0144	0.0125	33	0.0197	0.0136	55	0.0216	0.0182
12	0.0199	0.0125	34	0.0209	0.0137	56	0.0193	0.0185
13	0.0141	0.0125	35	0.0210	0.0138	57	0.0194	0.0188
14	0.0148	0.0126	36	0.0190	0.0139	58	0.0228	0.0196
15	0.0186	0.0126	37	0.0198	0.0141	59	0.0217	0.0200
16	0.0165	0.0126	38	0.0217	0.0142	60	0.0233	0.0204
17	0.0167	0.0126	39	0.0184	0.0144	61	0.0211	0.0209
18	0.0195	0.0127	40	0.0184	0.0145	62	0.0226	0.0213
19	0.0128	0.0127	41	0.0190	0.0147	63	0.0233	0.0218
20	0.0177	0.0127	42	0.0204	0.0149	64	0.0253	0.0223
21	0.0165	0.0128	43	0.0197	0.0151	65	0.0228	0.0228
22	0.0160	0.0128	44	0.0191	0.0153	66	0.0221	0.0234

SS_f : Suspended Solids removed by drum filter

Table (5.11): Continued.

Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}	Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}	Growth period, day	The measured SS_f kg m^{-3}	The predicted SS_f kg m^{-3}
67	0.0229	0.0239	88	0.0303	0.0412	109	0.0756	0.0800
68	0.0228	0.0245	89	0.0326	0.0422	110	0.0602	0.0826
69	0.0288	0.0251	90	0.0308	0.0447	111	0.0732	0.0854
70	0.0268	0.0257	91	0.0323	0.0461	112	0.0681	0.0883
71	0.0272	0.0263	92	0.0291	0.0474	113	0.0704	0.0912
72	0.0279	0.0270	93	0.0461	0.0489	114	0.0632	0.0942
73	0.0294	0.0278	94	0.0360	0.0503	115	0.0716	0.0973
74	0.0278	0.0285	95	0.0553	0.0518	116	0.0647	0.1004
75	0.0296	0.0293	96	0.0521	0.0534	117	0.0675	0.1037
76	0.0287	0.0300	97	0.0646	0.0549	118	0.0773	0.1070
77	0.0306	0.0309	98	0.0465	0.0567	119	0.0746	0.1105
78	0.0294	0.0316	99	0.0484	0.0585	120	0.0683	0.1142
79	0.0312	0.0325	100	0.0616	0.0604	121	0.0774	0.1179
80	0.0348	0.0333	101	0.0656	0.0623	122	0.0739	0.1218
81	0.0411	0.0342	102	0.0594	0.0642	123	0.0741	0.1257
82	0.0317	0.0350	103	0.0540	0.0662	124	0.0773	0.1297
83	0.0342	0.0359	104	0.0595	0.0683	125	0.0803	0.1339
84	0.0393	0.0369	105	0.0649	0.0706	126	0.0726	0.1391
85	0.0455	0.0379	106	0.0704	0.0727	127	0.0806	0.1425
86	0.0392	0.0390	107	0.0541	0.0751			
87	0.0336	0.0401	108	0.0553	0.0775			

Table (5.12): The daily average of suspended solids removed by drum filter.

Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day	Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day	Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day
1	0.11	0.11	23	0.39	0.32	45	0.98	0.78
2	0.13	0.12	24	0.51	0.34	46	1.01	0.82
3	0.12	0.12	25	0.49	0.35	47	0.95	0.85
4	0.18	0.13	26	0.54	0.37	48	1.03	0.88
5	0.17	0.14	27	0.53	0.39	49	1.02	0.92
6	0.17	0.14	28	0.61	0.40	50	1.12	0.95
7	0.23	0.15	29	0.60	0.42	51	1.27	0.99
8	0.20	0.16	30	0.58	0.44	52	1.18	1.02
9	0.24	0.17	31	0.59	0.46	53	1.16	1.06
10	0.20	0.18	32	0.66	0.48	54	1.18	1.10
11	0.21	0.19	33	0.72	0.50	55	1.40	1.14
12	0.31	0.19	34	0.79	0.52	56	1.40	1.18
13	0.23	0.20	35	0.82	0.54	57	1.27	1.22
14	0.25	0.21	36	0.77	0.56	58	1.30	1.27
15	0.33	0.22	37	0.83	0.59	59	1.56	1.34
16	0.31	0.23	38	0.94	0.61	60	1.51	1.39
17	0.32	0.25	39	0.82	0.64	61	1.65	1.45
18	0.40	0.26	40	0.85	0.67	62	1.51	1.50
19	0.27	0.27	41	0.90	0.69	63	1.65	1.56
20	0.39	0.28	42	0.99	0.72	64	1.73	1.62
21	0.38	0.29	43	0.11	0.11	65	1.90	1.68
22	0.38	0.31	44	0.98	0.75	66	1.74	1.74

SS_f : Suspended Solids removed by drum filter

Table (5.12): Continued.

Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day	Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day	Growth period, day	The measured SS_f kg/day	The predicted SS_f kg/day
67	1.71	1.81	88	3.23	3.85	109	5.99	8.40
68	1.80	1.87	89	2.93	3.99	110	8.23	8.70
69	1.81	1.94	90	3.18	4.12	111	6.56	9.01
70	2.32	2.02	91	3.02	4.39	112	8.01	9.35
71	2.19	2.09	92	3.21	4.58	113	7.48	9.69
72	2.24	2.17	93	2.91	4.75	114	9.45	10.04
73	2.33	2.26	94	4.65	4.92	115	8.50	10.40
74	2.48	2.34	95	3.65	5.10	116	9.64	10.77
75	2.37	2.44	96	5.64	5.28	117	8.73	11.15
76	2.56	2.53	97	5.34	5.47	118	9.13	11.53
77	2.51	2.63	98	6.66	5.67	119	10.47	11.93
78	2.70	2.72	99	4.82	5.88	120	10.12	12.35
79	2.62	2.82	100	5.05	6.10	121	7.64	12.78
80	2.80	2.92	101	6.45	6.32	122	10.53	13.22
81	3.16	3.02	102	6.91	6.55	123	10.07	13.67
82	3.76	3.13	103	6.28	6.79	124	10.11	14.14
83	2.93	3.24	104	5.74	7.04	125	10.56	14.61
84	3.18	3.35	105	6.35	7.29	126	10.98	15.10
85	3.69	3.46	106	6.96	7.56	127	11.43	15.70
86	4.30	3.59	107	7.58	7.82			
87	3.74	3.72	108	5.84	8.11			

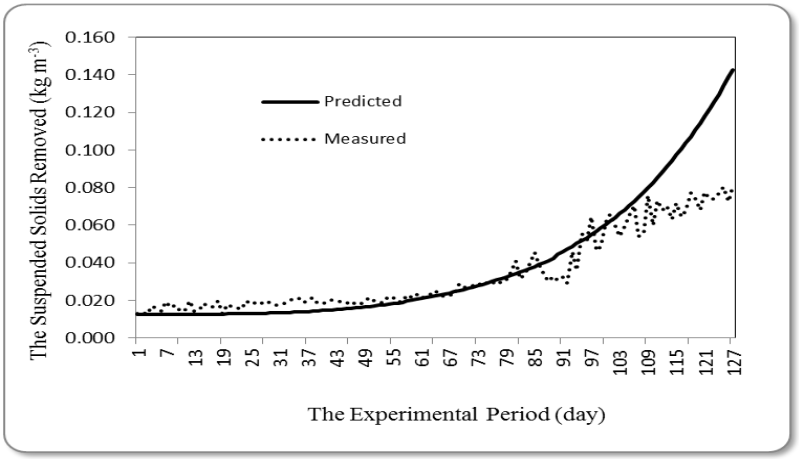

Figure (5.18): The predicted and the measured suspended solids removal from the system (RAS) during the growth period of fish.

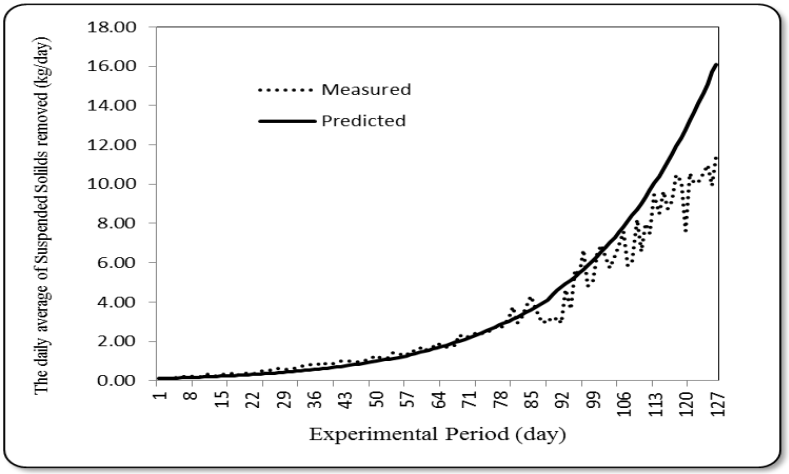

Figure (5.19): The daily average of suspended solids removed by the drum filter during the growth period of fish.

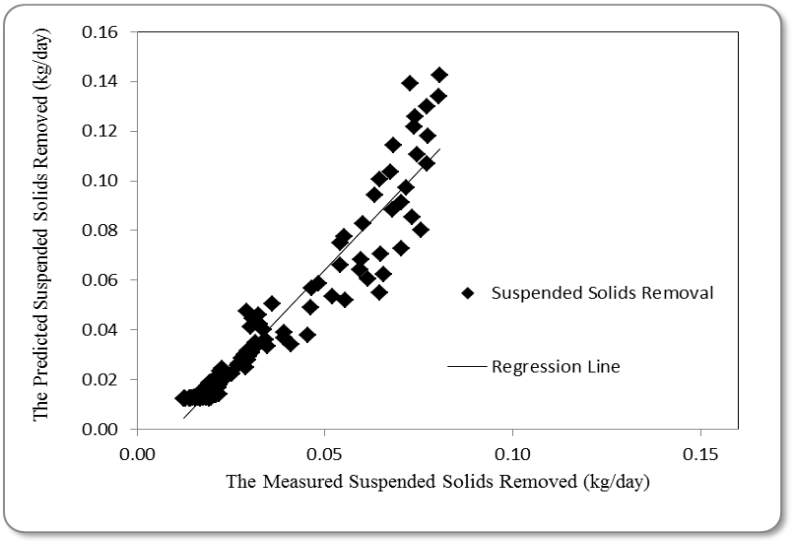

Figure (5.20): The predicted and the measured suspended solids removal from the system (RAS) during the growth period of fish.

