Water quality and rainbow trout performance in a Danish Model Farm recirculating system: Comparison with a flow through system

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Abstract:

The objective was to compare water quality and fish growth and mortality in a pilot scale recirculating system (RS) and a control tank in flow through system (FTS). The RS was designed after the Danish Model Trout Farm and operated with a make up water renewal rate of 9 m^3 per kg of fish produced. RS water quality did not decrease significantly with water flow rate decrease in the RS. During the experiment, the RS water treatment system presented solids removal efficiency of $59.6 \pm 27.7\%$ d^{-1}, ammonia oxidation of 45 ± 32 g m^{-3} d^{-1}, oxygenation yield of 392 ± 132 g of O_2 kWh^{-1} and CO_2 degassing of $23.3 \pm 11.9\%$ $pass^{-1}$. In the RS, nitrite concentration was 0.15 ± 0.07 mg l^{-1}, close to the toxicity threshold; a N_2 supersaturation phenomenon was measured, probably due to the air injection depth. The biofilter and sedimentation area management has to be improved to avoid organic matter decomposition and release of dissolved elements. Even if no N_2 over-saturation apparent effect on fish performance and aspect were detected, the airlift depth has to be modified in the case of industrial development of the RS. Some improvements of the water treatment system, especially on the airlift and sedimentation area, are suggested.
Concerning fish growth, no significant differences were observed between the RS and the FTS. No pathologies were detected and cumulative mortality rates (0.1%) were similar to the farm's usual data. There were no significant effects of water flow rate decrease in the RS on fish performance and energy savings were recorded of 0.7 kWh kg^{-1} of fish produced between RS_1 and RS_2. The global energy cost of the RS was 3.56 kWh kg^{-1} of fish produced (0.107 € kg^{-1} of fish produced). Even if the energy consumption of the water treatment system can be improved, the results confirm that recirculating system can be used for industrial trout on-growing, without fish performance deterioration.

Keywords: Recirculating system; Trout; Performance; Treatment system; Flow rate; Water quality; Energy cost

1. Introduction

In view of the legislation and sustainable development practices, fish farms are today confronted with water reduction and waste treatment questions. Some aquaculture rearing systems, called recirculating systems, can be associated with a treatment loop, for water reuse or water treatment before release. In those systems, the make up water needs, about 1 m^3 kg^{-1} of feed, are 100 times lower than in the traditional flow through systems (Mac Millan, 1992; Blancheton et al., 2007). Consequently, the waste flow rate is proportionally decreased, making waste treatment easier (Pagand, 1999; Blancheton, 2000; Léonard, 2000; Goldburg et al., 2001).

Recirculating systems include a number of treatment unit operations depending on the degree of water reuse, the economics and the water quality requirements which mainly depend on the fish species and size (Blancheton et al., 2007). Classically, the recirculating system treatment area is a combination of solid removal (mechanical filtration, decantation), gas control (oxygen supply, CO_2 degassing) and biological processes (ammonia nitrification by biofilter, disinfection by UV). In recirculating systems under aerobic conditions, the biological filter oxidises ammonia into nitrites and nitrates. Control of the physicochemical parameters is one of the advantages of the recirculating systems (Heinen et al., 1996). A combination of water quality factors such as dissolved O_2 (Wajsbrot et al., 1991; Foss et al., 2003), salinity (Alabaster et al., 1979; Sampaio et al., 2002), nitrite (Lemarié et al., 2004) CO_2 (Randall and Wright, 1989) and ammonia may cause fish health problems. On the contrary, fish can withstand large nitrate concentrations. Trout growth is affected by concentrations above 180 mg NO_3-N l^{-1} (Berka et al, 1981) and for other species, the maximum reported concentrations are about 500 mg NO_3-N l^{-1} (Otte and Rosenthal, 1979; Honda et al., 1993) and sometimes over 1000 mg NO_3-N l^{-1} (Colt, 2006).

Cost-effective salmonid recirculating systems have been developed over recent years (Summerfelt, 2006). Semi-closed systems for trout ongrowing were developed in Denmark some years ago when the Danish water legislation enforced strict measures on water consumption and waste discharge. Today, more than 10 % of the Danish trout production is produced in such farms. The Danish recirculating farms, working with 10 m^3 of make up water per kg of feed distributed present a simplified water treatment system with relatively low energy consumption. They are comprised of several raceway tanks divided into 30 m long rearing units and a centralised water treatment area. Each rearing unit includes an airlift pump system for water circulation and gas exchange (Mozes et $al.,$ 2002) and a solid removal system at the end of the rearing unit. The principle utilises fast water circulation in Foster-Lucas tanks, corresponding to 5 to 10 tank volumes per hour, compared to between 1 and 2 in flow through systems. The massive water flow circulation is generated by a low-head air driven pumping system (airlift), characterized by low energy requirements (Mozes et al., 2002). Through each circulation into the airlift, oxygen is supplied and CO_2 is stripped. This offers energy savings due to a lower pumping head (10-15 cm) than the conventional pumping systems (3-4 m) (Mozes et $al.,$ 2004). The solids removal system corresponds to a sedimentation area without fish, composed of cone settling systems (stoppers permit daily draining of the sludge, stored for valorisation as fertiliser). The farm's central water treatment system is comprised of a complementary solids removal system (mechanical drum or belt filtration) and a submerged biofilter (either moving or static bed, or a combination of both).

Although others authors have reported different recirculating systems for rainbow trout (Heinen and Hankins, 1996; Schuster and Stelz, 1998; Summerfelt et al., 2004a; Davidson and Summerfelt, 2005; Jo et al., 2006) and artic char (Summerfelt et al., 2004b), rainbow trout in these Danish model trout farm recirculating systems has not yet been studied to a significant level To define the system production limits and improve the design of new recirculating systems, a pilot scale system, based on the Danish principle, was set up in a French trout farm (Murgat, Beaufort, France), as a part of a regional program with the French water agency and IFREMER.

The first objective of our study was to document the operational aspects of the recirculating system, and quantify waste production. The second objective was to compare fish performance in the recirculating system with fish performance in a flow through system for a standard and constant stocking density.

