The Effect of Fish Biomass and Denitrification on the Energy Balance in African Catfish Farms

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Problem: The Dutch aquaculture industry is based on fish production in recirculating aquaculture systems. Enforced by legislation the fish farmers have to reduce the waste discharge and are not allowed to discharge farm effluents on the surface waters. The government expresses waste discharge in inhabitant equivalents (I.E = average daily waste production of 1 person during 1 year, expressed in g O\textsubscript{2} and measured as COD and Kjeldahl nitrogen) and charges levies between $29 and $60 per I.E. depending on the local water authority. In the near future, the government will impose stricter effluent and ground water permits and control procedures, which will force the farmers to invest in additional monitoring equipment and in waste water treatment. The latter may decrease the environmental load of a farm but may increase production costs considerably. Farm gate prices of African catfish are low and fluctuates around $1.50 per kg fish at an annual production of ±1000 kg/m\textsuperscript{3} tank volume and a water discharge of ± 100 l/kg feed per day. To create financial space for additional water treatment methods energy and production costs must be reduced further. The incorporation of denitrification may decrease the environmental load and energy costs for heating makeup water but can result in a demand for cooling during summer months.

Objectives: (1) to simulate the heat/energy balance of a 'standard' 100 tons catfish farm and to indicate the space for reduction of production costs.; (2) to predict the (significant) heat production of the standing stock in the total heat balance which for simplification was assumed to be negligible in a study of Singh and Marsh (1996); (3) to study the effect of denitrification (reduction of water, nitrogen and COD discharge) on the energy balance.

Material and methods: Two production system configurations were compared: a 'standard' commercial 100 tons configuration (default situation) and an experimental configuration incorporating a denitrification unit. These systems were compared for:

a. effluent (make up water, nitrate and organic matter)
b. energy balance (calculated with the model ANIPRO, van Ouwerkerk, 1999)

a). Effluent data were collected from a pilot RAS configuration operated and loaded as under scale up conditions, (3 fish tanks, final biomass ± 280 kg/m\textsuperscript{3}, lamella
sedimentation, bio-reactor) and (2) an configuration incorporating a denitrification unit, (3 fish tanks, drumfilter (60\(\mu\)m), bio-reactor, denitrification reactor (an Upflow Sludge Blanket reactor). Both systems were identical in biomass stocking and daily feed load. pH, Conductivity, O\(_2\), NH\(_4\)-N, NO\(_2\)-N, NO\(_3\)-N, COD, Dry Matter, Ash, Kjeldahl-N, NaHCO\(_3\), water discharge (volume and composition) and nutrient retention in fish were measured to produce mass balance criteria for system comparison.

The fish culture module of the ANIPRO model developed for the EU fish project Blue label was used to simulate the heat balance of both 100 tons system configurations. The model allows to design energy efficient and cost effective heating and cooling systems for fish farms in different geographical regions. The calculated heat production in the model is based on 1) conversion of feed (heat production from standing stock and water treatment) 2) pumps, 3) lighting (including UV for disinfecting); heat transmission into the building (especially solar radiation). Heat is lost from the system by: 1) ventilation air (sensible and latent heat); transmission of heat through floor, walls and roof; 3) makeup water. The indoor and basin temperatures iterate until there is a balance between heat production and heat loss (Aarnink et al. 2000). The parameters in the model have been obtained from Dutch catfish farmers and were calibrated with on farm measurements for the culture of African catfish.

The number of I.E. per farm is calculated by: \(Q/136^\times(COD+4.57 \text{ Kjeldahl nitrogen})\) (Q=waste wastewater).
Introduction

Nitrate, the end product of biological nitrification, is accumulated unless denitrification or the hydroponic system is connected to the water treatment process. Although nitrate is not generally regarded as an acute toxic compound to fish[1, 8], it should not be left to accumulate, because phytoplankton blooms, inhibition of nitrification and toxicity problems eventually occur at certain concentrations of nitrate[6]. Since the 1980s, biological denitrification has been performed using immobilized cells[4, 5]. However, the study on the denitrification process into marine aquacultural systems and aquaria has not been carried out except for denitrification by gram negative halophilic bacteria reported by Shieh et al.[7]. Therefore, the possibility of acclimation from fresh water denitrification to the marine system, the optimum acclimation method and the effect of HRT on marine denitrification were evaluated by the addition of sea water into fresh water denitrification system and total sea water exchange.

Preparation of denitrifiers immobilized in PVA

The immobilization of denitrifier consortium was carried out using the activated sludge acclimated to the denitrifier consortium(JangLim sewage treatment facility, Pusan, Korea) by feeding nitrate and glucose for 120 days. Immobilized denitrifiers were prepared by the PVA (polyvinyl alcohol)-boric acid method[2]. The experiment was run by four completely mixed continuous flow reactors. The working volume of each reactor is 1 L. The feed tank was in a cooling bath of 4°C to maintain the composition of feed solution. To acclimate denitrifier of the freshwater system to seawater, salinity was controlled by diluting seawater. The composition of the feed solution was KNO₃ 72.2 mg/L, Glucose 66.5 mg/L, Na₂HPO₄ 40 mg/L, and MnSO₄ 2 mg/L. Reactor 1(R-1) was kept in the fresh water denitrification system as the control and the salinity of reactor 2~4(R-2~4) were stepwise increased with increased sea water addition in order to evaluate the acclimation characteristics from the fresh water denitrification system to the marine system. The nitrate nitrogen loading rate was 20 g/m³/day. After the marine denitrification system was reached at a steady state, the
HRT was reduced from 12 hours to 1 hour to get the highest removal rate. The influent nitrate nitrogen concentration was 3.5 mg/L.

The effect of salinity on the denitrification process.

The effect of the salinity on the denitrification process was evaluated by the addition of sea water. The salinity of the raw coastal sea water was about 30 ppt and the salinity of each reactor was controlled to 0, 7.5, 15 and 30 ppt for R-1 to 4, respectively.