5.1.6.3. The efficiency in removing solids:

1. Hydrocyclone efficiency in removing settleable solids:

Hydrocyclone efficiency in removing settleable solids was determined by measuring the settleable solids concentration in the water entering the hydrocyclone and the settleable concentration in the water leaving it. The data represented in table (5.13) and figure (5.21) show that the efficiency of the hydrocyclone for settleable solids removal from the system ranged from 27.4 to 57.79 %. These results are in agreement with those obtained by **Twarowska *et al.* (1997)**.

Table (5.13): The efficiency of the removal settleable and suspended solids (%)

Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %	Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %	Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %
1	41.78	57.71	23	34.86	27.94	45	37.57	37.12
2	57.79	39.80	24	35.66	37.15	46	46.03	33.00
3	43.92	40.37	25	33.85	23.66	47	42.50	38.53
4	34.61	47.37	26	37.14	24.15	48	43.00	39.78
5	49.08	42.22	27	29.80	28.96	49	33.71	39.31
6	49.60	55.03	28	32.21	37.41	50	38.87	35.60
7	52.08	45.61	29	27.41	29.57	51	37.02	37.91
8	39.51	28.80	30	39.76	25.23	52	38.31	36.00
9	52.59	31.89	31	40.35	41.49	53	37.93	30.58
10	40.82	18.86	32	42.26	36.99	54	42.05	43.85
11	38.98	20.48	33	38.65	40.41	55	56.22	43.22
12	44.55	24.94	34	46.71	40.30	56	37.56	28.30
13	42.69	20.12	35	29.78	41.42	57	42.41	28.57
14	38.46	18.09	36	43.69	30.95	58	48.09	43.28
15	41.30	23.70	37	39.93	32.18	59	38.36	43.57
16	49.63	36.85	38	40.26	42.81	60	44.99	36.02
17	38.54	21.99	39	45.76	38.83	61	47.21	20.83
18	40.17	21.21	40	40.65	38.37	62	48.70	23.69
19	45.08	15.46	41	38.57	36.54	63	46.42	46.25
20	37.61	23.68	42	34.47	31.05	64	42.80	36.51
21	45.71	35.92	43	30.45	30.77	65	42.76	25.32
22	43.89	38.96	44	36.34	33.66	66	37.02	22.20

Table (5.13): Continued.

Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %	Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %	Growth period, day	Hydrocyclone efficiency %	Drun filter efficiency %
67	36.94	23.52	88	39.11	51.26	109	45.23	70.65
68	36.97	24.72	89	40.82	48.32	110	45.00	72.26
69	39.84	29.61	90	39.60	56.06	111	41.34	73.69
70	43.23	31.20	91	42.73	56.01	112	39.67	71.60
71	46.99	30.28	92	44.56	36.06	113	40.83	71.53
72	45.23	30.77	93	39.74	52.15	114	38.02	63.13
73	47.37	30.92	94	46.10	50.53	115	41.39	65.19
74	40.05	37.78	95	46.14	57.02	116	43.20	68.64
75	40.56	33.40	96	43.79	56.56	117	43.82	67.74
76	38.98	34.15	97	39.21	54.61	118	40.21	71.15
77	36.40	42.43	98	41.43	42.47	119	40.89	73.09
78	39.44	32.37	99	42.42	47.92	120	41.18	71.62
79	48.02	39.72	100	44.68	66.68	121	39.02	69.30
80	44.30	48.99	101	41.80	67.75	122	34.97	72.84
81	43.42	51.51	102	41.20	65.69	123	43.03	74.41
82	42.76	37.02	103	41.95	64.66	124	43.92	72.65
83	43.87	51.75	104	41.00	64.20	125	44.72	72.28
84	40.70	44.68	105	45.13	65.26	126	40.44	70.69
85	44.42	45.38	106	42.72	66.13	127	39.91	73.37
86	44.42	42.73	107	40.63	64.75			
87	40.69	45.74	108	43.85	68.24			

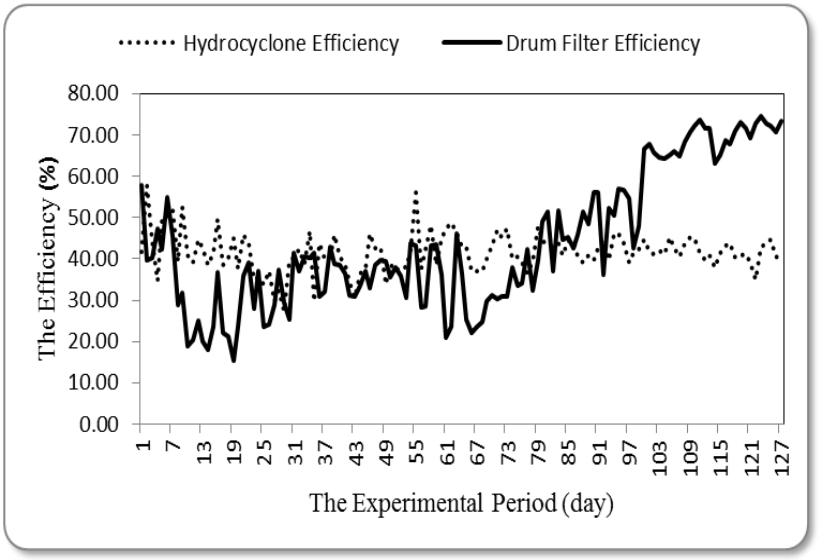

Figure (5.21): The efficiency of the settleable and suspended solids removal from the recirculating aquaculture system (RAS) during the growth period of fish.

2. The drum filter efficiency:

The efficiency of the drum filter was determined by measuring the suspended solids concentration in the water entering the drum and the suspended concentration in the water leaving the drum. Since the drum was continuously rotated, washing is always takes place, which keeps the filter ables to remove the suspended solids with good efficiency a convenient means of measuring drum efficiency. The data presented in table

(5.14) and figure (5.21) show the efficiency of the drum filter for suspended solids removal from the system which ranged from 15.46 to 74.41 %. These results are in agreement with **d'Orbcastel *et al.* (2009)** whose found that the suspended solids efficiency of 40 ± 18.5%.

5.1.7. Fish Growth Rate:

Table (5.15) and figure (5.22a and b) show the predicted and the measured growth rate of the individual fish. It could be seen that the daily average fish growth rate from the system ranged from 0.26 to 1.46 g/day experimentally while it was from 0.11 to 1.96 g/day theoretically. These results are in agreement with **Imsland *et al.* (1996)** and **Rodrigo and Olivares (2004)**.

Regression analysis was carried out to find a relationship between the measured and the predicted fish growth rate values for the system was as follows:

$$FGR_p = 1.3115\ FGR_m - 0.1952 \qquad R^2 = 0.929 \qquad (5.12)$$

Where:-

FG_P is the predicted fish growth rate, g/day

FG_M is the measured fish growth rate, g/day

Table (5.15): The comparison between the measured and the predicted fish growth rate.

Growth period, day	The measured FGR g/day	The predicted FGR g/day	Growth period, day	The measured FGR g/day	The predicted FGR g/day	Growth period, day	The measured FGR g/day	The predicted FGR g/day
1	0.26	0.11	23	0.59	0.61	45	1.01	0.81
2	0.26	0.12	24	0.59	0.62	46	1.01	0.81
3	0.26	0.14	25	0.59	0.63	47	1.01	0.82
4	0.26	0.18	26	0.59	0.64	48	1.01	0.82
5	0.26	0.20	27	0.59	0.65	49	1.01	0.83
6	0.26	0.24	28	0.59	0.65	50	0.89	0.84
7	0.26	0.28	29	0.72	0.68	51	0.89	0.84
8	0.35	0.33	30	0.72	0.69	52	0.89	0.86
9	0.35	0.36	31	0.72	0.70	53	0.89	0.88
10	0.35	0.40	32	0.82	0.71	54	0.89	0.89
11	0.35	0.41	33	0.62	0.72	55	0.89	0.92
12	0.35	0.44	34	0.72	0.74	56	0.89	0.94
13	0.35	0.47	35	0.72	0.75	57	0.98	0.92
14	0.35	0.50	36	0.82	0.76	58	0.98	0.93
15	0.45	0.52	37	0.82	0.77	59	0.98	0.93
16	0.45	0.53	38	0.82	0.77	60	0.98	0.94
17	0.45	0.54	39	0.82	0.78	61	0.98	0.94
18	0.45	0.56	40	0.82	0.78	62	0.98	0.94
19	0.45	0.56	41	0.82	0.78	63	0.98	0.95
20	0.45	0.58	42	0.82	0.79	64	1.02	0.96
21	0.45	0.60	43	1.01	0.79	65	1.02	0.97
22	0.59	0.60	44	1.01	0.80	66	1.02	0.97

FGR : Fish Growth Rate

Table (5.15): Continued.