2. Materials and methods

Water quality and rainbow trout (*Oncorhynchus mykiss*) performance in the recirculating system (RS) were compared during 200 days against the classical flow through system (FTS) in the same farm. Fish were kept at near a maximal density of 60 kg m^{-3}. A comparison of fish performance and welfare at different stocking densities was also carried out to define the maximum carrying capacity of the recirculating system, as described in Roque d'orbcastel *et al.* (2009a).

2.1. Experimental rearing systems

The recirculating system (RS) was built in two existing raceways (75 m length, 6 m width, 0.8 m depth) and was divided into two areas (Fig.1): the rearing area presenting a variable length (rearing volume from 70 to 350 m^3) and the water treatment area (volume of 127 m^3) comprised of two airlift pumps, a sedimentation area and a moving bed filter.
The water flow circulation, aeration and CO_2 stripping are induced by the airlift pumps (4.20 m deep) equipped with a P.V.C rack air diffuser and fed with an air compressor. Parallel to this aeration system, pure oxygen diffuser was installed to be used only in case of emergency. Water flow circulation is controlled through frequency adjustment of the air compressor. For sedimentation, twelve settling cones are installed in the bottom of the tank, equipped with stoppers permitting daily draining. The collected particles are injected into the farm's sludge thickening system before storage for land application. The moving bed biofilter, filled at 52 % with polythene plastic media (800 m^2 m^{-3} of specific area), is set in permanent motion with an air compressor. The make up water is supplied by gravity, with a renewal flow rate fixed at 9 m^3 kg^{-1} of feed (corresponding to 4.5 l.s^{-1} and 6.6 l.s^{-1} for the studied period).
A flow through system (FTS) was used as a control tank. The FTS is one batch of the 4 concrete raceways situated in the second sector of the on-growing farm. The FTS receives the water coming from the first sector of the on-growing unit, entirely filtered (mechanical drum filtration) and reoxygenated with pure oxygen using a low head oxygenator. In the raceway, the oxygen concentration is continuously recorded with submerged probes, and surface aerators are triggered when the tank outlet concentration drops below 6 mg l^{-1} (fixed by the farmer). Classically, the make up water renewal rate in the FTS varies according to natural fluctuations between 40 and 120 m^3 kg^{-1} of feed; during the experiment the average value in the FTS was 58 m^3 kg^{-1} of feed. During the experiment, the FTS volume varied according to commercial constraints of the farm, 45 m^3 for the first period and 10 m^3 for the second period.

2.2. Experimental rearing series

During the first period (called "RS$_1$"), the recirculating system was running under a maximal water flow rate recirculation and a maximal oxygen availability. During the second period (called "RS$_2$"), the water flow rate was reduced to find a compromise between energy savings by water flow rate decrease while maintaining correct fish performance. The water velocity was 8.2 ± 1.2 cm s^{-1} during the RS$_1$ and 5.7 ± 0.2 cm s^{-1} during the RS$_2$, 3 to 4 times higher than the water velocity of the FTS (2.2 ± 0.7 cm s^{-1}) (Table 1).
During RS$_1$ (from 08-23-2006 to 11-23-2006), 23464 fish (104.6 ± 17.1 g) from a same population, were stocked in the RS and the FTS. The fish number was controlled using a HELIOS40, Faivre® counter, 1.6% precision level. The stocking density was maintained close to 60 kg m^{-3} in the RS during RS$_1$, by random fish removal every other week. The

stocking density of the FTS was fixed according to the farm's management constraints. The flow of recirculated water in the RS was maximal during RS_1.

During RS_2 (from 11-23-2006 to 03-07-2007), 24053 fish (230 $\pm$ 8.7 g) from a same population were dispatched in the RS and the FTS, with an initial stocking density of 50 kg m^{-3}. The stocking density was also maintained at 60 kg m^{-3} during RS_2, by random fish removal every other week. The flow of recirculated water in the RS was progressively decreased by adjusting the pump frequency.

In both systems, fish were manually fed twice a day. The daily feed ratio varied from 0.8 to 1.1% of the biomass according to feeding tables. The feed composition of the two Skretting® commercial diets used (2P and 3P, according to the fish weight) varied between 46% protein and 26% lipid and 45% protein and 28% lipid, respectively.

2.3. Measurements

2.3.1. Water quality monitoring

O_2 and temperature were continuously recorded in both systems with SEDIA® probes. The other parameters were monitored every other week. Total CO_2 was measured using an Oxyguard® portable analyser and total gaseous pressures with the 300 ETM tensionometer®.

Water samples were taken 4h after the morning meal, when the post-prandial pick was the highest (Kaushik, 1980; Dosdat, 1992, 2001). Total suspended solid (TSS) concentrations were determined after GF/C filtration (NFEN872) and dissolved elements were measured by spectrophotometry. Total ammonia nitrogen (TAN), nitrite nitrogen (NO_2-N), urea-N, orthophosphates (PO_4-P) were analysed using an Alliance Instruments Evolution II (NFT90015 and ISO 67771984F) (Benschneider and Robinson, 1952; Solorzano, 1969). Nitrate nitrogen (NO_3-N) was measured with a Technicon®Autoanalyzer II (Wood, 1970).

Water velocity was measured in the tanks using a FLO-MATE® electromagnetic sensor. Water circulation flow rates were calculated by integration of 21 water velocities measured in the wet section; every meter in width, 3 water velocities were measured in the water column (surface, middle and bottom).

Make up water renewal rates (expressed as m^3.kg of feed distributed^{-1} or m^3.kg of fish produced^{-1}) and other system metrics were calculated, as the time required for make up water to exchange the entire system volume (T_1), the time required for recirculated water flow to exchange the rearing tank volume (T_2) and the volumetric fraction of water reused in the system (R):

T_1 (h) = V_S / q
T_2 (h) = V_p / Q
R (unitless) = Q / (Q + q)

With V_S = system volume (m^3), q = RS make-up water flow rate (m^3 h^{-1}), Q = RS recirculated water flow rate (m^3 h^{-1}), V_p = rearing tank volume (m^3).