Fig. 1(a) shows the nitrate nitrogen concentrations of the influent and effluent at each reactor with different salinity levels. The average influent nitrate nitrogen concentration was 10.3 mg NO₃⁻-N/L and the effluent nitrate nitrogen concentration was stable from the start of the operation for the control reactor, R-1, and its concentration was average 1.5 mg NO₃⁻-N/L. However, the reactors containing salt showed less nitrate nitrogen removal in the reactor for 4 days of operation. The concentrations reached 3.4 mg NO₃⁻-N/L at a salinity level of 7.5 ppt in R-2, 4.5 mg NO₃⁻-N/L at salinity level of 15 ppt in R-3 and 7.2 mg NO₃⁻-N/L at salinity level of 30 ppt in R-4. Therefore, the addition of salt inhibited the denitrification reaction at the initial operation periods. When salinity was high, the inhibition for denitrification was severe and showed 30% of removal efficiency with sea water. However, effluent nitrate nitrogen concentrations of all reactors became similar to that of the control reactor after 10 days of operation and they reached 2 mg NO₃⁻-N/L with a steady state condition.

Effluent nitrite nitrogen concentration was shown in Fig. 1(b). At the control reactor, R-1, the concentration was lower than 0.05 mg NO₂⁻-N/L without nitrite accumulation. However, at the reactor with a salinity level of 7.5 ppt, the nitrite nitrogen concentration suddenly increased to 0.75 mg/L and was maintained for 15 days of operation and then decreased to lower than 0.05 mg NO₂⁻-N/L after 18 days of operation. When the salinity level was higher than 15 ppt, the nitrite concentrations were maintained at 0.5-0.75 mg NO₂⁻-N/L as soon as the sea water was added. According to Wickins[9], nitrite toxicity was more severe than ammonia toxicity in an intensive fish culture facility, especially in the recirculation culturing system. Nitrite could accumulate in a recirculating system as a result of incomplete bacterial reduction. Although nitrite is a considerable toxic compound, the toxicity of nitrite to marine and estuarine fish might be low. Therefore, Wickins[9] recommended a maximum of 1.0 mg NO₂⁻-N/L in sea water. This indicates that the process in this study is safe for the fish because the nitrite concentrations were maintained lower than 1.0 mg NO₂⁻-N/L.

Fig. 1(c) shows that denitrification efficiency was affected by salinity. In the early stage of the operation, when the salinity was high, denitrification efficiency decreased, however, the activity recovered after 10 days of operation regardless of salinity. The denitrifiers were surrounded by extracellular polymers, which enabled them to endure the changes in cultivation conditions[2] and adjust to a new environment.
The effect of acclimation method on the denitrification process.

Fig. 2. shows nitrate removal rates and nitrite nitrogen concentrations of the acclimation method from the fresh water denitrification system to the marine system. R-1 was maintained to the fresh water system as the control reactor to correct changes in cultivation conditions, for example temperature, pH and DO, because all reactors were operated at room temperature and 4 months were required for the operation.

In the control reactor, R-1, the nitrate nitrogen removal rates were reduced to 18.5, 13.3 and 8.6 g NO$_3^-$-N/m$^3$/day at each step and the nitrite nitrogen concentration was lower than 0.05 mg NO$_2^-$-N/L during operating periods and temperatures in the reactor were measured 27~28, 20~23 and 17~18 °C at each step, respectively. Decrease in room temperature might cause reductions of nitrate nitrogen removal rates[3]. In R-2, the salinity was increased to 30 ppt by 3 steps, and the nitrate removal rates were 18.2, 12.6 and 7.9 g NO$_3^-$-N/m$^3$/day and the rates were reduced on salinity, however, these were 98.4, 94.7 and 91.5 % compared to the control of the same periods, respectively. Nitrite nitrogen concentration was 0.05, 0.15 and 0.27 mg NO$_2^-$-N/L, respectively. In R-3, salinity was increased to 30 ppt by 2 steps nitrate nitrogen removal rates were 16.3 and 11.9 g NO$_3^-$-N/m$^3$/day and nitrite nitrogen concentrations were 0.68 and 0.70 mg NO$_2^-$-N/L. As the nitrate nitrogen removal rate was compared to the same method of R-2, these were 88.1 and 89.5 %. In R-4 with seawater, the nitrate nitrogen removal rate was 17.4 g NO$_3^-$-N/m$^3$/day and it was 94.1 % compared to the control and nitrite nitrogen concentration was 0.69 mg NO$_2^-$-N/L.

Therefore, direct acclimation was more efficient than stepwise acclimation when the freshwater denitrification system was converted to the marine system, although the nitrite nitrogen concentration showed 0.69 mg NO$_2^-$-N/L. However, nitrite concentrations could be maintained within the criteria in the marine system[9]. Also, the direct acclimation method required less time periods to convert the fresh water system to the marine system.
The effect of HRT on the marine denitrification system.

Fig. 3 shows the nitrate nitrogen removal rate and denitrification efficiency on HRT (hydraulic retention time). As HRT was reduced the nitrate nitrogen removal rate increased until 3 hours of HRT. However, the rate suddenly decreased at HRT under 3 hours. The denitrification efficiency decreased by the decrease in HRT. Even though the efficiency decreased, the nitrate removal rate increased with the decrease of HRT due to the high flow rate until 3 hours of HRT. Considering the nitrate removal rate and denitrification efficiency, the optimum HRT was limited to 3 hours although denitrification efficiency was somewhat low as 36%. The maximum nitrate nitrogen removal rate was 10 g NO$_3^-$-N/m$^3$/day at 3 hours of HRT.

Fig. 2. Nitrate removal rate and nitrite concentration by the acclimation method of the fresh water system to marine system.

Fig. 3. Nitrate removal rate and denitrification efficiency on HRT in marine denitrification system.

REFERENCES


Basic Design Considerations for Small Fish Holding Facilities: For the Biologist/Aquarist

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Introduction

With an increasing number of aquariums, zoos, and educational institutions holding aquatic animals, there is much to be mentioned as to their needs for aquatic facilities. Universities and high schools often use aquatic systems for studying aquatic animals and their behaviors, while other universities may stock tanks for aquacultural research. Public aquariums and zoological institutions which have aquatic exhibits may also have holding facilities for receiving and dispositioning animals as well as for caring for ill animals. All aquatic systems should be designed according to their intended use. Moreover, a facility or system often turns into another with a different use later on. This is resourceful by utilizing existing equipment, but we must consider the components and the original design before placing a load of fish into an existing system and expecting good results.