Growth period, day	The measured FGR g/day	The predicted FGR g/day	Growth period, day	The measured FGR g/day	The predicted FGR g/day	Growth period, day	The measured FGR g/day	The predicted FGR g/day
67	1.02	0.98	88	1.12	1.28	109	1.36	1.68
68	1.02	0.98	89	1.12	1.31	110	1.36	1.70
69	1.02	0.99	90	1.12	1.33	111	1.36	1.73
70	1.02	1.00	91	1.02	1.34	112	1.36	1.75
71	1.1	1.01	92	1.02	1.35	113	1.36	1.77
72	1.1	1.02	93	1.2	1.36	114	1.41	1.78
73	1.1	1.03	94	1.2	1.36	115	1.41	1.79
74	1.1	1.04	95	1.2	1.36	116	1.41	1.80
75	1.1	1.05	96	1.2	1.37	117	1.41	1.81
76	1.1	1.06	97	1.2	1.39	118	1.41	1.82
77	1.1	1.08	98	1.2	1.42	119	1.41	1.82
78	1.04	1.10	99	1.2	1.44	120	1.41	1.83
79	1.04	1.12	100	1.19	1.47	121	1.46	1.84
80	1.04	1.14	101	1.19	1.51	122	1.46	1.86
81	1.04	1.15	102	1.19	1.54	123	1.46	1.88
82	1.04	1.16	103	1.19	1.56	124	1.46	1.90
83	1.04	1.18	104	1.19	1.58	125	1.46	1.92
84	1.04	1.20	105	1.19	1.61	126	1.46	1.94
85	1.12	1.21	106	1.19	1.63	127	1.46	1.96
86	1.12	1.23	107	1.36	1.64			
87	1.12	1.25	108	1.36	1.66			

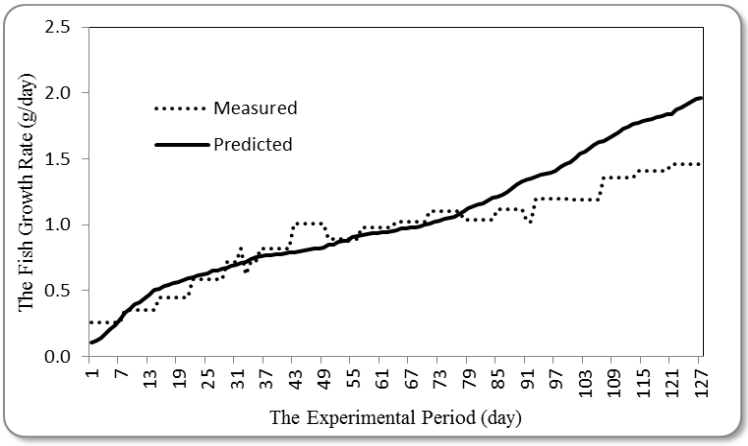

Figure (5.22a): The measured and the predicted fish growth rate in recirculating aquaculture system (RAS) during the growth period of fish.

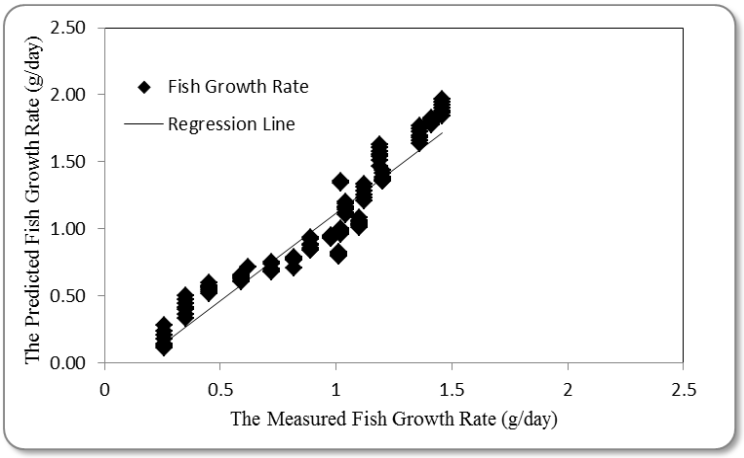

Figure (5.22b): The comparison between the measured and the predicted fish growth rate in recirculating aquaculture system (RAS) during the growth period of fish.

5.1.8. Specific Growth Rate (SGR):

The specific growth rate is an indicator of the daily weight gained of the fish at a certain times. The table (5.16) and figure (5.23) show the actual and the theoretical specific growth rate. These results showed that the specific growth rate ranged from 1.18 to 4.83 % actually while it was estimated to be from 1.26 to 5.42 % theoretically. These results similar to those reported by **Poxton *et al.* (1982)**, **Imsland *et al.* (1996)** and **Rodrigo and Olivares (2004)**.

The variations between the actual and the theoretical specific growth rate of fish in recirculating aquaculture system (RAS) are shown in figure (5.23). It shows that the actual and the theoretical specific growth rate are in a reasonable agreement. The best fit for the relationship between the actual and the theoretical specific growth rate values was as follows:

$$SGR_{th} = 0.9435 SGR_{act} + 0.2529 \qquad R^2 = 0.87 \qquad (5.13)$$

Where:

SGR_{th} is the theoretical specific growth rate, %

SGR_{act} is the actual specific growth rate, %

Table (5.16): The actual and theoretical specific growth rate (%).

Growth period, day	SGR_{act} %	SGR_{act} %	Growth period, day	SGR_{act} %	SGR_{act} %	Growth period, day	SGR_{act} %	SGR_{act} %
1	4.30	3.33	23	4.78	4.88	45	3.53	3.79
2	3.92	3.29	24	4.57	4.71	46	3.01	2.87
3	3.59	4.67	25	4.37	4.55	47	2.98	2.98
4	3.30	4.25	26	4.18	4.39	48	2.58	2.91
5	4.03	4.26	27	4.02	4.25	49	2.89	2.55
6	4.79	4.88	28	3.67	4.12	50	2.69	2.50
7	4.57	4.21	29	4.53	4.00	51	2.62	2.45
8	4.84	4.38	30	4.33	3.88	52	2.83	2.41
9	4.52	4.26	31	4.15	3.77	53	2.20	2.37
10	4.23	4.15	32	4.53	3.67	54	2.42	2.87
11	4.97	5.42	33	3.29	4.36	55	2.37	2.54
12	4.73	5.22	34	3.69	3.71	56	2.31	2.50
13	4.52	5.03	35	3.56	3.61	57	2.91	3.44
14	4.32	4.86	36	3.91	3.51	58	2.37	3.35
15	4.30	4.69	37	3.76	4.32	59	2.31	2.79
16	4.03	4.54	38	3.62	3.53	60	2.26	2.28
17	4.79	4.40	39	3.50	3.23	61	2.21	2.24
18	4.57	4.27	40	3.38	3.15	62	2.07	2.20
19	4.37	4.15	41	3.27	3.28	63	2.16	2.77
20	4.19	3.85	42	3.16	3.20	64	2.20	2.75
21	4.28	4.36	43	3.76	4.04	65	2.16	2.36
22	4.02	4.64	44	2.92	3.91	66	2.11	2.32

SGR : Specific Growth Rate

Table (5.16): Continued.

Growth period, day	SGR_{act} %	SGR_{act} %	Growth period, day	SGR_{act} %	SGR_{act} %	Growth period, day	SGR_{act} %	SGR_{act} %
67	2.07	2.08	88	1.61	1.61	109	1.61	1.61
68	2.02	2.04	89	1.58	1.45	110	1.58	1.45
69	1.98	2.01	90	1.56	1.43	111	1.56	1.43
70	1.95	1.98	91	1.40	1.55	112	1.40	1.55
71	2.06	1.95	92	3.14	3.13	113	3.14	3.13
72	2.02	1.93	93	1.57	1.76	114	1.57	1.76
73	1.98	1.90	94	1.55	1.48	115	1.55	1.48
74	1.94	2.05	95	1.52	1.47	116	1.52	1.47
75	1.90	2.02	96	1.50	1.45	117	1.50	1.45
76	1.87	1.82	97	1.48	1.44	118	1.48	1.44
77	1.83	1.79	98	1.46	1.42	119	1.46	1.42
78	1.70	1.77	99	1.56	1.41	120	1.56	1.41
79	1.67	1.75	100	1.40	1.63	121	1.40	1.63
80	1.64	1.57	101	1.50	1.61	122	1.50	1.61
81	1.62	1.55	102	1.59	1.36	123	1.59	1.36
82	1.59	1.53	103	1.34	1.46	124	1.34	1.46
83	1.57	1.67	104	1.43	1.44	125	1.43	1.44
84	1.54	1.65	105	1.41	1.32	126	1.41	1.32
85	1.57	1.70	106	1.39	1.52	127	1.39	1.52
86	1.58	1.69	107	1.45	1.50			
87	1.64	1.63	108	1.32	1.28			

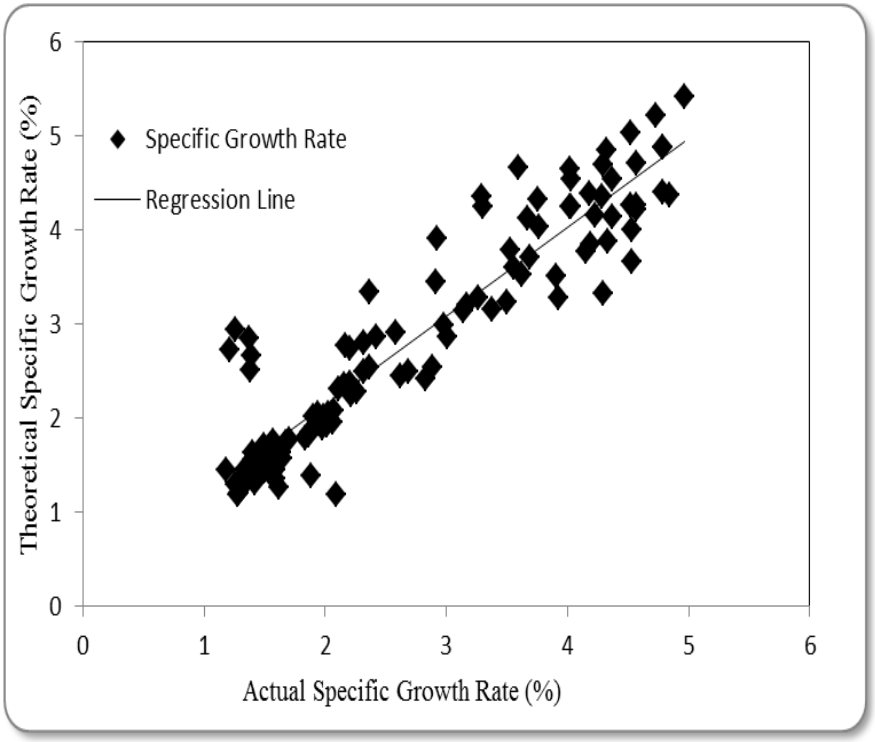

Figure (5.23): The actual and theoretical specific growth rate of fish in recirculating aquaculture system (RAS).

5.1.9. Feed Conversion Rate

Table (5.17) and figure (5.24) show the actual and the theoretical feed conversion rate (kg feed/kg added to the fish weight) during the whole period of fish growth in recirculating aquaculture system (RAS). These results showed that the feed conversion rate ranged from 0.61 to 2.25 kg feed / kg fish actually, while, it was estimated to be from 0.50 to 1.94 kg feed / kg fish theoretically. These results are in agreement with **Labatut (2001)** who found that the feed conversion rate about 0.8 to 1.9 kg feed / kg fish.