Air flow rates were calculated by using the ideal gas law, inlet-outlet mass balance and the compressor characteristics (blower shaft power, motor speed, outlet temperature and associated curves from technical specifications) as follows:

$P * V = n * R * T$ giving $P_{inlet} * V_{inlet} / T_{inlet} = P_{outlet} * V_{outlet} / T_{outlet}$

where P = pressure of gas, V = volume of gas, n = number of moles of gas, R = universal gas constant and T = absolute temperature;

$Q_{outlet} = Q_{inlet} * (P_{inlet} / P_{outlet}) * (T_{outlet} / T_{inlet})$

where Q_{inlet}, Q_{outlet} = air inlet/outlet flow rates, P_{inlet}, P_{outlet} = air pressure at the compressor inlet and the air pressure measured at the compressor outlet (reading with a precision manometer), T_{inlet} = air temperature at the compressor inlet; T_{outlet} = air temperature at the compressor outlet. Electric consumption of the compressor was read on a totalising electric gauge.

The airlift oxygenation and degassing capacities were calculated with inlet-outlet mass balance of O_2 and CO_2 in the system (equations 6 and 7):

Oxygenation yield (% pass^{-1}) = 100 * k / K

where $k\ (kg\ d^{-1}) = (C_2 - C_1) * Q * 24 / 1000$
$K\ (kg\ d^{-1}) = Q_a * 24 * O_2\% * 32 / 22.4$
with k= O_2 transfer (kg d^{-1}); K = O_2 quantity available in the air flow rate (kg d^{-1}); C_1 = O_2 concentration in water at the airlift inlet (mg l^{-1}); C_2 = O_2 concentration in water at the airlift outlet (mg l^{-1}); Q = water flow rate passing in the airlift system (m^3 h^{-1}); Q_a = air flow rate (m^3 h^{-1}); O_2% = O_2 percentage in the air (21%). The airlift oxygenation yield was also expressed in g of O_2 per kWh, by using the electric consumption of the compressor.

CO_2 degassing yield (% pass^{-1}) = 100 * ([CO_2]$_{inlet}$ - [CO_2]$_{outlet}$) / [CO_2]$_{inlet}$

with [CO_2]$_{inlet}$ = CO_2 concentration in water at the airlift inlet (mg l^{-1}) and [CO_2]$_{outlet}$ = CO_2 concentration in water at the airlift outlet (mg l^{-1}).

The TAN oxidation kinetic of the biofilter (R_b, equation 10) was deduced from the inlet-outlet TAN mass balances at the rearing system level (equation 8) and at the biofilter level (equation 9):

$[C_e * (Q_1 + q)] + [R_p * V_p] = C_i * (Q_1 + q)$
$[C_i * Q_1] = [R_b * V_b] + [C_e * Q_1]$
$R_b = [(C_i - C_e) * Q_1] * 24 / V_b$

with R_b = TAN oxidation kinetic of the biofilter (g m^{-3} d^{-1}); C_i = TAN inlet concentration in the biofilter (mg l^{-1}); C_e = TAN outlet concentration (mg l^{-1}); Q_1 = water flow rate passing in the biofilter (m^3 h^{-1}), q = RS make-up water flow rate (m^3 h^{-1}), R_p = TAN production kinetic of the fish (g m^{-3} d^{-1}), V_b = biofilter volume (m^3), V_p = rearing tank volume (m^3).

The TAN removal efficiency across the biofilter in a single pass was also calculated as follows:

TAN removal efficiency (% pass^{-1}) = 100 * ([TAN]$_{inlet}$ - [TAN]$_{outlet}$) / [TAN]$_{inlet}$

with [TAN]$_{inlet}$ = TAN concentration in water at the biofilter inlet and [TAN]$_{outlet}$ = TAN concentration in water at the biofilter outlet.

The net change of total inorganic nitrogen (TAN, NO_2-N and NO_3-N) concentrations produced across the RS (outlet – inlet mass balance) was also calculated, in order to evaluate the water use intensity of the RS and a potential nitrate denitrification occurring into the biofilter.

The efficiency of the sedimentation system was calculated with inlet-outlet mass balance of TSS. Inlet TSS daily quantity was evaluated using the nutrient balance model developed by Papatryphon *et al.* (2005) giving the theoretical TSS excreted by the fish for a given quantity of feed distributed. Outlet TSS daily quantity was calculated using the weight of TSS retained by the cones for the same 24h period.

TSS removal efficiency (% d^{-1}) = 100 * [TSS$_{inlet}$ – TSS$_{outlet}$] / TSS$_{inlet}$
= 100 * [(TSS$_{excreted}$) – (TSS$_{excreted}$ - TSS$_{retained}$)] / TSS$_{excreted}$

with TSS$_{excreted}$ = TSS excreted by the fish (kg d^{-1}) evaluated using the model developed by Papatryphon *et al.* (2005), TSS$_{retained}$ = TSS retained by the cones (kg d^{-1}) for the same 24 h period.

The RS and FTS waste fluxes were measured *in situ* with classical hydrobiological methods, based on water sampling and flow rate measurements (Roque d'orbcastel *et al.*, 2008) and calculated with the nutritional method, based on feed digestibility (Papatryphon *et al.*, 2005). The energy cost of the RS water treatment system (airlift and biofilter) was calculated with compressors' technical specifications and expressed in kWh per kg of fish produced during the whole experiment period and in € per kg of fish produced.

The global energy cost of the RS was calculated by summing all the costs of the system: make up water pumping, water treatment (sedimentation system pump, biofilter compressor), aeration system, feed distribution and fish handling and fuel and gas consumptions (Roque d'orbcastel *et al.*, 2009b).

2.3.2. Fish growth and mortality

Fish mortality in the two rearing systems was counted daily to evaluate the cumulative mortality rate over the entire study period. Fish growth was evaluated from fortnightly biometrics, by individual weighing of 100 fish, to calculate the specific growth rate (SGR) and

the thermal-unit growth coefficient (TGC), as follows (with W_i and W_f as the initial and final mean body weight of the fish, respectively) :

$SGR = 100 * (ln\ W_f - ln\ W_i) / number\ of\ days$

$TGC = (W_f^{1/3} - W_i^{1/3}) * 100 / sum\ degree\ day$

The Muller-Feuga (1998) growth prediction model was also used to correct the temperature effect.

The Food conversion ratio (FCR) was calculated from the total feed intake during a period divided by the total fish biomass gain obtained during this period. The global FCR of the two systems were calculated for the two experiments, 94 day and 106 day experiments; the global FCR were compared to the average FCR of the two systems calculated at each fortnightly period (corresponding to the biometric frequency).