Holding accommodations can be as advanced as having multiple recirculation systems in a temperature controlled building or simple as basic single tank systems. Facility or system design depends directly upon the desired use of the system as well as many other factors. Typical uses may include: display exhibits, quarantine, hospital tanks, holding, breeding, growout, spawning or any combination of these. Even after the original application is decided the actual components may depend yet upon another set of factors which also need to be evaluated. These may include: water availability and cost, feeding rates, fish density, electrical availability, maintenance, and climate.

Design Considerations

Systems

There are two basic types of systems, recirculating and flow through or somewhere in between. A flow through system consists of water entering tanks and leaving at the other end and is not recycled through the system again. In water reuse systems, water is reused multiple times and in some instances it is filtered and reused, which is referred to as a recirculation system. Most practical water reconditioning systems recycle 90-95% of the water (Piper et al. 1982). A daily partial water loss is necessary for backwashing of filters as well as to remove nitrates and to replace minerals and trace elements (Lawson 1995). Recirculating systems consist of various components, some of the basic requirements include: mechanical filter, biological filter, sterilization/disinfection, and a temperature
control unit. Two distinct advantages of this type of system is the control over certain water quality parameters, and water conservation.

Good water quality and an inexpensive source of water must be available for flow through systems to be considered economically feasible. A higher flow rate is needed to keep water quality conditions favorable when high densities of fish are housed. However, such systems can be beneficial when a continual water supply is offered at little expense. Isolation of ill fish or quarantining fish where the water may become contaminated by pathogenic organisms is also a motive for using a flow through system. Water quality is usually not a problem in these types of systems as long as the incoming water is optimal for the species involved and turnover rates are adequate.

Holding Containers

There are many different types, shapes, and sizes of holding tanks that are available today. The most popular being circular or rectangular in shape. Much of the selection with container shapes is based on personal preferences. Although, some have distinct advantages over others. A major difference outlined by Piedrahita (1991) is the water quality in circular tanks tends to be uniform and follow the continuous flow stirred tank reactor model (CFSTR), while raceways follow a plug flow reactor (PFR) model by a distinct degradation of water quality between the inlet and outlet.

Rectangular tanks can be placed side by side with little wasted space between them. Ellis (1994) found rectangular tanks to be superior over circular designs in survivability, feed conversion, yield, and growth in Florida red tilapia fry. If flow rates are not adjusted correctly in raceways they can act as a solids settling device. Boersen and Westers (1986) added baffles in raceways to help move solids to the end of raceways where they could be easily vacuumed out. Rectangular tanks are often used for fry and for hatching purposes in aquacultural operations, whereas circular tanks are often used as growout tanks. Dividers can also be placed in narrow rectangular tanks with little effort compared to ones in circular tanks.

Circular tanks offer the distinct advantage of being “self-cleaning”. Incoming water can be angled to create a circular motion in the tank with the solids being swept towards the middle where they are removed by a center drain. Lawson (1995) reminds us that flow velocity must not be so great that the fish expand all of their energy swimming. Moreover, water velocities high enough to keep particulate matter suspended may also create conditions in which gill irritation develops from the suspended particles, thus possibly leading to bacterial gill disease (Wedemeyer 1996). Circulation and mixing are such that solids are more evenly distributed, making the water quality more uniform throughout the tank. This could have a beneficial effect or a negative impact depending upon the water quality conditions. The capture of fish from circular tanks can be difficult if the proper equipment such as a swinging crowder gate is not available, whereas in rectangular tanks a simple screen can be used to crowd the fish to one end.
Aeration

Dissolved oxygen (D.O) is a limiting factor in fish culture (Piper et al. 1982). Inadequate D.O. levels may lead to reduced growth, increase of disease problems, and can cause mass mortality (Colt and Tchobanoglous 1981). As the density increases in a system, so must the amount of available oxygen. Species, life stage, environmental conditions, size, and physiological condition are all variables in the amount of oxygen needed for fish to survive. In most cases, long-term D.O. levels above 6.0 mg/l will prevent any problems associated with oxygen deficiency in any species of fish.

Subsurface aeration techniques are the most common among small fish holding systems. Aerating water not only adds valuable oxygen to the water, but it can also off-gas CO₂, which is a byproduct of fish metabolism that is toxic to fish at elevated levels. Facilities that are planning for high densities of fish, pure oxygen injection may be preferred, which is typically designed by an engineer. Speece (1981), and Colt and Watten (1988) go into detail with different types of pure oxygen systems and their uses. For low densities of fish, using a professional judgment from previous setups or colleagues can be a great help and save time with calculations. If previous experience is limited, it is recommended that the actual amount of oxygen consumed by the fish be taken into consideration (Table 1.0). Even among the same species, oxygen uptake can be very inconsistent because of

Table 1.0
Oxygen consumption values for various freshwater fish species.

<table>
<thead>
<tr>
<th>Species</th>
<th>Size (g)</th>
<th>Feeding Status</th>
<th>Temp (°C)</th>
<th>O₂ consumption mg/kg/day</th>
<th>Original Source</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Cyprinus carpio</em></td>
<td>806</td>
<td>+</td>
<td>12</td>
<td>1,921</td>
<td>Nakanishi and Itzawa 1974(1)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>+</td>
<td>10</td>
<td>4,080</td>
<td>Beamish 1964(2)</td>
</tr>
<tr>
<td></td>
<td>100</td>
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<td>20</td>
<td>11,520</td>
<td>Beamish 1964(2)</td>
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<tr>
<td></td>
<td>100</td>
<td>+</td>
<td>25</td>
<td>16,800</td>
<td>Beamish 1964(2)</td>
</tr>
<tr>
<td><em>Oncorhynchus nerka</em></td>
<td>28.6</td>
<td>+</td>
<td>15</td>
<td>6,600</td>
<td>Brett and Zala 1975(3)</td>
</tr>
<tr>
<td></td>
<td>28.6</td>
<td></td>
<td>15</td>
<td>5,600</td>
<td>Brett and Zala 1975(3)</td>
</tr>
<tr>
<td><em>Ictalurus punctatus</em></td>
<td>100</td>
<td>+</td>
<td>26</td>
<td>14,600</td>
<td>Andrews and Matsuda 1975(1)</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td></td>
<td>30</td>
<td>13,440</td>
<td>Andrews and Matsuda 1975(2)</td>
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<tr>
<td></td>
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<td><em>Onchorhynchus mykiss</em></td>
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<td>11</td>
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<td></td>
<td>100</td>
<td></td>
<td>15</td>
<td>7,200</td>
<td>Liao 1971 (2)</td>
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Sources: (1) Kepenyes and Varadi (1983)
(2) Creswell (1993)
(3) Colt (1981)
the many variables that are involved with the rate of oxygen consumption. Considerations such as the D.O. level entering the tank and turnover rates are also important in designing an aeration system. Computing for an incoming D.O. level of 0 mg/l can provide a safety margin of not relying on the systems run performance to maintain proper D.O. levels.