The variations between the actual and the theoretical feed conversion rate are shown in figure (5.25). It shows the actual and the theoretical feed conversion rate are in a reasonable agreement. The best fit for the relationship between the actual and the theoretical feed conversion rate values was as follows:

$$FCR_{th} = 0.7771 FCR_{act} + 0.2345 \qquad R^2 = 0.808 \qquad (5.14)$$

Where:

FCR_{th} is the theoretical feed conversion rate, kg feed/kg fish

FCR_{act} is the actual feed conversion rate, kg feed/kg fish

Table (5.17): The actual and theoretical feed conversion rate.

Growth period, day	FGR_{act}	FCR_{th}	Growth period, day	FGR_{act}	FCR_{th}	Growth period, day	FGR_{act}	FCR_{th}
1	0.62	0.48	23	0.82	0.80	45	1.11	1.04
2	0.66	0.49	24	0.86	0.83	46	1.31	1.12
3	0.70	0.50	25	0.90	0.86	47	1.32	1.32
4	0.74	0.53	26	0.94	0.89	48	1.53	1.35
5	0.78	0.53	27	0.98	0.92	49	1.37	1.55
6	0.82	0.56	28	1.07	0.95	50	1.47	1.58
7	0.86	0.62	29	0.86	0.98	51	1.51	1.61
8	0.67	0.89	30	0.90	1.01	52	1.39	1.64
9	0.71	0.92	31	0.94	1.04	53	1.80	1.67
10	0.75	0.94	32	0.86	1.07	54	1.63	1.37
11	0.79	0.72	33	1.20	1.09	55	1.67	1.55
12	0.83	0.75	34	1.06	1.06	56	1.71	1.58
13	0.87	0.78	35	1.10	1.09	57	1.79	1.14
14	0.91	0.80	36	1.00	1.12	58	1.67	1.17
15	0.74	0.83	37	1.04	1.12	59	1.71	1.41
16	0.78	0.86	38	1.08	1.11	60	1.75	1.73
17	0.82	0.89	39	1.12	1.22	61	1.77	1.76
18	0.86	0.92	40	1.16	1.25	62	1.79	1.76
19	0.90	0.94	41	1.20	1.20	63	1.83	1.24
20	0.94	1.02	42	1.24	1.23	64	1.80	1.27
21	0.91	0.90	43	1.04	1.17	65	1.84	1.68
22	0.78	0.84	44	1.35	1.00	66	1.88	1.71

FGR: Feed Conversion rate (kg feed/kg added to the fish weight)

Table (5.17): Continued.

Growth period, day	FGR_{act}	FCR_{th}	Growth period, day	FGR_{act}	FCR_{th}	Growth period, day	FGR_{act}	FCR_{th}
67	1.92	1.91	88	1.85	1.85	109	1.84	1.60
68	1.96	1.94	89	1.88	1.58	110	2.02	1.47
69	1.50	1.48	90	1.91	1.79	111	2.17	1.70
70	1.53	1.50	91	1.53	1.92	112	2.20	1.93
71	1.44	1.52	92	1.41	1.84	113	1.39	1.41
72	1.47	1.54	93	1.89	1.69	114	2.26	1.73
73	1.50	1.57	94	1.92	1.61	115	2.28	1.67
74	1.53	1.45	95	1.95	1.53	116	1.95	1.68
75	1.56	1.47	96	1.98	1.53	117	1.33	1.16
76	1.59	1.64	97	2.01	1.75	118	1.54	1.50
77	1.62	1.66	98	2.04	1.80	119	1.56	1.51
78	1.75	1.68	99	1.91	1.82	120	1.58	1.53
79	1.78	1.70	100	2.12	1.83	121	1.54	1.65
80	1.81	1.90	101	1.99	1.85	122	1.56	1.67
81	1.84	1.92	102	1.87	1.79	123	1.58	1.67
82	1.87	1.94	103	2.22	1.74	124	1.85	1.63
83	1.90	1.79	104	2.08	1.67	125	1.95	1.69
84	1.93	1.81	105	2.11	1.64	126	1.82	1.79
85	1.82	1.83	106	2.14	1.96	127	1.65	1.73
86	1.78	1.84	107	2.06	1.98			
87	1.83	1.87	108	2.25	1.74			

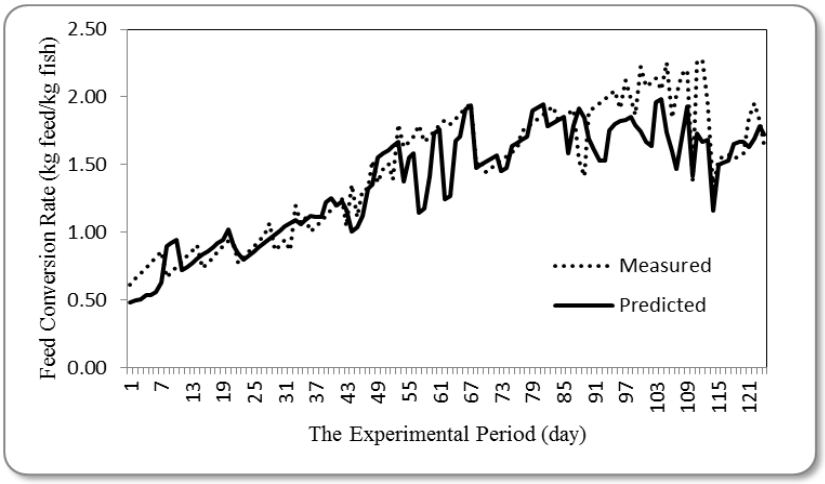

Figure (5.24): The actual and theoretical feed conversion rate.

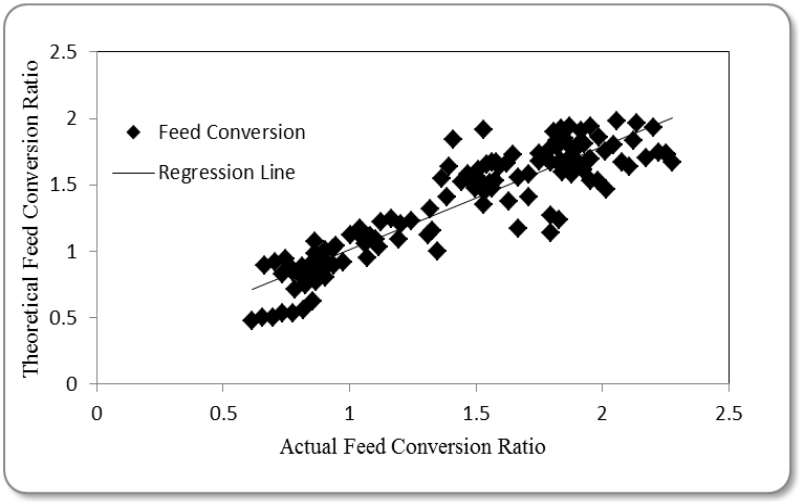

Figure (5.25): The comparison between the actual and theoretical feed conversion rate.

5.1.10. Power and Energy

Table (5.18) and figure (5.26) show the power consumed by the recirculating aquaculture system which include: water pump, durm filter motor, biological filter motor, air blower and water heater. The highest value of power consumption was 5.10 kW for water heater during the whole period of fish growth in recirculating aquaculture system (RAS), but the lowest value of power consumption was 0.35 kW for durm filter motor.

Table (5.18) and figure (5.27) show the energy was consumed by water pump, durm filter motor, biological filter motor, air blower and water heater per day during the whole period of fish growth in recirculating aquaculture system (RAS). The highest value of energy consumption per day was 110276.40 kJ for water heater, but the lowest value of energy consumption per day was 30155.04 kJ for durm filter motor.

The actual energy consumption by whole system duringthe whole day was 377252.50 kJ.day.

Table (5.18): Power and energy consumption in the recirculating aquaculture system.

Items	Power, kW	Energy, kJ.day
Pump water	0.90	77656.92
Drum filter motor	0.35	30551.04
Biofilter motor	0.59	51193.30
Air blower	1.24	107557.63
Heater	5.11	110276.40

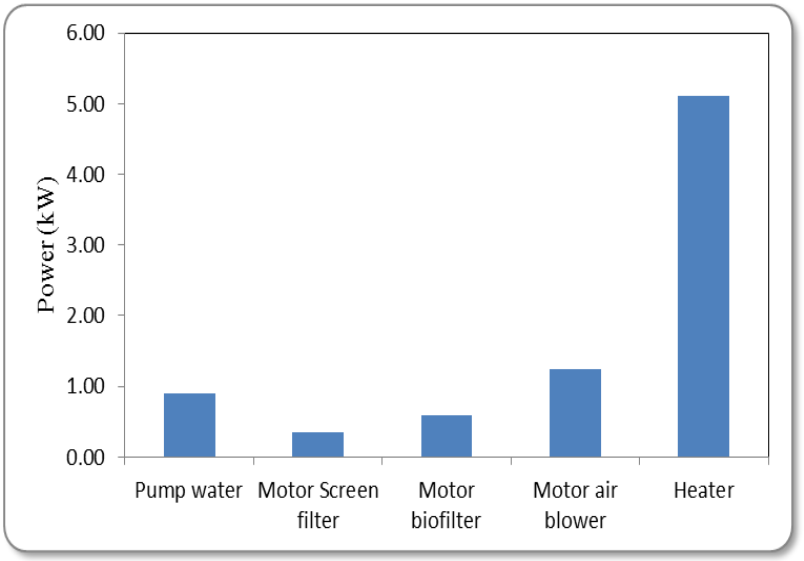

Figure (5.26): Power used in the recirculating aquaculture system.