Fish morphology was calculated with the Fulton condition factor (K) (W = mean body weight of the fish (g) and L = mean body length of the fish, at the fork (cm)):

$K = W * 100 * L^{-3}$

2.3.3. Statistical analysis

Water quality and biological differences between the RS and the FTS were tested using a one-way ANOVA with a fixed effect system during the whole 200 day period. The differences between the two systems were also compared for the RS_1 and RS_2 periods. Statistics were performed using XLstat®.

3. Results

3.1. Water flow rates and physico-chemical qualities

Table 1 presents water metrics (flow rates, renewal rates, …) of the two systems. The make up water quality was roughly constant during the whole experiment, 9 m^3 per kg of fish produced (Table 2). The make up water renewal rate of the RS was 7 times lower than in FTS.

The rearing water physico-chemical quality for the RS and the FTS are presented in tables 3 and 4.

The TSS average concentration was higher in the RS than in the FTS water, but without significant difference (due to the high variability of the results). On the contrary, some significant differences were observed on the dissolved N results, with TAN concentrations significantly lower in the RS and NO_2-N and NO_3-N significantly higher. Subsequently to the RS water flow rate decrease, water quality was not significantly degraded (Table 3).

Concerning the dissolved gas (Table 4), O_2 outlet concentration was significantly higher in the RS than in the FTS, and the CO_2 concentration was lower. In the RS, the pH value was higher, a constant N_2 over-saturation was observed, without change when the water flow rate was reduced (RS_2). The water temperature in the RS was more variable than in the FTS.

3.2. Water treatment system efficiency and waste quantification

Table 5 presents the RS water treatment system efficiency, under RS_1 and RS_2 conditions.

During the whole experiment (200 day period), the average airlift oxygenation capacity was 20.4 ± 12.4 g of O_2 m^{-3} of air, corresponding to 290 ± 177 g of O_2 per pass through the airlift. The airlift pumps released on average 392 g of O_2 kWh^{-1} (maximum of 690 g of O_2 kWh^{-1}) corresponding to an energy yield of 2.4 ± 0.8 kWh kg^{-1} of fish produced. No pure oxygen was used during the whole experiment (0 kg of O_2 kg^{-1} of fish produced). The CO_2 degassing capacity of the airlift pumps was 23.3 ± 11.9 % per pass through the airlift. The water flow rate decrease had no effect on the oxygenation and degassing yields and reduced the airlift energy consumption by 0.7 kWh kg^{-1} of fish produced (between RS_1 and RS_2).

The water flow rate decrease had no real effect on the sedimentation system efficiency ($P = 0.04$).

The TAN oxidation kinetic for the moving bed was 34.5 ± 13.9 g m^{-3} of media per day, corresponding to a TAN removal efficiency of $27.7 \pm 6.0\%$ per pass across the biofilter, with an average TAN inlet concentration of 0.27 ± 0.05 mg l^{-1} and an average NO$_2$-N outlet concentration of 0.10 ± 0.03 mg l^{-1} (Table 6, Fig. 2). The water flow rate decrease had no significant effect on biofilter efficiency. The maximal TAN oxidation kinetic was 72.55 g m^{-3} of media per day.

The energy cost of the RS water treatment system was 2.49 ± 0.05 kWh kg^{-1} of fish produced. The global energy cost of the RS is 3.56 kWh kg^{-1} of fish produced in comparison with 1.00-1.72 kWh kg^{-1} of fish produced in the FTS (according to the pumping level of inlet water). The electric cost of the two systems were 0.107 € kg^{-1} of fish produced and 0.052 € kg^{-1} of fish produced for the RS and the FTS respectively.

Table 7 presents the net change of inorganic nitrogen (TAN, NO$_2$-N and NO$_3$-N) concentrations produced across the RS.

Waste production for the two systems is presented in Table 8. The waste evaluation showed TSS wastes fluxes 3 times lower in the RS than the FTS, TAN and PO$_4$ - P waste fluxes 6 times lower. On the contrary, NO$_2$ - N and NO$_3$ - N waste fluxes were higher in the RS waste than in FTS, by multiples of 2 and 6 respectively.

3.3. Fish performance

Table 9 presents the biological indexes in the two systems, for the two periods, RS$_1$ and RS$_2$. During the first period, the global FCR of the RS was 0.84 and the global FCR of the FTS was 1.10, values similar to those calculated with the average FCR from 15 day periods (Table 9). During the second period, the global FCR of the RS and the FTS was 0.97.

RS$_1$ period results

No disease appeared in the two systems during the RS$_1$ period and the cumulative mortality rates were similar in the two systems (cumulative mortality rates of 0.1% over the entire study period). No significant differences were noted on the biomass increase between the RS and the FTS (Fig.3).

No significant differences were noted on the weight dispersion between the RS and the FTS (Variation coefficient of 17% in the RS and 19% in the FTS) and there was no evolution over time of these coefficients.

RS$_2$ period results

Fish were kept at 59 ± 7 and 60 ± 8 kg.m^{-3} in the RS and FTS respectively, and fed at 0.9% of biomass per day. No disease appeared during the RS$_2$ period as well, and cumulative mortality rates were similar in both systems (0.1%). No significant differences were noted on the biomass increase between the RS and the FTS (Fig.4).

The RS weight dispersion was a little lower than in the FTS, without variation over time (VC of 13.7% in the RS and 17.1% in the FTS at the end of the period, respectively).

Fish morphology was similar in the two systems, with Fulton's K index of 1.40 ± 0.05 in the RS and 1.41 ± 0.07 in the FTS.