Air blowers or air compressors are usually the choice for subsurface aeration devices. Air blowers are designed to provide large volumes of air at low pressures (<4 psi). Blowers are typically used for multiple tanks systems where air piping is minimal and used at shallow depths. Air compressors can be used when greater depths and long runs of piping are needed. Correct sizing is critical for both blowers and compressors. Oversizing can generate excess amounts of air and may need to be “blown off”, thus wasting electricity. One that is too small may not fully supply all the airstones, or operate only at shallow depths. The total amount of pressure and volume of air is required for sizing an aeration device, which is dependent upon three variables:

1. The depth of water at which the airstone will be set at. This is calculated by using a simple measuring instrument (1 psi = 2.31’ of water at 60° F). Keep in mind that if multiple depth tanks are used, the one that with the greatest airstone depth will be used in the calculation for pressure (psi) requirements.

2. Different size diffusers and pore size will determine the amount of air needed to operate them, the volume needed is given in cubic feet per minute (CFM). This can be obtained from the manufacturer of the diffuser; most airstones used for small systems are well under 1 CFM. A total of all diffusers used is required for a total volume of air.

3. Friction losses in the pipe: Creswell (1993) compiled information on frictional losses (psi loss / 100’ pipe) for air as a function of pipe size and flow rate.

Once the volume of air needed is known (CFM), amount of pressure (psi) required, and type of aeration device preferred, a simple graph provided by a supplier will give the proper size of compressor or blower that is needed for the job.

**Pump**

Although multiple factors play into the required flow rates, a tank exchange at least once an hour is usually sufficient in lightly loaded systems for maintaining water quality needed for proper fish health. If heavy feeding regimes or excellent clarity is necessary, a faster turnover rate should be considered. Wheaton et al. (1997) uses oxygen consumption as a factor in the determination of flow rate. Losordo and Westers (1997) also suggest a more in depth approach to the design of a system in a process called mass balance analysis, where the desired flow rate is computed by taking many variables into consideration.
Recirculation systems generally utilize pumps for moving water from the tank through filters or from a sump through a filtering system. Four items are needed to correctly size a pump:

(1) Desired flow rate (gpm or lpm)
(2) Friction loss from the piping and fittings (suction & discharge side)
(3) Vertical distance in which the water is to be pumped
(4) Pressure required by filters (1 psi = 2.31 head feet)

Creswell (1993) and Lawson (1997) gathered information on friction losses for selected valves and fittings as “equivalent length of pipe”. Using this information, the total length of all fittings is added to the length of straight pipe needed to give a total length of pipe which is then used in the Hazen-Williams Formula. Major pipe sizes and their corresponding friction losses are shown in Table 2. Lawson (1997) recommends using a C-value of 100 for permanent installations of PVC piping due to future biofouling; new PVC pipe has a C-value of 150. This calculation along with vertical lift and pressures required by any filters will give the total dynamic head (ft or m). This information along with the desired flow rate and a manufacturers pump graph will present the correct size pump for the system.

Table 2.0
Losses are given in head feet per 100’ pipe using the Hazen-Williams formula. A C-value of 130 is used as the coefficient using Schd. 40 PVC pipe. Velocities (v) are given in ft/sec.

<table>
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<th>GPM</th>
<th>0.75</th>
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<tr>
<td></td>
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<td>3.05</td>
<td>4.54</td>
<td>4.28</td>
</tr>
</tbody>
</table>

Note: Generally 5 ft/sec is considered to be safe. Higher velocities may be used in cases where the operating characteristics are known and that sudden changes in flow velocity can be controlled.
Filtration

Recirculation systems rely upon filtration to take out waste products and to carry out the nitrification processes. Basic components of a recirculation system typically include: mechanical filtration, biological filtration, sterilization, and heating/cooling. Various other components such as: fractionators, carbon filters, and degas towers may also be additional features to a system. Many combinations and variations of filters can be used.

Mechanical filters are typically the first filter in a filtration sequence. These filters remove any suspended solids in the system. Mechanical filters are generally sized according to the flow rate, which manufacturers will give for different size filters. A good review of mechanical filters are found in Wheaton 1977; Chen et al. 1997; and Lawson 1997. The biological filtration of interest for fisheries professionals is the nitrification process in which two genera of autotrophic bacteria oxidize unionized ammonia (NH$_3$) to nitrite (NO$_2$) then to nitrate (NO$_3$). Biofilters serve as a source of surface area for nitrifying bacteria to colonize in which the water has to pass over or through. A biological filtering device should be located following the mechanical filter. Popular reviews in biological filtration devices used in fish systems include: Wheaton 1977; Rogers 1985; Malone et al. 1993; Westerman et al. 1993; and Wheaton et al. 1997.