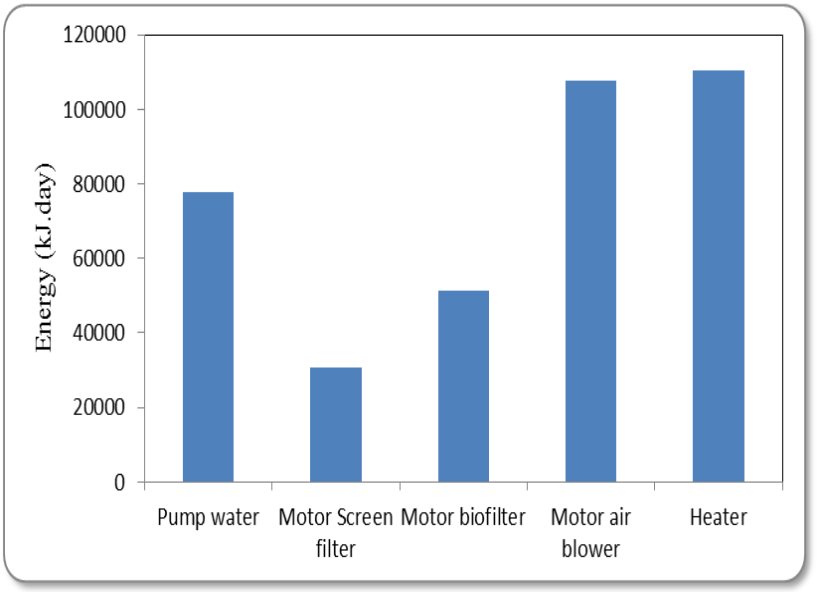

Figure (5.27): Energy consumption in the recirculating aquaculture system

The average contribution for each energy vector is shown in figure (5.28). The model had tendency to over-estimate the temperature. This tendency to over-predict may be explained in the following ways:

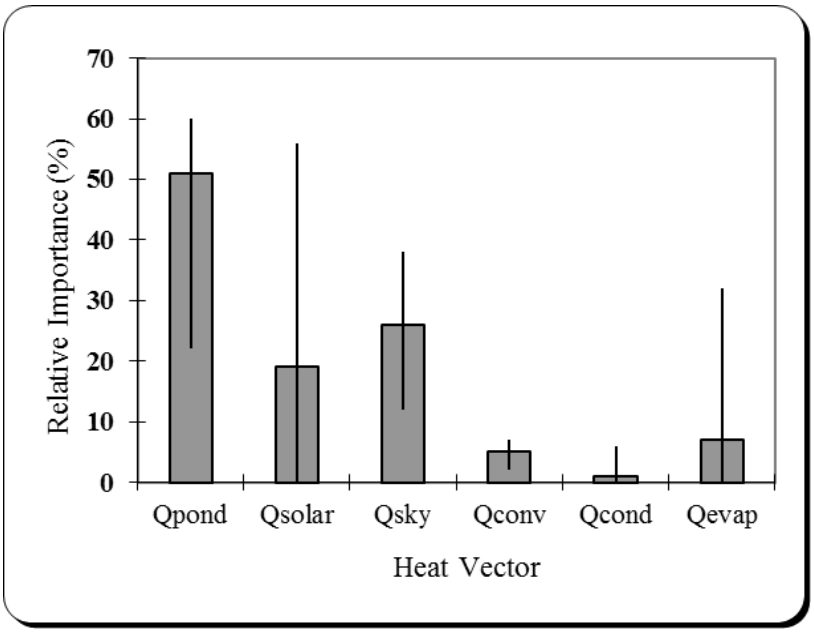

Figure (5.28): The relative importance for each energy vector for model run. The bars represent the average relative importance while the line extensions represent the range.

- Model was sometimes over-estimating energy vectors entering the pond. Such energy vectors included solar radiation and longwave sky radiation. By over-estimating the amount of energy entering the system, the system internal energy and temperature were also over-estimate.

- Model was under-estimating energy losses, perhaps because the evaporation rate was being under-estimated. Evaporation was important to the energy balance. Evaporation, on average, account for 0 to 32% of all energy transit. The equation (3.31) was designed to predict the daily evaporation over a lake using the daily average wind speed and not the instantaneous wind speed recorded every hour as does model.
- For natural system, the importance of air convection and wall conduction was between 1 - 4% of the total (figure 5.26). Because the temperature gradient between the pond and its environment, the driving force behind both heat transfer mechanisms, was small, these vectors were not as important as radiation energy transfer mechanisms (for instance, the average importance for longwave sky radiation ranged from 0 to 56%).
- The importance of surface convection and evaporation was greater for heated pond because of the greater temperature gradient between the pond and the air. Both sets of equations used by model to predict the size of both surface energy vectors were empirical and might not have been accurate when they dominated other modes of energy transfer. This happened at night or on cloudy days when there was little

solar radiation and no bulk movements of energy associated with water flows.

Energy transfer mechanisms which were important to uncontrolled ponds were radiation heat transfer mechanisms (figure 5.28). The average importance of pond radiation, longwave sky radiation and solar radiation were 51%, 26% and 19% (ranged between 22 - 60%, 0 – 56% and 12 – 38%), depending on the time of day and year. Solar and longwave sky radiation were, therefore the two most important influxes of energy for ponds while pond radiation was the greatest source of heat loss. Evaporation also seemed to be important (range, 0–32%) although its average importance was small (7%) compared to the radiation heat transfer mechanisms. Air convection (average importance, 2–7%) and wall conduction (average importance, 0–6%) were not as important because the temperature difference which drove these heat transfer mechanisms was relatively small.

5.2. Model Experimentations:

5.2.1. Water temperature at different ambient air temperatures:

The average hourly water temperature was determined at different ambient air temperatures (23, 25, 27, 29 and 31˚C) for an average day during the period as shown in table (5.19) and figure (5.29). It indicates that the average hourly water temperature increases with increasing the ambient air temperature. The results indicate that when the ambient air temperature increased from 23 to 31 ˚C, the water temperature increased from 18.92 to 26.74 ˚C at 6:00 am, while it increased from 23.73 to 32.37 ˚C at 18:00. It seems that the water temperature changed by the same level as the ambient air temperature changed. It could be noticed that averaged water temperature was always less than the ambient air temperature.

Table (5.19): The water temperature at different ambient air temperatures.

Ambient Temperature ˚C / Timing,Hour	23	25	27	29	31
	Water Temperature ˚C				
6.00	18.92	20.35	24.66	26.03	26.74
7.00	19.18	20.99	24.78	26.48	27.21
8.00	19.54	21.40	25.14	26.80	27.69
9.00	19.96	22.01	25.48	27.15	28.15
10.00	20.20	22.53	25.73	27.42	28.80
11.00	20.75	23.1	26.23	27.95	29.27
12.00	21.28	23.97	26.91	28.34	29.81
13.00	21.79	24.29	27.33	28.78	30.22
14.00	22.13	24.71	27.86	29.02	30.70
15.00	22.68	25.14	28.09	29.66	31.09
16.00	23.01	25.48	28.43	30.17	31.54
17.00	23.42	25.76	28.81	30.81	32.01
18.00	23.73	25.99	28.96	31.18	32.37
19.00	23.58	25.82	28.75	30.64	32.03
20.00	23.17	25.19	28.26	30.05	31.61
21.00	22.89	24.8	27.83	29.49	31.12
22.00	22.31	24.09	27.19	28.87	30.74
23.00	21.94	23.71	26.86	28.41	30.16
0.00	21.55	23.28	26.33	27.76	29.70
1.00	21.06	22.93	25.92	27.33	29.09
2.00	20.72	22.16	25.48	27.08	28.53
3.00	20.30	21.55	24.96	26.74	27.94
4.00	19.94	21.03	24.73	26.31	27.31
5.00	19.52	20.67	24.69	25.96	27.00
6.00	19.08	20.14	24.68	25.50	26.62

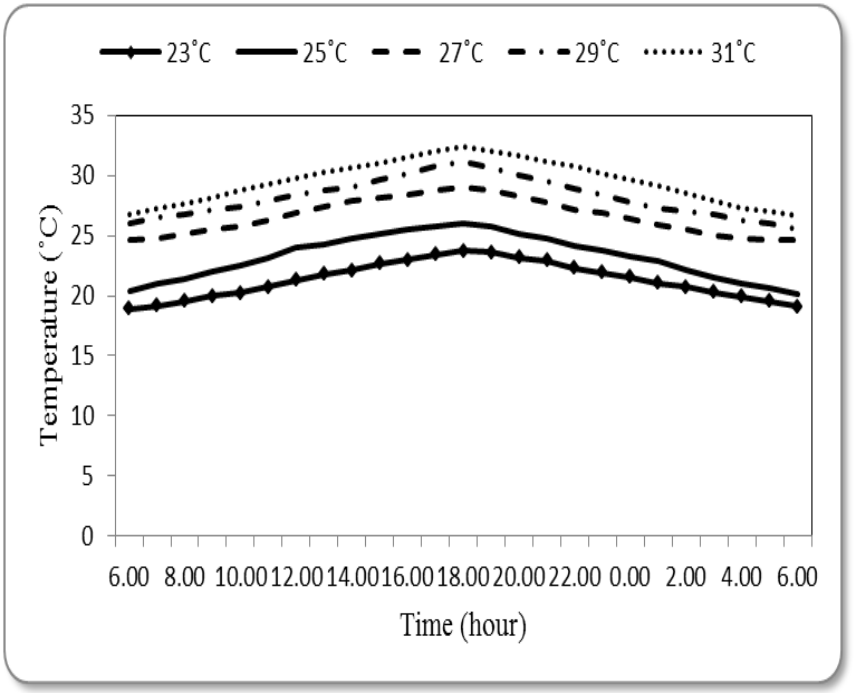

Figure (5.29): The water temperature at different ambient air temperatures.

5.2.2. The oxygen consumption:

Oxygen consumed mainly by fish and partially by nitrification and bacteria respiration.

5.2.2.1. The oxygen consumption of fish at different water temperatures:

The oxygen consumption (OC) at different water temperatures (24, 26, 28, 30 and 32˚C) are shown in table (5.20) and figure (5.30). It indicates that the oxygen consumption increases with increasing water temperature, meanwhile, the oxygen consumption decreases with increasing fish weight, where, it increased from 302.02 to 732.70 mg O_2/kg fish. hour when the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g).

Table (5.20): The effect of water temperature and fish weight on the oxygen consumption.