4. Discussion

In both systems, the value of the water quality key parameters was kept close to the recommended values for salmonid aquaculture (Brett, 1979; Thurston et al., 1981; Pedersen, 1987; Fivelstad et al., 1993; Jobling, 1994; Heinen et al., 1996; US EPA, 1998; Fivelstad et al., 1999, 2003; Neori et al., 2004; Colt, 2006; Crab et al., 2007): the outlet O2 concentration was always above 6 mg l-1 and the TAN concentration lower than 1 mg l-1. In our RS, the make up water renewal rate was around 9 m3 per kg of fish produced. Summerfelt et al. (2004a) reported make up water needs around 13 m^3 per kg of fish produced in a partial

reuse system without biofilter but with a high average TAN concentration of 2.7 ± 0.07 mg l^{-1}. In this system, to keep the TAN concentration under the recommended value of 1-1.5 mg l^{-1} (Thurston *et al.*,1981; US EPA,1998; Neori *et al.*, 2004; Colt, 2006; Crab *et al.*, 2007) would necessitate 23-24 m^3 per kg of fish produced (around 20-25% of the water needs of current FTS), which could be an economic option in some specific situations. In our RS, the biofilter activity resulted in lower TAN concentrations, higher nitrite and nitrate concentrations than in the FTS; the nitrite concentration was close to the recommended threshold (0.15 ± 0.07 mg l^{-1}). In the RS, the CO_2 concentration was always below 10 mg l^{-1}, when it was above the 10-20 mg l^{-1} (recommended values after Heinen *et al.,* 1996; Fivelstad *et al.,* 1999; 2003) in the FTS, due to the airlift stripping system. Consequently, the pH was higher. The major potential problem in the RS was a chronic over-saturation of N_2, with a concentration always above the toxicity threshold of 105% (Hussenot and Leclercq, 1987) which was due to the depth of air injection (Belaud, 1996; Blancheton *et al.,* 2006). This over-saturation had no apparent effect on trout performance and no gas bubble disease was observed, but it may be a problem for more vulnerable fish and could require reduction of the air injection depth. A compromise has to be found between a sufficient depth for increasing oxygenation, CO_2 degassing and water circulation efficiency, and a lower depth for over-saturation limitation.

When the water flow rate was decreased in the RS (corresponding to a water velocity of 2.67 cm s^{-1}, equivalent to the water velocity in the FTS) the water quality was not significantly altered. This can be explained by the biofilter efficiency and the airlift O_2 and CO_2 exchange capacity. With the water flow rate decrease, 0.7 kWh kg^{-1} of fish produced were saved. In the RS, the energy consumption of 3.56 kWh kg^{-1} of fish produced (69.9% allocated to the water treatment system) is higher than the Danish system reference (1.9 to 2.3 kWh kg^{-1} according to Lareau *et al.,* 2004) and can be improved. The airlift oxygenation and CO_2 degassing capacities were constant during the whole experiment, whatever the water flow rate. The oxygenation capacity was 392 ± 132 g O_2 kWh^{-1} whereas Mozes and Conijeski (2004) found more than 500 g O_2 kWh^{-1}, which can be explained by a high O_2 concentration at the inlet of the airlift: as described in the Fick diffusion law, the gas transfer depends on the O_2 and CO_2 water tension before the airlift. The airlift system could be optimised by testing other air flow rates and/or diffusion systems and/or injection depths, in order to define the economical and technical optimum. The sedimentation system showed a good but highly variable efficiency (60 ± 28 %). However, the remaining suspended solids are circulating and degraded into the system, with the risk of undesirable sedimentation areas and water quality degradation. An additional filtration treatment could contribute to maintaining an optimal water quality at high standing stocks without high additional head loss.

The biofilter efficiency (34 ± 14 g TAN m^{-3} d^{-1}) was relatively low along the experiment. As O_2 and pH were not limiting in the RS, 7.4 ± 1.4 mg l^{-1} and 7.5 ± 0.3 respectively, the low efficiency could be explained by other factors, cumulative or not, such as the low TAN concentration (0.27 ± 0.00 mg l^{-1}) and the organic load (Rusten *et al*, 2006). As no backwash was planned during the experiment, an increase of the organic load into the biofilter resulting in semi-anaerobic areas being established (Olsen, 1981 ; Diab and Shilo, 1988; Van Rijn and Rivera, 1990) was probably the reason of this low efficiency (Chen *et al.,* 2006; Michaud *et al.,* 2006). The biofilter efficiency could be improved by backwashing the packing media.

During the whole experiment, no pathologies were detected and the cumulative mortality rates were similar to the usual data of the farm: 0.1% in the two systems. As the farm is an area "exempted of the mean salmonid diseases", no preventive treatments were applied on the rainbow trout.

The growth performance of the rainbow trout was similar in the RS and the FTS, with a slightly lower weight dispersion in the RS.

The FCR of the RS (0.83-0.84 for RS1 and 0.82-0.97 for RS2) were close to the reference farm FCR (best results) for the same weight categories: 0.82 for 100-350g fish (RS1) and 0.93 for 230-700g fish (RS2). The FCR obtained in the RS were better than those of the FTS, especially during the first period (1.06-1.1). Given that growth was similar for the first period in the two systems, this difference in FCR could be explained by potential feed losses. Even if the feed distribution and registration were managed by the same operator in the two

systems, it is difficult to perfectly control the uneaten feed in batches of fish individuated in a large raceway production tank.

There were no significant effects of the water flow rate decrease on fish performance. In the RS, the minimal water flow rate tested was still higher (twice) than the FTS flow rate. During this RS_2 period, the water treatment system, especially aeration, was sized in order to ensure the usual trout performance of the farm and a correct water quality.

It would be worth testing the RS on more sensitive species as arctic char or brook trout (Wallace *et al.,* 1988 ; Jorgensen *et al.,* 1993).

Conclusion

Rainbow trout growth performance between 100 and 700 g was similar in a pilot scale recirculating system (70 m^3) to a control in regular flow through system. No pathologies were observed, even at the extreme temperatures reached (from 9 to 23°C). In comparison with the Danish recommendation, the RS presents a large improvement potential (pumping airlift system, biofilter and sedimentation area management) which is still necessary to ensure an industrial development of the system in French climatic conditions.

Acknowledgements

References

Alabaster, J.S., Shurben, D.G., Knowles, G., 1979. The effect of dissolved oxygen and salinity on the toxicity of ammonia to smolts of salmon, *Salmo salar* L. Journal of Fish Biology, 15, 705-712.

Belaud, A., 1996. Oxygénation de l'eau en aquaculture intensive. Cépaduès Editions, collection Polytech, 207p.

Benschneider, K., Robinson, R.J., 1952. A new spectrophotometric determination of nitrite in seawater. Journal of Marine Research., 11, 87-96.

Berka, R., Kujal, B., Lavicky, J., 1981. Recirculating systems in Eastern Europe. Proc. World Symp. On Aquaculture in Heated Effluents and Recirculation Systems, vol. 2, Stavanger, 28–30 May 1980, Berlin.