Biological filtration design is not an exact science in fish systems due to limited scientific literature on ammonia production by fish and inconsistent data (Wheaton 1997). Biological filters are sized according to the amount of surface area that is needed for nitrifying bacteria. Meade (1985) reviewed information on ammonia production and found ranges of 20-78.5 g/kg of diet per day. Three out of the five sources cited by Meade found production rates between 31-37.4g/kg-diet/day. Piper (1982) found that much of the literature on trout and salmon total ammonia production rates which were fed a dry-pelleted food produced 32 g/kg-food. For smaller lightly-loaded systems submerged or trickling biofilters are commonly the preferred choice and are relatively inexpensive. Wheaton (1977) reviewed literature on nitrification rates for a submerged gravel biofilter to be 1.0 g/NH$_3$/N/m$^2$-day at 20$^\circ$ C. Miller and Libey (1985) found a trickling filter to have removal rates from 0.14-0.25 g N/m$^2$-day. Using these data or findings by others the following formula is used in determining the surface area needed.

$$\frac{\text{ammonia produced (g)}}{\text{ammonia removed (g/m}^2/\text{day)}} = \text{m}^2 \text{ surface area}$$

Poor performance is often caused by uneven flow across all of the media. All of the nitrifying bacteria must have an ample supply of nutrients and an adequate supply of oxygen to survive. Hochheimer and Wheaton (1991) also review light to be an inhibiting factor on nitrifying bacteria growth. Like aeration design, a mass-balance approach is commonly used for high density fish systems.
Calculations

The following example is for a recirculating system used as a holding area for freshwater fishes. The following information is used in the design considerations:

A. Low-density system with 10-1000g. fish. Total biomass not to exceed 50 kg.
B. Total feed is not to exceed 2kg/day.
C. 750 gal. system (2-250 gal circular tanks and 1-250 gal rectangular trough).
D. Components will consist of a sand filter, trickling biofilter, UV sterilizer, and supplemental aeration.

1. FLOW RATE: Turnover rate 1x/hr. (750 gal./60 min = 13 gpm flow rate)
   1” PVC pipe will be used, which has a velocity of about 5 ft/sec and a head loss of around 40 head feet/100’ pipe (Table 2.0).

2. PLUMBING FITTINGS: From Creswell (1993), the following losses are given:

<table>
<thead>
<tr>
<th>Discharge</th>
<th>Suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(8) 90° elbows</td>
<td>= 20 ft. pipe</td>
</tr>
<tr>
<td>(4) 45°</td>
<td>= 5.3</td>
</tr>
<tr>
<td>(2) Tees (branch flow)</td>
<td>= 10</td>
</tr>
<tr>
<td>(6) Gate Valves (Open)</td>
<td>= 6.5</td>
</tr>
<tr>
<td>Straight pipe</td>
<td>= 10</td>
</tr>
<tr>
<td><strong>TOTAL SUCTION</strong></td>
<td><strong>8 feet pipe</strong></td>
</tr>
<tr>
<td><strong>TOTAL DISCHARGE</strong></td>
<td><strong>51.8 feet pipe</strong></td>
</tr>
</tbody>
</table>

3. FILTRATION COMPONENTS:
   Vertical distance from sump water to the highest point where the water is discharged into the trickle filter = 7’
   Sand filter = 1 psi = 2.3 head feet
   UV = minimal

4. TDH (total dynamic head) = friction head + pressure head + static head

   **59.8’ pipe (suction + discharge)**
   Head loss 40’/100’ pipe (from #1) = (59.8’)(40’)=(100’)a
   a = 24’

   TDH = 24’ + 2.3’ + 7’ = 33 head feet
   Therefore, a pump that would supply 13 gpm at 33 feet of head is needed.

5. AERATION REQUIREMENTS:
   From Table 1, we find **14,600 mg/kg/day** O₂ consumption for catfish at 26°C.
   According to a supplier, 6” airstones output is 8g O₂/hr (192,000 mg O₂/day).
   (50kg fish)(14,600mg/kg/day) = 730,000 mg/day O₂ consumption
   730,000 mg/day O₂ consumption / 192,000 mg O₂/day output each = (4) 6” airstones
6. AERATION DEVICE:
6” airstones are suggested to run at 0.5 CFM (supplied from manufacturer) each.
\[ 0.5 \times 4 = 2.0 \text{ CFM} \]
Friction loss due to flow and pipe size is minimal for this volume of air (Creswell (1993). With a depth of 2’, about 1 psi of pressure is required.
This minimal air volume will require a small air pump capable of \(2\text{-}3 \text{ CFM @ 1.5-2 psi}\), and at these figures there is a buffer.

7. BIOLOGICAL: Feeding at a rate of 2 kg/day and using a production rate of 35g/kg.feed. = 70 g. N \text{ produced/day}
Using a removal rate of 0.14g/m\(^2\)/day
\[ 70 \text{ g. N} \div 0.14 \text{ g./m}^2\text{/day} = 500 \text{m}^2 \text{ surface area} \]
1” bioballs = 532m\(^2\)/m\(^3\) (given by supplier)
Therefore, one cubic meter of 1” bioballs is needed for the trickling filter.
If a round cylinder of 0.5m diameter is used, the height of the container would be calculated by the following:
\[ V = \pi r^2 h \]
\[ 1m^3 = (3.14) (0.5)^2 \times (h) \]
\[ h = 1.2 \text{ m} \]
The considerations mentioned are a few of many for the design of an aquatic holding system, although they will give a starting point in the design phase and eliminate some of the guess work in system design. Much of the information for system design is limited, and for the most part, very inconsistent because of the many variables that are involved. In the end, the most versatile facility/system will work out the best over time.

**Literature Cited**


Heat Budget Model for Predicting Water Temperature in Outdoor Intensive Fish Tanks Under Greenhouse Cover

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Introduction

Intensive fish culture in Israel is generally practised in covered outdoor tanks. The transparent covers trap solar energy, resulting in water temperature that enables fish to overwinter successfully in northern Israel and even to achieve some growth in southern Israel. Common cover materials are semi-transparent white or green PVC and PE sheets.

The objectives of this study were: (a) to examine experimentally the influence of different cover materials on tank water temperature and (b) to develop energy budget models to quantify energy fluxes in a covered tank and to predict tank water temperature.

Data were collected between 1996-1999 at the experimental aquaculture research station at Genosar (northern Israel) and at the National Center for Mariculture (NCM) in Eilat (southern Israel). Two models were developed: (a) an extended dynamic model (EM), which was used to estimate the relative importance of the various energy fluxes, and (b) an equilibrium radiation model (RM), which was used to predict mean water temperatures.