Temperature, ˚C / Fish weight (g)	24	26	28	30	32
	Oxygen Consumption mg O_2/kg fish.hour				
5	302.06	362.56	454.50	577.88	732.70
15	280.56	336.86	424.60	543.78	694.40
25	260.46	312.56	396.10	511.08	657.50
35	241.76	289.66	369.00	479.78	622.00
45	224.46	268.16	343.30	449.88	587.90
55	208.56	248.06	319.00	421.38	555.20
65	194.06	229.36	296.10	394.28	523.90
75	180.96	212.06	274.60	368.58	494.00
85	169.26	196.16	254.50	344.28	465.50
95	158.96	181.66	235.80	321.38	438.40
105	150.06	168.56	218.50	299.88	412.70
115	142.56	156.86	202.60	279.78	388.40
125	136.46	146.56	188.10	261.08	365.50
135	131.76	137.66	175.00	243.78	344.00
145	128.46	130.16	163.30	227.88	323.90
155	126.56	124.06	153.00	213.38	305.20
165	126.06	127.36	144.10	200.28	287.90
175	126.96	126.06	136.60	188.58	272.00
185	124.26	124.46	130.50	178.28	257.50
195	122.96	123.66	125.80	169.38	244.40
200	121.33	123.23	123.97	165.45	238.37

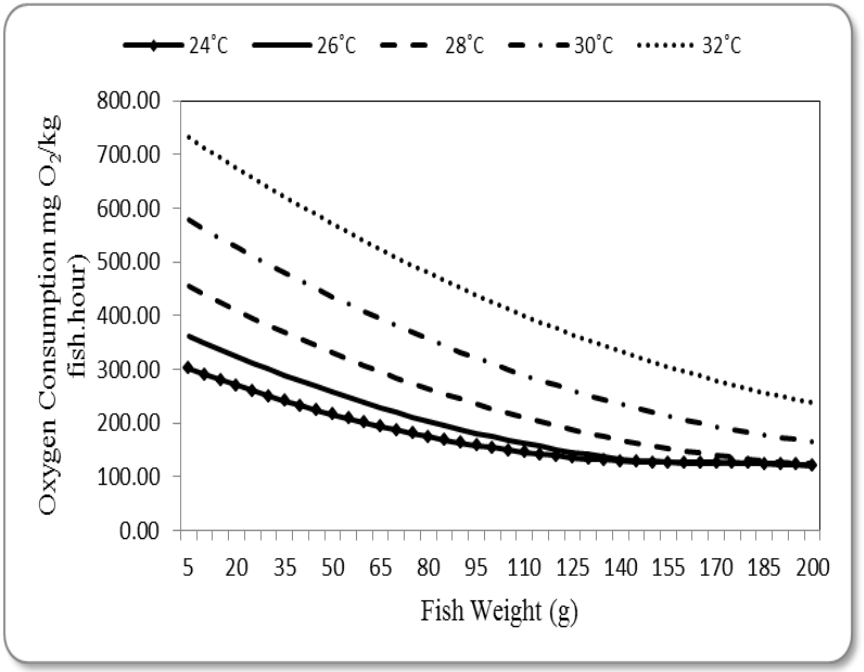

Figure (5.30): The effect of water temperature and fish weight on oxygen consumption.

On the other hand, oxygen consumption decreased from 302.02 to 121.33 mg O_2/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C, oxygen consumption decreased from 732.70 to 238.37 mg O_2/kg fish. hour with increasing the fish weight from 5 to 200 g.

5.2.2.2. Oxygen Consumption by Nitrification and bacteria respiration:

Figure (5.31) and appendix (B) show the predicted oxygen consumed by the nitrification and bacteria respiration. It was found that the predicted oxygen consumption values from the nitrification process ranged from 0.83 to 25.71 mg O_2/ hour, which represents from 0.17 to 9.35% from the total oxygen consumption. The results indicate the bacteria respiration consumed from 1.90 to 59.85 mg O_2/ hour, which represents from 0.40 to 21.51% of of the total oxygen consumption (282.41 to 480.62 mg O_2/hour).

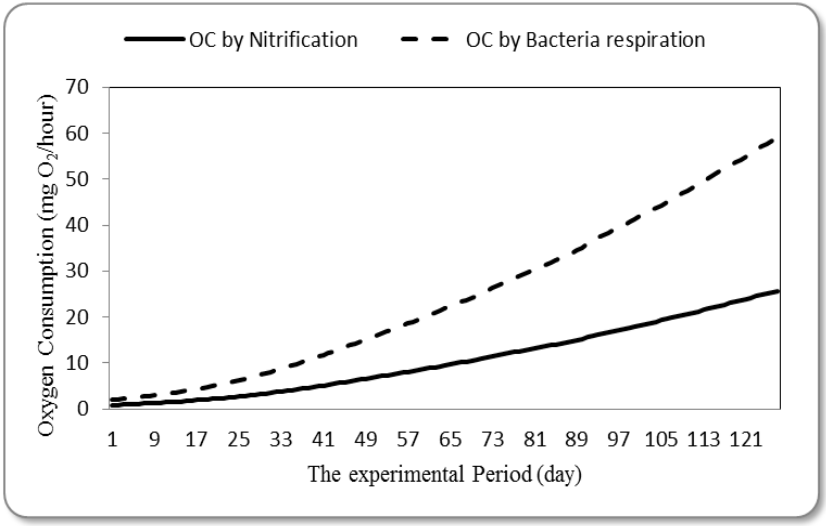

Figure (5.31): The predicted amount of oxygen consumed by nitrification and bacteria respiration.

5.2.3. Ammonia production at different water temperatures:

The ammonia production at different water temperatures (24, 26, 28, 30 and 32˚C) are shown in table (5.21) and figure (5.32). It indicates that the ammonia production increases with increasing water temperature but it decreases with increasing fish weight. Where, it increased from 43.20 to 52.94 mg NH_3/kg fish. hour when the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g). On the other hand, ammonia production decreased from 43.20 to 5.98 mg NH_3/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C, ammonia production decreased from 52.94 to 12.82 mg NH_3/kg fish. hour with increasing the fish weight from 5 to 200 g.

Table (5.21): The effect of water temperature and fish weight on ammonia production for the recirculation aquaculture system (RAS).

Temperature, ˚C / Fish weight (g)	24	26	28	30	32
	Ammonia Production mg NH_3/kg fish.hour				
5	43.20	45.63	48.07	50.50	52.94
15	38.08	40.46	42.85	45.23	47.62
25	33.34	35.67	38.01	40.34	42.68
35	28.98	31.26	33.55	35.83	38.12
45	25.00	27.23	29.47	31.70	33.94
55	21.40	23.58	25.77	27.95	30.14
65	18.18	20.31	22.45	24.58	26.72
75	15.34	17.42	19.51	21.59	23.68
85	12.88	14.91	16.95	18.98	21.02
95	10.80	12.78	14.77	16.75	18.74
105	9.10	11.03	12.97	14.90	16.84
115	7.78	9.66	11.55	13.43	15.32
125	6.84	8.67	10.51	12.34	14.18
135	6.28	8.06	9.85	11.63	13.42
145	6.10	7.83	9.57	11.30	13.04
155	6.08	7.78	9.50	11.25	12.96
165	6.04	7.65	9.46	11.18	12.94
175	6.02	7.63	9.39	11.09	12.92
185	6.01	7.60	9.32	11.06	12.89
195	5.99	7.56	9.27	10.03	12.84
200	5.98	7.54	9.24	10.01	12.82

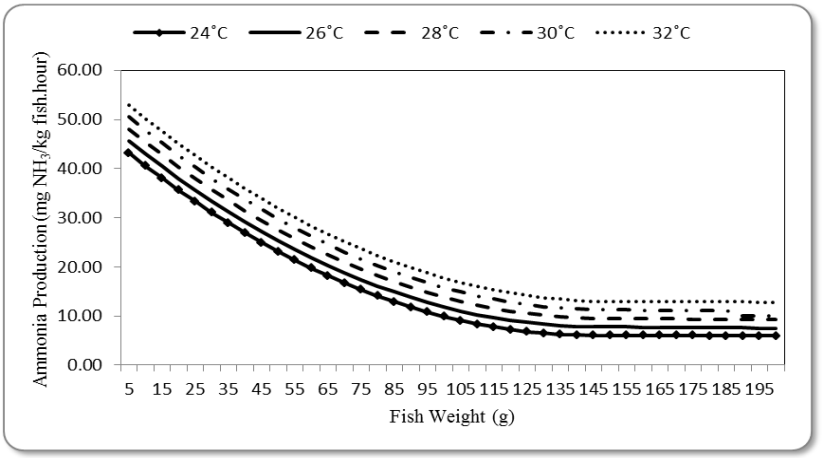

Figure (5.32): The effect of water temperature and fish weight on ammonia production.

5.2.4. Nitrate production at different water temperatures:

The nitrate production at different water temperatures (24, 26, 28, 30 and 32˚C) are shown in table (5.22) and figure (5.33). It could be seen that the nitrate production increases with increasing water temperature and it decreases with increasing fish weight. It increased from 187.48 to 229.75 mg NO_3/kg fish. hour when the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g). On the other hand, nitrate production decreased from 187.48 to 25.95 mg NO_3/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C, nitrate production decreased from 229.75 to 55.63 mg NO_3/kg fish. hour with increasing the fish weight from 5 to 200 g.

Table (5.22): The effect of water temperature and fish weight on nitrate production for the recirculation aquaculture system (RAS).

Temperature, ˚C / Fish weight (g)	24	26	28	30	32
	Nitrate Production mg NO_3/kg fish.hour				
5	187.48	198.05	208.61	219.18	229.75
15	165.26	175.61	185.96	196.31	206.66
25	144.68	154.82	164.95	175.09	185.22
35	125.76	135.68	145.59	155.51	165.43
45	108.49	118.19	127.89	137.59	147.29
55	92.87	102.35	111.83	121.31	130.80
65	78.89	88.16	97.42	106.69	115.95
75	66.56	75.61	84.66	93.71	102.76
85	55.89	64.72	73.55	82.38	91.216
95	46.86	55.48	64.09	72.71	81.32
105	39.48	47.88	56.28	64.68	73.07
115	33.75	41.94	50.12	58.30	66.48
125	29.67	37.64	45.60	53.57	61.53
135	27.24	34.99	42.74	50.49	58.23
145	26.46	33.99	41.52	49.05	56.58
155	26.37	33.78	41.22	48.84	56.26
165	26.21	33.21	41.05	48.53	56.17
175	26.14	33.13	40.76	48.14	56.06
185	26.09	32.99	40.47	47.99	55.95
195	26.00	32.83	40.22	43.54	55.71
200	25.95	32.74	40.10	43.44	55.63

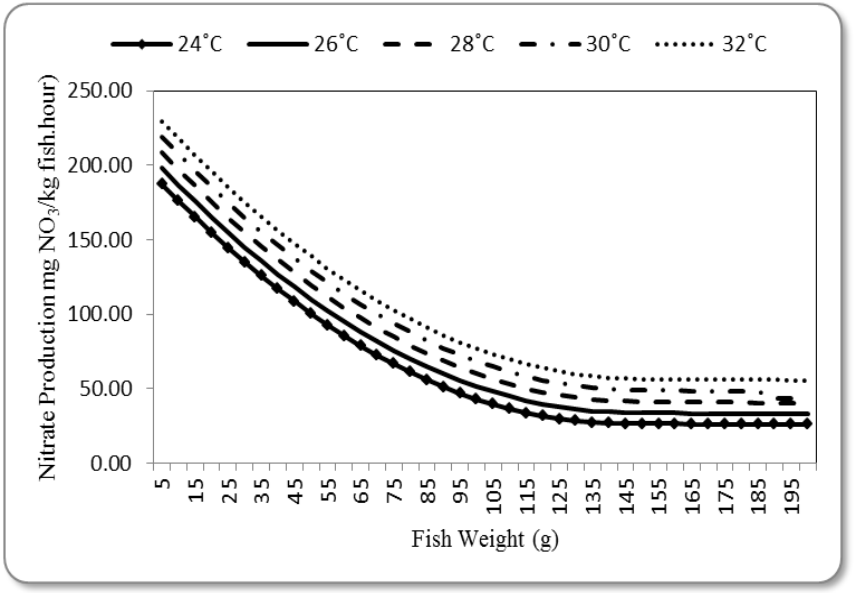

Figure (5.33): The effect of water temperature and fish weight on nitrate production.