Blancheton, J.P., 2000. Developments in recirculation systems for Mediterranean fish species. Aquacultural Engineering, 22, 17-31.

Blancheton, J.P., Piedrahita, R., Belaud, A., Moutounet, Y., Fievelstadt, S., Lemarié, G., 2006. Gas control in land based aquaculture, physiological and technical aspects. Aqua 2006: Linking tradition & technology highest quality for the consumer, International conference Aquaculture Europe 2006 & World Aquaculture 2006, Firenze (Florence), Italy, May 9-13, 2006, Abstracts. World aquaculture society and European aquaculture society (CD-ROM).

Blancheton, J.P., Piedrahita, R., Eding, E.H., Roque d'orbcastel, E., Lemarié, G., Bergheim, A., Fivelstad. S., 2007. Intensification of landbased aquaculture production in single pass and reuse systems. Chapter 2. In Aquaculture engineering and environment.

Brett, J.R., 1979. Environmental factors and growth. In: Hoar, W.S., Randall, D.J., Brett, J.R. (Eds.), Fish Physiology. Bioenergetics and growth, vol. 8. Academic Press, New York, pp. 599–675.

Chen, S., Lingk, J., Blancheton, J.P., 2006. Nitrification kinetics of biofilm as affected by water quality factors. Aquacultural Engineering, 34, 3, 179-197.

Colt, J., 2006. Water quality requirements for reuse systems. Aquacultural Engineering, 34, 143–156.

Crab, R., Avnimelech, Y., Defoirdt, T., Bossier, P., Verstraete, W., 2007. Nitrogen removal techniques in aquaculture for a sustainable production. Aquaculture, 270, 1–14.

Davidson, J., Summerfelt, S.T., 2005. Solids removal from a coldwater recirculating system – comparison of a swirl separator and a radial-flow settler. Aquacultural Engineering, 33, 47-61.

Diab, S., Shilo, M., 1988. Effect of light intensity on the activity and survival of *Nitrosomomas* sp. and *Nitrobacter* sp. isolates from fish ponds. Israeli J. Aquacult-Bamidgeh, 40, 50-56. *In Van Rijn, 1996. The potential for integrated biological treatment systems in recirculating fish culture - A review. Aquaculture, 139, 181-201.*

Dosdat, A., 1992. L'excrétion chez les poissons téléostéens I : L'azote. Pisciculture Française, 108, 25-40.

Dosdat, A., 2001. Environmental impact of aquaculture in the Mediterranean: nutritional and feeding aspects. Cahiers Options Méditerranée, 55, 23–36.

Fivelstad, S., Kallevik, H., Iversen, H. M., Møretrø, T., Våge, K., Binde, M. 1993. Sublethal effects of ammonia in soft water on Atlantic salmon smolts at a low temperature. Aquacult.Int., 1, 157-169.

Fivelstad, S., Olsen, A. B., Kløften, H., Ski, H.W., Stefansson, S. 1999. Effects of carbon dioxide for Atlantic salmon (*Salmo salar* L.) smolts at constant pH in bicarbonate rich freshwater. Aquaculture, 178, 171-187.

Fivelstad, S., Olsen, A., Åsgård, T., Bæverfjord, G., Rasmussen, T., Vindheim, T., Stefansson, S.O., 2003. Long-term sub-lethal effects of carbon dioxide on Atlantic salmon smolts: ion regulation, haematology, element composition, nephrocalcinosis and growth parameters. Aquaculture, 215, 301-319.

Foss, A., Røsnes, B.A., Øiestad, V. 2003. Graded environmental hypercapnia in juvenile spotted wolffish (*Anarhichas minor Olafsen*): effects on growth, food conversion efficiency and nephrocalcinosis. Aquaculture, 220, 607-617.

Goldburg, R.J., Elliott, M.S., Naylor, M.A., 2001. Marine Aquaculture in the United States: Environmental Impacts and Policy Options. Pew Oceans Commission, Arlington, VA, 44 pp.

Heinen, J.M., Hankins, J.A., 1996. Water quality and waste production in a recirculating trout-culture system with feeding of a higher-energy or a lower-energy diet. Aquaculture Research, 27, 699-710.

Heinen, J.M., Hankins, J.A., Weber, A.L., Watten, B.J., 1996. A semi-closed recirculating water system for high density culture of rainbow trout. Progressive Fish Culturist, 58, 11-22.

Honda, H., Watanaba, Y., Kikuchi, K., Iwata, N., Takeda, S., Uemoto, H., Furata, T., Kiyono, M., 1993. High density rearing of Japanese flounder, Paralichthys oliuuceus, with a closed seawater recirculation system equipped with a denittification unit. Suisanzoshoku, 41, 19-26.

Hussenot, J., Leclercq, D., 1987. La sursaturation des gaz dissous, un phénomène souvent mal connu en aquaculture. Aquarevue ,11, 27-31.

Jo, J.Y., Kim, I.B., Seo, K.H., Park, J.H., 2006. Rainbow trout culture in a Semi-Recirculating System, 6th International Recirculating Aquaculture Conference, July 20-23, Roanoke, Virginia, 364-373.

Jobling, M., 1994. Fish Bioenergetics. Chapman and Hall, London. 309 pp.

Jørgensen, E.H., Christiansen, J.S., Jobling, M., 1993. Effects of stocking density on food intake, growth performance and oxygen consumption in Arctic charr (*Salvelinus alpinus*). Aquaculture, 110, 191–204.

Kaushik S.J., 1980. Influence of nutritional status on the daily patterns of nitrogen excretion in the carp (*Cyprinus carpio* L.) and the rainbow trout (*Salmo gairdneri* R.). Reproduction Nutrition Development, 1980. 20 (6) p 1751.

Lareau, S., Champagne, R., Gilbert, E., Vandenberg, G., 2004. Rapport sur les missions d'évaluation de la technologie danoise pour l'élevage en eau douce des salmonidés.

Léonard, N., 2000. Recherche et élimination des facteurs inhibiteurs de croissance dans les élevages piscicoles en circuit fermé. Thèse de doctorat de l'université de Montpellier 2. Montpellier, France, 165 p.