Experimental procedure

The effect of several cover types on water temperature was studied in ten 50 m³ concrete tanks at Genosar. Materials used were semi-transparent white or green PVC and PE sheets. The tanks were occupied by overwintering tilapia fish. All tanks had the same water exchange rate (10-50%/day, depending on the year) and the same number of paddlewheel aerators. Data were collected on an hourly basis for 3 months over three winters (1996/97 to 1998/99). These included wind speed and direction, as well as inside and outside solar radiation, air temperature and humidity. Also measured were the temperatures of the tank water, inflow water, tank cover and sky.

At the NCM in Eilat, similar tests, utilizing three 100 m³ sea water tanks for sea bream culture, were conducted in the winters of 1996/97 and 1997/98. One tank was covered with green semi-transparent PVC, another with white PVC and the third remained cover-less. All three tanks had the same high water exchange rate (240%/day) and the same number of paddlewheel aerators.

The air exchange rate under the covers was determined by the tracer (here CO₂) decay method (Nederhoff et al., 1985; Boulard et al., 1996). The measurements were
carried out for both the 50 m$^3$ and the 100 m$^3$ tanks (air volumes of 85 m$^3$ and 200 m$^3$, respectively).

**Extended energy budget Model (EM)**

The EM consists of three energy balance equations, corresponding to the three components of the system (tank water, inside air and cover, see Figure 1), and one mass balance equation of water vapor in the air.

1. energy balance of the water:  \( \alpha_w S_i - L_i - H_w - \lambda E_w - H_r - H_m = \rho_w dC_w dT/dt \)
2. energy balance of the air:  \( H_w - H_c - H_v + \lambda E_w - \lambda E_c - \lambda E_v = 0 \)
3. energy balance for the greenhouse cover :  \( S_o - S_i + L_i - L_o + H_c + \lambda E_c - H_o = 0 \)
4. mass balance of water vapor:  \( E_w - E_c - E_v = 0 \)

![Figure 1: Energy fluxes in the covered tank system.](image)

The explicit expressions for the various fluxes utilized conductive, convective and radiative transfer coefficients, which were adapted from experiments and from the greenhouse literature (Kittas, 1985; Papadakis et al., 1992; Seginer et al., 1988). The meteorological and control variables were taken from the experiments.

**Radiation Model (RM)**

An analysis of the results obtained with the EM (to be described briefly in the Results and Discussion section) indicated that the convective fluxes were relatively unimportant when the structure over the tank was not ventilated (as in winter). For such conditions a simplified model, RM, with emphasis on the radiative fluxes was developed (after Seginer et al., 1988).

The EM consists of only two energy balance equations, one for the tank water and one for the cover.

5. Energy balance for the water :  \( \alpha_w \tau G - (F_w - F_c) - \beta (F_v - F_s) - H_r = 0 \)
6. Energy balance for the cover :  \( \alpha_c G + (1-\gamma)(F_w - F_c) + (\beta - \eta)(F_v - F_s) = 0 \)

where $F_i$ is a shorthand notation for $\sigma T_i^4$
The RM requires only two meteorological inputs: solar radiation and air temperature (sky temperature is estimated from air temperature), while the EM requires wind speed and humidity as well. The RM was used to predict quasi-equilibrium (monthly mean) water temperature.

Results & Discussion

Greenhouse experiments. The different types of cover material resulted in similar tank water temperatures, meaning that their role as convective barriers was far more important than the differences in their spectral properties. At Genosar the covers raised tank water temperature (on average) by 3°C relative to the incoming water temperature, which was 16°C, and by 6°C relative to the uncovered (control) tank. In Eilat, both covered tanks maintained water temperature at 22°C, the same as that of the incoming sea water. The water in the control tank was cooler by 4°C.

Ventilation rate. The exchange rate of the inside air (k) was found to be linearly related to the external wind speed (V). With V in m/s and K in 1/h, the mean relationship, valid for both the small and large tanks, up to a wind speed of 7 m/s, is:

$$K = 0.22 V + 0.44 \quad (R^2=0.91)$$

This is similar to the results of Nederhoff et al. (1985).

Energy fluxes estimated with the EM. The EM, with calculated coefficients (from the literature and experiments), was used to estimate the winter-time energy fluxes. Results for February 1998 in Genosar are presented in Figure 2.

Figure 2: Average energy fluxes in a covered tank. Genosar, February 1998

The results show that the main dissipation routes are via long-wave radiation and convection from the cover to the surroundings, as well as by loss of heat to the cold fresh water. Condensation on the inside of the cover is also a significant energy flux. These results are in agreement with Zhu et al., 1998, who reported a radiative loss of 70 W/m², compared to 90 W/m² in this study.

Temperature prediction with the RM. Meteorological data available to fish farmers is generally just from monthly means. On the basis of such data, it is only
possible to predict mean monthly tank temperatures. The RM was fitted to the Genosar 1997/98 winter data, utilizing regression analysis. The resulting values for the four coefficients are: \( \frac{\beta - \eta}{\alpha_c} = -2.43 \), \( \frac{1 - \gamma}{\alpha_c} = 6.55 \), \( \alpha_w \tau_c = 0.6 \) and \( \beta = 0.3 \). The calibrated RM was then tested with the 1998/99 data from Genosar and Eilat (Table 1).

Table 1: Measured and predicted water temperature of covered tanks. First two data sets were used for training.

<table>
<thead>
<tr>
<th>Location</th>
<th>Period</th>
<th>Measured temperature (^\circ\text{C})</th>
<th>Predicted temperature (^\circ\text{C})</th>
<th>Deviation (^\circ\text{C})</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Genosar</td>
<td>Jan 98</td>
<td>18.3</td>
<td>18.2</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Genosar</td>
<td>Feb 98</td>
<td>19.6</td>
<td>19.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Genosar</td>
<td>Jan 99</td>
<td>19.7</td>
<td>18.8</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Genosar</td>
<td>Feb 99</td>
<td>20.5</td>
<td>20.2</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td>Eilat</td>
<td>Jan 99</td>
<td>22.2</td>
<td>22.0</td>
<td>0.2</td>
<td>0.9</td>
</tr>
<tr>
<td>Eilat</td>
<td>Feb 99</td>
<td>21.3</td>
<td>21.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 1 shows that the RM produced good predictions (less than 1\(^\circ\text{C}\) deviation from measured values) of tank temperature.