5.1.5. Solids Generation:

5.2.5.1. Settleable and suspended solids at different water depths.

The settleable and suspended solids were determined at different water depths (0.8, 1.0, 1.2, 1.4 and 1.6 m) in the recirculating as shown in table (5.23) and figure (5.34) and (5.35). Figure (5.34) indicates that the settleable solids decreases with increasing water depth, where, it decreased from 0.039 to 0.019 kg m^{-3} at water depths of 0.8 to 1.6 m.

Table (5.5) and figure (5.35) show the suspended solids was increased from 0.0124 to 0.0145 kg m^{-3} when the water depth increased from 0.8 to 1.6 m at the same fish weight (5 g). On the other hand, suspended solids increased from 0.0124 to 0.1607 kg m^{-3} with increasing fish weight from 5 to 200 g at 0.8 m water depth. At 1.6 m water depth, suspended solids increased from 0.0145 to 0.1628 kg m^{-3} with increasing the fish weight from 5 to 200 g. The suspended solids increased from 0.0124 to 0.0145 kg m^{-3}, where the depth increased from 0.8 to 1.6 m at 5g fish weight. It is very worthy to notice that the suspended solids variations due to the change of water depth are more less than that of the fish weight.

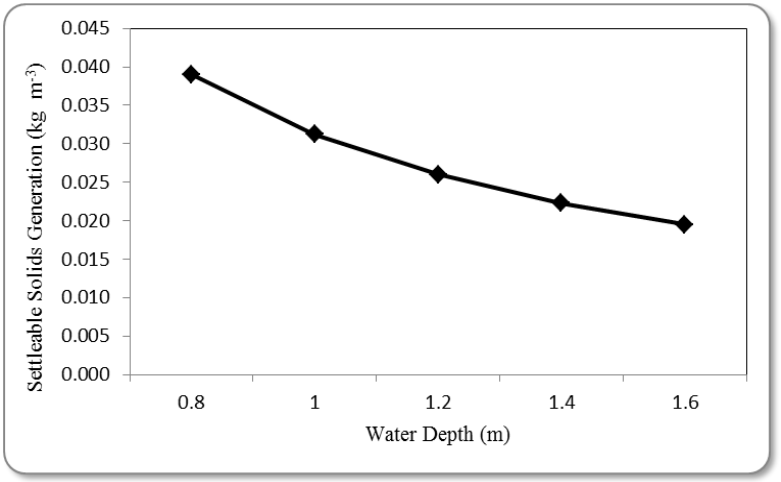

Figure (5.34): The settleable solids generated at different water depths.

Table (5.23): The suspended solids generated at different water depths at 2.08 m h^{-1} settling velocity.

Depth (m) / Fish weight (g)	0.8	1.0	1.2	1.4	1.6
	Suspended Solids Generation kg m^{-3}				
5	0.0124	0.0132	0.0138	0.0142	0.0145
15	0.0126	0.0135	0.0141	0.0145	0.0148
25	0.0132	0.0140	0.0146	0.0150	0.0153
35	0.0141	0.0149	0.0155	0.0159	0.0162
45	0.0154	0.0162	0.0168	0.0172	0.0175
55	0.0172	0.0180	0.0186	0.0190	0.0193
65	0.0195	0.0203	0.0209	0.02132	0.0216
75	0.0224	0.0233	0.0238	0.0243	0.0246
85	0.0261	0.0269	0.0275	0.0279	0.0282
95	0.0305	0.0314	0.0320	0.0324	0.0327
105	0.0359	0.0368	0.0374	0.0378	0.0381
115	0.0424	0.0433	0.0439	0.0443	0.0446
125	0.0501	0.0510	0.0516	0.0519	0.0523
135	0.0592	0.0600	0.0606	0.0610	0.0613
145	0.0697	0.0706	0.0712	0.0716	0.0719
155	0.0819	0.0828	0.0834	0.083782	0.0841
165	0.0959	0.0968	0.0974	0.0978	0.0981
175	0.111871	0.1127	0.1133	0.1137	0.1140
185	0.129836	0.1307	0.1313	0.1317	0.1320
190	0.139597	0.1405	0.1410	0.14145	0.1418
200	0.160681	0.1615	0.1621	0.1625	0.1628

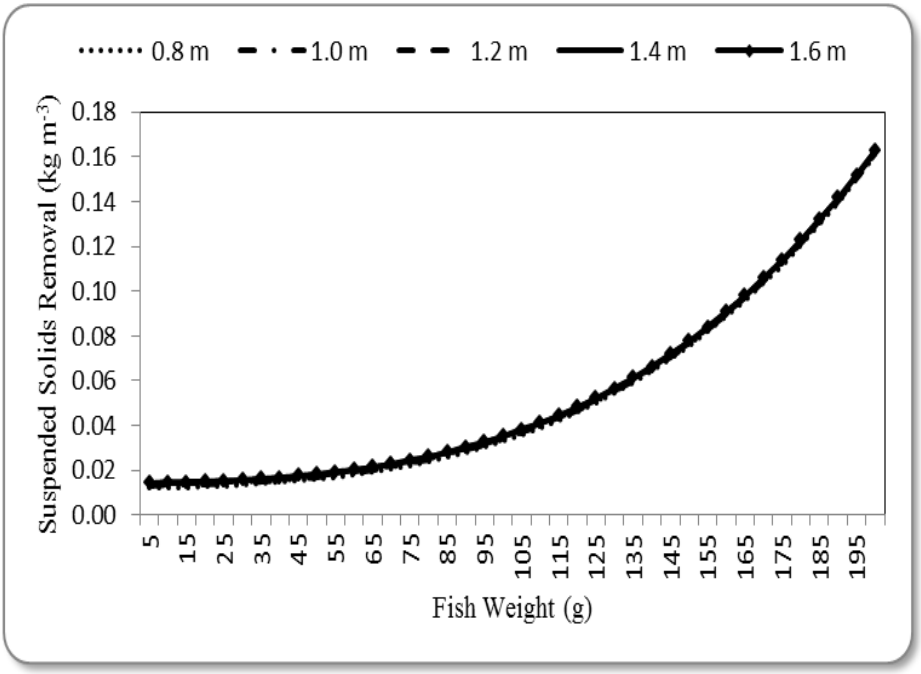

Figure (5.35): The suspended solids generated at different water depths.

5.2.5.2. Settleable solids at different settling velocities

The settleable solids were determined at different settling velocities (1.25, 1.67, 2.08, 2.50 and 2.90 m hour^{-1}) as shown in figure (5.36). It indicates that the settleable solids increase with increasing settling velocity. It increased from 0.0234 to 0.0544 kg m^{-3} at settling velocities increased from 1.25 to 2.90 m hour^{-1}.

The settleable solids at optimum settling velocity (2.08 m hour^{-1}) was 0.039 kg m^{-1}, which indicates that the settleable solids of 0.039 kg m^{-1} is taken as a guide for designing and managing the recirculating aquaculture system (RAS).

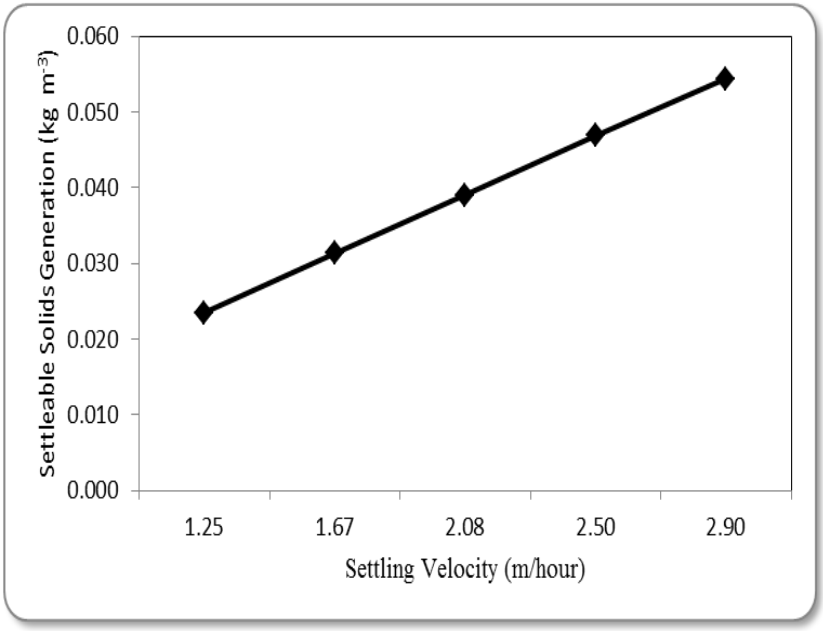

Figure (5.36): The settleable solids generation at different settling velocities.

5.2.6. Energy Consumption:

5.2.6.1. Energy consumption at different ambient air temperatures:

The energy consumption by the water heater per day was determined at different ambient air temperatures (23, 25, 27, 29 and 31˚C) as shown in figure (5.37). It indicates that the energy consumption decreases with increasing the ambient air temperature, where, it ranged from 110276.4 to 441105.7 kJ.day. It was as high of 441105.7 kJ.day at 23 ˚C and as low as 110276.4 kJ.day at 31 ˚C.