Lemarié, G., Dosdat, A., Covès, D., Dutto, G., Gasset, E., Person-Le Ruyet, J., 2004. Effect of chronic ammonia exposure on growth of European seabass (*Dicentrarchus labrax*) juveniles. Aquaculture, 229, 479-491.

MacMillan, R., 1992. Economic implications of water quality management for a commercial trout farm. In: Blake, J., Donald, J., Magette,W. (Eds.), National Livestock, Poultry, and Aquaculture Waste Management. American Society of Agricultural Engineers, St. Joseph, Michigan, 185–190.

Michaud, L., Blancheton, J.P., Bruni, V., Piedrahita, R., 2006. Effect of particulate organic carbon on heterotrophic bacterial populations and nitrification efficiency in biological filters. *Aquacultural Engineering*, *34, 3, 224-233.*

Mozes, N., Eshchar, M., Conijeski, D., Fediuk, M., Ashkenazy, A., Milanez, F., 2002. "Marine Water Recirculating Systems in Israël –Performance, Production Cost Analysis and Rationale for Desert Conditions", 404-413. In T. Rakestraw, L. Douglas and G. Flick (Eds). Proceeding of the Fourth International Conference on Recirculating Aquaculture, July 18-21 2002, Roanoke, Virginia, USA.

Mozes, N., Conijeski, D., 2004. Performance Evaluation and Fish Production Cost Assessment in two Pilot-Scale Mega-Flow Low-Head Recirculating system in Israël. Proceeding of the Fifth International Conference on Recirculating Aquaculture, Roanoke, Virginia, USA, pp. 527-534.

Mozes, N., Haddas, I., Conijeski, D., Eshchar, M., 2004. The Low-Head Mega-Flow air driven Recirculating system - minimizing biological and operational risks. Proc. Aquacult. Eur. Conf., Barcelona, Spain, pp. 598-599.

Muller-Feuga, A., 1998. Growth as a function of rationing : a model applicable to fish and microalgae. Journal of Experimental Marine Biology and Ecology, 236, 1-13.

Neori, A., Chopin, T., Troell, M., Buschmann, A.H., Kraemer, G.P., Halling, C., Shpigel, M., Yarish, C., 2004. Integrated aquaculture: rationale, evolution and state of the art emphasizing seaweed biofiltration in modern mariculture. Aquaculture 231, 361–391.

Olsen, R.J., 1981. Differential photoinhibition of marine nitrifying bacteria: a possible mechanism for the formation of the primary nitrite maximum. Journal of Marine Research., 39, 227-238.

Otte, G., Rosenthal, H., 1979. Management of closed brackish-water system for high density fish culture by biological and chemical water treatment. Aquaculture, 18, 169-181.

Pagand, P., 1999. Traitement des effluents piscicoles marins par lagunage à haut rendement algal. Thèse de doctorat de l'université de Montpellier 1, Montpellier, France, 220 p.

Papatryphon, E., Petit, J., Hayo, V., Kaushik, S.J., Claver, K., 2005. Nutrient-balance modelling as a tool for environmental management in aquaculture: The case of trout farming in France. Environmental Management, 35 (2), 161-174.

Pedersen, L.C. 1987, Energy budget for juvenile rainbow trout at various oxygen concentrations. Aquaculture, 62, 289-298.

Randall, D. J., Wright, P. A. 1989. The interaction between carbon dioxide and ammonia excretion and water pH in fish. Canadian Journal of Zoology, 67, 2936-2942.

Roque d'orbcastel, E., Blancheton, J.P., Boujard, T., Aubin, J., Moutonnet, Y., Przybyla, C., Belaud, A., 2008. Comparison of two methods for evaluating waste of a flow through trout farm. Aquaculture, 274, 72-79.

Roque d'Orbcastel, E., Person-Le-Ruyet, J., Le Bayon, N., Blancheton, J.P., 2009a. Comparative growth and welfare in rainbow trout reared in re-circulating and flow through rearing systems. Aquacultural Engineering, 40 (2), 79-86.

Roque d'orbcastel, E., Blancheton, J.P., Aubin, J., 2009b. Towards environmentally sustainable aquaculture: comparison between two trout farming systems using Life Cycle Assessment. Aquacultural Engineering, In Press, Corrected Proof, Available online 4 January 2009,doi:10.1016/j.aquaeng.2008.12.002.

Rusten, B., Eikebrokk, B., Ulgenes, Y., Lygren, E., 2006. Design and operations of the Kaldnes moving bed biofilm reactors. Aquacultural Engineering, 34 (3), 322-331

Sampaio, L.A., Wasielesky, W., Miranda-Filho, K.C. 2002. Effect of salinity on acute toxicity of ammonia and nitrite to juvenile *Mugil platanus*. Bulletin of Environmental Contamination and Toxicology, 68, 668-674.

Schuster, C., Stelz, H., 1998. Reduction in the make-up water in semi-closed recirculating aquaculture systems. Aquacultural Engineering, 17, 167-174.

Solorzano, L., 1969. Determination of ammonia in natural waters by the phenol-hypochlorite method. Limnology and Oceanography, 14, 799-801.

Summerfelt, S.T., 2006. Design and management of conventional fluidized-sand biofilters. Aquacultural Engineering, 34, 275-302.

Summerfelt, S.T., Davidson, J.W., Waldrop, T.B., Tsukuda, S.M., Bebak-Williams, J., 2004a. A partial-reuse system for coldwater aquaculture. Aquacultural Engineering, 31, 3-4, 157-181.

Summerfelt, S.T., Wilton, G., Roberts, D., Rimmer, T., Fonkalsrud, K., 2004b. Developments in recirculating systems for Arctic char culture in North America. Aquacultural Engineering, 30, 31-71.

Thurston, R.V., Phillips, G.R., Russo, R.C., Hinkins, S.M., 1981. Increased toxicity of ammonia to rainbow trout (*Salmo gairdneri*) resulting from reduced concentrations of dissolved oxygen. Canadian Journal of Fisheries and Aquatic Sciences 38, 983-988.

US EPA (United States Environmental Protection Agency), 1998. Update of ambient water quality criteria for ammonia. *EPA* 822-R-98-008, 148 p

Wajsbrot, N., Gasith, A., Krom, M.D., Popper, D.M., 1991. Acute toxicity of ammonia to juvenile gilthead seabream *Sparus aurata* under reduced oxygen level. Aquaculture, 92, 277-288.