In conclusion it seems that the EM can be used to estimate energy fluxes and the RM can be used to predict water temperatures in covered aquaculture tanks.

References


Appendix - List of Symbols

**EM model fluxes (W/m²)**
- So - solar radiation that reaches the cover (minus reflection)
- Si - solar radiation that penetrates into the greenhouse via the cover
- Li - long wave radiation between the tank surface and the cover
- Hr - sensible heat resulting from water exchange
- Lo - long wave radiation between the cover and the surrounding outer air
- Hw - sensible heat between the tank surface and the greenhouse air
- Hc - sensible heat between the cover and the greenhouse air
- Ho - sensible heat between the cover and the surrounding outer air
- Hm - sensible heat from the sides of the tank
- Ec - latent heat between the cover and the greenhouse air
- Ew - latent heat between the tank surface and the greenhouse air
- Hv - latent heat in exchange between the greenhouse air and the surrounding outer air
- Ev - latent heat in exchange between the greenhouse air and the surrounding outer air

**RM model fluxes (W/m²)**
- G - solar radiation
- Fc - long wave radiation from the cover
- Fw - tank water long wave radiation
- Fs - sky long wave radiation
- Hr - heat flux due to water exchange

**Symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>T</td>
<td>K</td>
</tr>
<tr>
<td>V</td>
<td>m/s</td>
</tr>
<tr>
<td>K</td>
<td>l/h</td>
</tr>
<tr>
<td>C_w</td>
<td>J/(kg/K)</td>
</tr>
<tr>
<td>d</td>
<td>m</td>
</tr>
<tr>
<td>t</td>
<td>s</td>
</tr>
<tr>
<td>ρ</td>
<td>kg/m³</td>
</tr>
<tr>
<td>α</td>
<td>-</td>
</tr>
<tr>
<td>λ</td>
<td>J/kg[water]</td>
</tr>
<tr>
<td>σ</td>
<td>W/(m²K)</td>
</tr>
<tr>
<td>τ</td>
<td>-</td>
</tr>
</tbody>
</table>

**Subscripts**
- a - air
- c - cover
- i - inside structure
- m - walls of tank
- o - outside structure
- r - incoming water
- s - sky
- v - ventilation
- w - water
Recirculation Systems for Farming Eel in Western Europe: Towards a Certified Environmental Performance

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Present status of eel farming in recirculation systems
Eels are considered a delicacy in some countries in Western Europe and have traditionally fetched high prices, in the near past in the order of 8-10 US$/kg. The high value and decreasing landings from fisheries have been a strong impetus for developing eel culture over the last 30 years. Eels need a water temperature of 23 to 25 °C for optimal growth. Given the climate in Western Europe, farming of eel is only an option using warm effluent from power stations or recirculation technology. Although some of the early initiatives were utilising warm effluent in a flow-through mode, this approach has been virtually abandoned because it proved not to be reliable. The first recirculation systems for eel were built at the end of the seventies. Slowly and with much difficulty eel farming has expanded, mainly in Denmark and The Netherlands, to a business comprising approximately 100 farms with a production of 6700 tonnes in 1999. Although other species like sea bass, sea bream, turbot, sturgeon and African catfish are reared in recirculation systems occasionally, farming of eel is still the backbone for application of recirculation technology in Western Europe.

Developments in design and management of systems
To our knowledge, no studies are available which compare long-term technical performance of systems at a commercial level. Studies available usually cover instantaneous performance or only a certain aspect of performance (Gousset, 1990; Heinsbroek & Kamstra, 1990). Moreover, failure or success of certain systems in the strict technical sense is often difficult to disentangle from other factors regarding for example the management of the fish or the economic performance.

In the early days a range of techniques was used for removal of suspended solids: sedimentation bassins, swirl separators, fixed-bed upflow filters and some mechanical filtration. Today, only microscreens are used, which have shown strong technical development. Fine solids (bioflocs) are sometimes removed with upflow filters or UV;
exact criteria for design are lacking here however. Nitrification and removal of soluble COD is usually performed in fixed-bed reactors in upflow or downflow (trickling) mode. Clogging, a frequent problem in the early days, is countered with high hydraulic loads and facilities for cleaning. In the Netherlands, most systems currently operate at a low pH (5-6) which seems to be beneficial for fish growth but results in incomplete nitrification. In Denmark denitrification is applied in most farms, using methanol or sludge as a carbon source. Some farms are using chemical phosphorus removal as an end-of-pipe method. Methods for collection and treatment of waste water differ considerably according to differences in local regulations with regard to waste water. Technical (liquid) oxygen is applied in all cases.

The ‘Blue Label project’; towards a certified environmental performance
In 1998 ‘Hesy’, one of the largest producers of systems in the Netherlands, decided to evaluate its design of farms together with a number of manufacturers of system-components and research institutes. This idea was developed into an EU-sponsored project which started at the end of 1998 and will end in 2001. Participants in the project are Hydrotech (microscreens), Distrimex (pumps), Hoekloos (Linde; oxygenation), van Cooten (eel farming), RIVO, DIFTA and IMAG. The aim of the project was to:
- develop an integrated recirculation system able to meet the strictest regulations concerning effluents in a certifiable way;
- reduce the consumption of energy and water
- develop a tool to calculate heat balances of farms in order to decide on options for cooling, heating and insulation.

The technical objectives are to reduce consumption of water from 500 to 100 l per kg of fish produced and energy consumption from 10 to 6 kWh per kg produced. The final effluent should be within the limits mentioned below.