5.2.6.2. Daily energy consumption:

The energy consumption by the water heater per hour was determined at (the optimum temperature 27˚C) as shown in figure (5.38). It indicates that the highest energy consumed was 7918.88 kJ.hour at 6:00 am (24.66 ˚C). While, the lowest value of the daily energy consumption was 335.13 kJ.hour at 14:00. It refers that, the heater will be working during the period of 19 hours. The energy consumption by whole system was 359896.5 kJ.day.

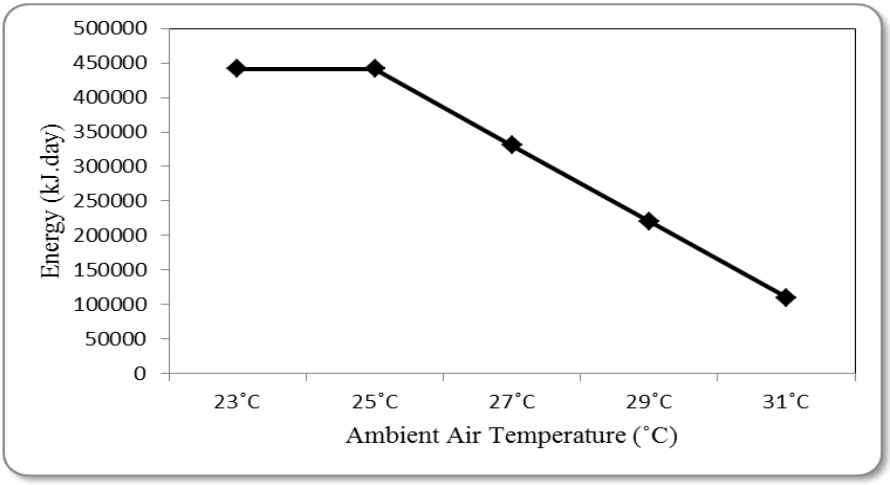

Figure (5.37): The energy consumption at different ambient air temperatures.

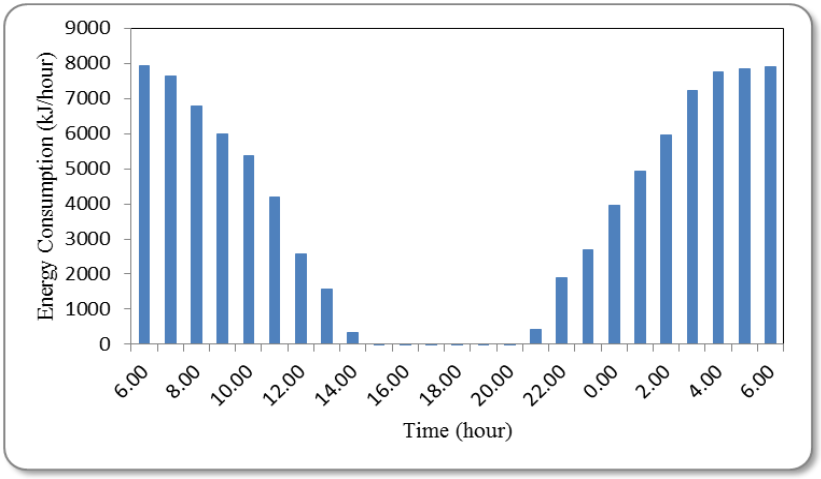

Figure (5.38): The energy consumption at ambient air temperatures (27˚C).

6. SUMMARY AND CONCLUSION

A simulation model for the recirculating aquaculture system (RAS) was developed successively according to heat and mass balance to optimize the main factors affecting the performance of RAS through studying of water temperature, oxygen consumption, ammonia production, nitrate production, biological filter volume, solids generation, fish growth rate, specific growth rate, feed conversion rate and system energy consumption at different operation conditions. Also, carrying out an experiment to validate the model results through measuring: water temperature, oxygen consumption, ammonia, nitrite, nitrate, solids, fish growth rate, specific growth rate, feed conversion rate and system energy consumption. The most important results obtained can be summarized in the following points:

6.1. Model results:

- The model showed that the predicted water temperature increases with increasing the air ambient temperature, where, the ambient air temperature increased from 23 to 31 ˚C during the whole day, the water temperature increased from 18 to 26 ˚C at 6:00 am, while it increased from 23 to 32 ˚C at 18:00 pm.

- The model showed that the predicted oxygen consumption increases with increasing water temperature, meanwhile, the oxygen consumption decreases with increasing fish weight during the whole growth period. The Oxygen consumption increased from 302.02 to 732.70 mg O_2/kg

fish. hour, when, the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g). Oxygen consumption decreased from 302.02 to 121.33 mg O_2/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C, oxygen consumption decreased from 732 to 238.37 mg O_2/kg fish. hour with increasing the fish weight from 5 to 200 g.

- The model showed that the predicted ammonia production increases with increasing water temperature, while, it decreases with increasing fish weight during the whole growth period. The ammonia production increased from 43.20 to 52.94 mg NH_3/kg fish. hour, when, the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g). The ammonia production decreased from 43.20 to 5.98 mg NH_3/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C, ammonia production decreased from 52.94 to 12.82 mg NH_3/kg fish. hour with increasing the fish weight from 5 to 200 g.

- The model showed that the predicted nitrate production increases with increasing water temperature, whereas, it decreases with increasing fish weight during the whole growth period. The nitrate production increased from 187.48 to 229.75 mg NO_3/kg fish. hour when the water temperature increased from 24 to 32 ˚C at the same fish weight (5 g). The nitrate production decreased from 187.48 to 25.95 mg NO_3/kg fish. hour with increasing fish weight from 5 to 200 g at 24 ˚C water temperature. At 32 ˚C,

nitrate production decreased from 229.75 to 55.63 mg NO_3/kg fish. hour with increasing the fish weight from 5 to 200 g.

- The model showed that the predicted settleable and suspended solids increased with increasing water depth. The settleable solids increased from 0.039 to 0. 195 kg m^{-3} at depths of 0.8 to 1.6 m, while the suspended solids increased from 0.0124 to 0.0145 kg m^{-3} when the water depth increased from 0.8 to 1.6 m at the same fish weight (5 g). The suspended solids increased from 0.0124 to 0.1607 kg m^{-3} with increasing fish weight from 5 to 200 g at 0.8 m water depth. At 1.6 m, suspended solids increased from 0.0145 to 0.1628 kg m^{-3} with increasing the fish weight from 5 to 200 g.

- The model showed that the predicted settleable solids increased with increasing settling velocity. It increased from 0.0234 to 0.0544 kg m^{-3} at settling velocities from 1.25 to 2.90 m/hour.

- The model showed that the predicted energy consumption by the heater per day decreases with increasing the ambient air temperature, where, it ranged from 110276.4 to 441105.7 kJ/day. It was as high of 441105.7 kJ/day at 23 ˚C and as low as 110276.4 kJ/day at 31 ˚C. The highest energy consumption by the heater per hour was determined at (the optimum temperature 27˚C) 7918.88 kJ/hour at 6:00 am. While, the lowest value of the daily energy

consumption was 335.13 kJ/hour at 14:00.The energy consumption by whole system was 359896.5 kJ/day.

6.2. Model Validation:

- The predicted water temperature was in a good agreement with the measured water temperature with a coefficient of determination of 0.999, where, it ranged 28.00 to28.86˚C experimentally, while, it was 28.00˚C theoretically during the whole day.

- The predicted oxygen consumption was in a good agreement with the measured oxygen consumption with a coefficient of determination of 0.988. The predicted oxygen consumption values were between 189.13 to 457.56 mg O2/kg fish per hour, while, the measured oxygen consumption values are from 197.42 to 467.61 mg O2/kg fish per hour during the whole growth period.

- The predicted ammonia production was in an agreement with the measured ammonia production with a coefficient of determination of 0.915. The average ammonia production from the system ranged from 10.56 to 55.99 mg NH_3/kg fish.hour experimentally, while, it was from 10.45 to 48.61 mg NH_3/kg fish.hour theoretically during the whole growth period.

- The predicted nitrate production was in a good agreement with the measured nitrate production with a coefficient of determination of 0.993. the average nitrate production from the system ranged from 41.61 to 222.31 mg NO_3/kg

fish.hour experimentally, while, it was from 45.34 to 210.97 mg NO_3/kg fish.hour theoretically during the whole period of fish growth.

- The predicted settleable solids was in a good agreement with the measured settleable solids with a coefficient of determination of 0.999. The average settleable solids removed from the system was 0.0429 ± 0.0127 kg m^{-3} (42.90 ± 12.70 mg l^{-1}). The daily average of solids removed from the system ranged from 0.33 to 6.62 kg/day experimentally while it ranged from 0.34 to 4.41 kg/day theoretically during the whole period of fish growth.

- The predicted suspended solids was in a reasonable agreement with the measured suspended solids with a coefficient of determination of 0.915. the suspended solids removed by the system increased with growth period, where it was 0.0123 kg m^{-3} (12.30 mg l^{-1}) at the beginning and increased rapidly to reach 0.0806 kg m^{-3} (80.60 mg l^{-1}) after 3 months. The daily average solids removed from the system ranged from 0.11 to 11.34 kg/day experimentally while it was from 0.11 to 15.70 kg/day theoretically during the whole period of fish growth.

6.3. Wastes removal efficiency:

- The efficiency of the biological filter for ammonia removal from the system ranged from 11.11 to 63.64 %.

- The efficiency of the hydrocyclone for settleable solids removal from the system ranged from 27.4 to 57.79 %.

- The efficiency of the screen filter for suspended solids removal from the system which ranged from 15.46 to 74.41 %.

6.4. The biological parameters:

- The predicted fish growth rate was in an agreement with the measured fish growth rate with coefficient of determination of 0. 929. The daily average fish growth rate from the system ranged from 0.26 to 1.46 g/day experimentally while it was from 0.11 to 1.96 g/day theoretically during the whole period of fish growth.

- The predicted specific growth rate was in a reasonable agreement with the measured specific growth rate with coefficient of determination of 0. 880. The specific growth rate ranged from 1.18 to 4.83 % actually while it was estimated to be from 1.26 to 5.42 % theoretically during the whole period of fish growth.

- The predicted feed conversion rate was in a reasonable agreement with the measured feed conversion rate with coefficient of determination of 0. 808. The feed conversion rate ranged from 0.61 to 2.25 kg feed / kg fish actually, while, it was estimated to be from 0.50 to 1.94 kg feed / kg fish theoretically during the whole period of fish growth.

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