Table 1. Water quality criteria for effluent from the ‘blue label’ system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>In any 24-hour composite sample (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biochemical oxygen demand (BOD5)</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>Total nitrogen (N-total)</td>
<td>&lt; 20</td>
</tr>
<tr>
<td>Ammonium (NH4)</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Suspended solids (SS)</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>Total phosphorus (P-total)</td>
<td>&lt; 1</td>
</tr>
</tbody>
</table>

The research was separated in three different directions. Firstly, the performance of a number of existing ‘Hesy-systems’ was evaluated by on-site measurements resulting in a new design which also incorporated other elements from the study. Secondly, the relationship between fish performance and recirculating flow and the effect of mesh size on microscreen performance was established in a number of experiments at DIFTA. Thirdly, a computer model was developed which could calculate the needs for heating and cooling in relation to the design of the building, the management and the climate. At this stage, most of the experimental work is finished and a pilot-system with a production capacity of 25 tonnes of eel per year is being built. The performance
of this pilot-system will be evaluated as a final milestone in the project. In this paper some of the results achieved so far will be highlighted.

**System lay-out and design philosophy of the ‘Blue Label system’**

Formerly, the water treatment of the Hesy-system basically consisted of a microscreen filter (drum or disc) and a trickling filter. In most systems an upflow filter was incorporated for removal of small suspended solids. Denitrification was not applied standardly; oxygen was dissolved at a relatively high pressure of 1.3 bar. In figure 1 the lay-out of the new system (Blue Label) is given.

In the Blue Label system, denitrification is achieved in a moving bed biofilter fed with sludge from the disc filter and approximately 5% of the recirculating water flow. The effluent from this reactor is mixed with a flocculant and fed to a belt-filter which separates it into sludge and a clean water fraction. Part of this effluent, from which nitrate and phosphorus are largely removed, is bled to a sewer. The main advantage of this system is that all treatment processes work continuously. Fluctuations in water quality by back-flushing of filters and the associated labour are much reduced this way. The oxygen reactor is re-designed and built in a sump in order to reduce pressure loss. The recirculating flow is increased.

**Figure 1. Lay-out of the Blue Label system**

![Diagram of the Blue Label system]

**Legend**

1 - Fish tanks  
2 - Microscreen filter  
3 - Trickling filter  
4 - Oxygen reactor  
5 - Denitrification reactor  
6 - Belt filter  
7 - Storage sludge  
8 - Sewer or surface water  
9 - UV-treatment

**The effect of mesh size on microscreen efficiency**

During a large scale feeding trial at DIFTA, three different mesh sizes (100, 60 and 30 micron) were tested in a Hydrotech drum-filter for their effectiveness in removing suspended solids, COD, nitrogen and phosphorus. The water treatment in the system consisted of a drum-filter, two submerged biofilters, a trickling filter and a denitrification filter. In each experimental period of roughly three weeks a different
mesh was used. The system was stocked with eels of 40 grams and the daily feed load to the system was approximately 10 kg.

Water consumption was measured routinely; at the end of each experimental period a mass-balance over the drum-filter was established by intensive sampling over 24-hour.

The relative water consumption of the drum filter (expressed per kg of feed fed) increased during the experimental period with the 30 micron mesh but was stable with the other mesh sizes tested. Table 2 gives the results. Water consumption is significantly increased with smaller mesh size.

**Table 2. The average water consumption of a drum filter in stable conditions**

<table>
<thead>
<tr>
<th>Mesh size (micron)</th>
<th>30</th>
<th>60</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water consumption (l/kg feed)</td>
<td>239</td>
<td>106</td>
<td>75</td>
</tr>
</tbody>
</table>

There are many ways in which the mass balance over the drum filter can be calculated and the efficiency expressed. The most straightforward calculation of the efficiency is:

\[
\text{("in sludge" } \times 100) / (\text{("with feed" } - \text{("in fish" } + \text{"respiration/excretion")})
\]

This efficiency is a measure of the fraction of particulate material, originating from feed loss and faeces, that is recovered in the sludge from the drum filter. Because the drum-filter also catches bioflocs from the biological treatment, this figure has to be corrected for this contribution. Table 3 summarises the results.

**Table 3. The removal efficiency of a drum filter using 30, 60 or 100 micron mesh.**

<table>
<thead>
<tr>
<th>Mesh size</th>
<th>Suspended solids</th>
<th>COD</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 micron</td>
<td>75%</td>
<td>62%</td>
<td>62%</td>
<td>43%</td>
</tr>
<tr>
<td>60 micron</td>
<td>36%</td>
<td>36%</td>
<td>29%</td>
<td>39%</td>
</tr>
<tr>
<td>100 micron</td>
<td>16%</td>
<td>13%</td>
<td>14%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Table 2 shows that there is a significant effect of mesh size on removal efficiency of different substances. It is obvious that this effect has strong implications for the design of other parts of the water treatment which have to deal with the fraction that is not removed directly.

**The heat-balance of an eel farm**

The main idea behind recirculation of water in eel farming is to reduce costs for heating water. For this purpose, expensive well-insulated buildings are used which require a high productivity. Practical experience shows that in this type of building, cooling of water may become a problem when water consumption is reduced. In order to assess different options for insulation and energy-management in relation to climate, a simulation model was developed. The model ANIPRO has been developed for husbandry of livestock like pigs and chicken (van Ouwerkerk, 1999). A special module was added to simulate conditions for farming eel. The model uses information on climate, design of the building and system, feeding and feed utilisation to calculate a heat balance of the farm and the energy used (Figure 2). The model has been validated by measurements at two commercial eel farms.
Figure 2. The main screen of the energy simulation model ANIPRO, giving access to other parts of the model.

The main control strategy in the model is that at increasing outdoor temperatures the ventilation is increased from minimum to maximum and that subsequently the water suppletion to the system is increased to reach the desired water temperature. One of the results of simulations with the model is that increasing ventilation through the trickling filter by applying a larger fan is a very efficient option for temperature control. Depending on local conditions, alternative techniques can be used.

Future developments
Currently, a pilot-system with a production capacity of 25 tonnes of eel is being built according to the Blue Label principle. At the end of this year, the performance of this system will be evaluated. Apart from specific design of systems, interesting work remains to be done on design of buildings for farming fish.

The example of the development of eel farming in Western Europe clearly shows that a main drive for system development is business opportunity for farming certain species in closed systems.

References