Wallace, J.C., Kolbeinshavn, A., Reisnes, T.G., 1988. The effects of stocking density on early growth in Arctic charr, Sal6elinus alpinus (L.). Aquaculture, 73, 101–110.

Wood, J.W., 1970. Diseases of Pacific Salmon: Their Prevention and Treatment. State of Washington Department of Fisheries, Olympia, WA, USA.

Figures

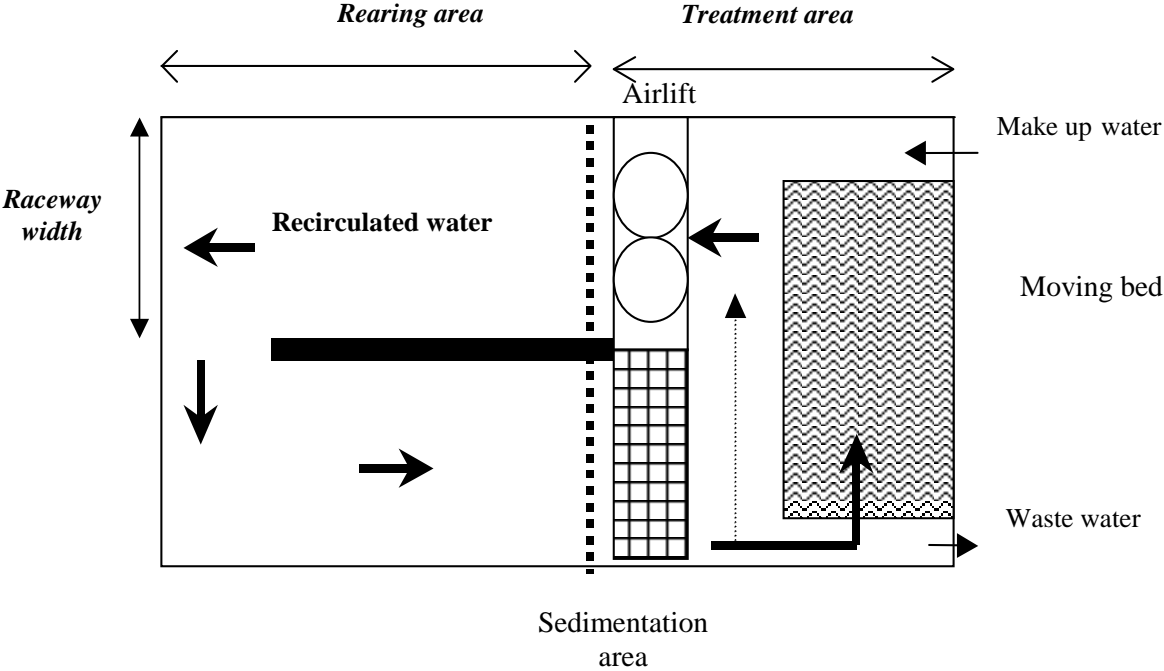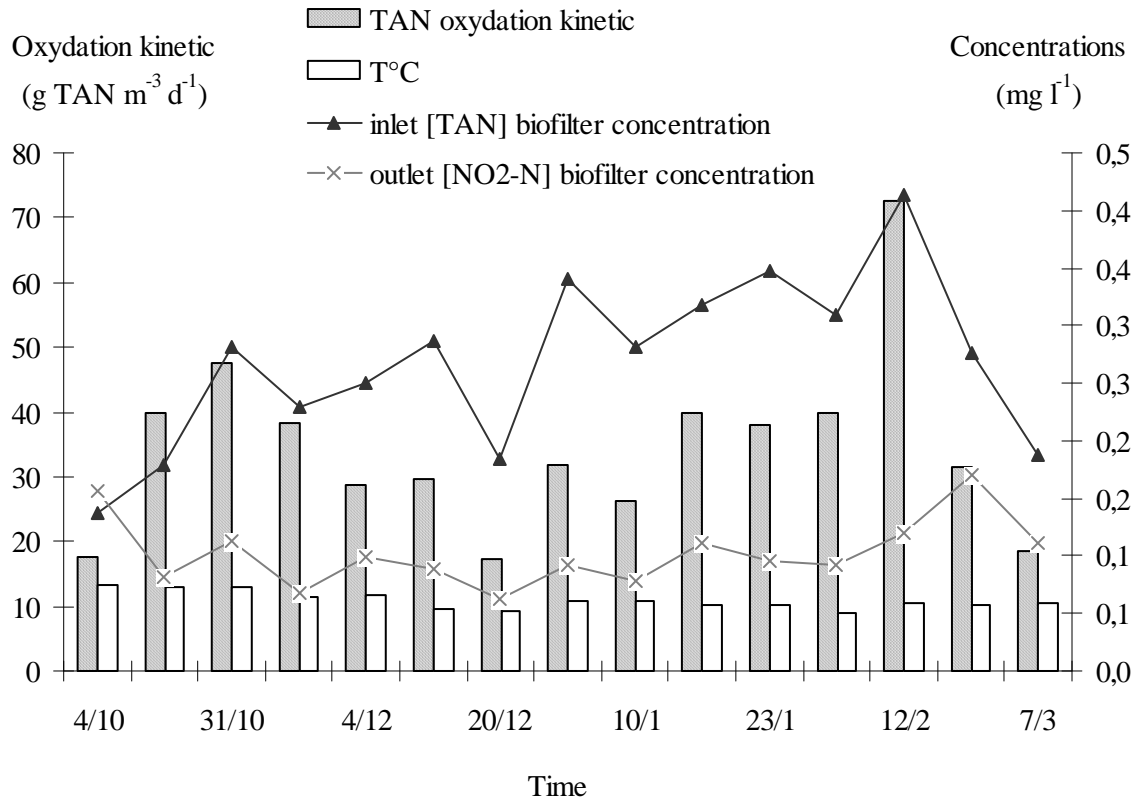Figure 1. The recirculating system (RS) (Roque d'Orbcastel *et al., submitted*)

Figure 2. TAN oxidation kinetic of the biofilter, inlet TAN concentration and residual [NO$_2$-N] concentration over time.
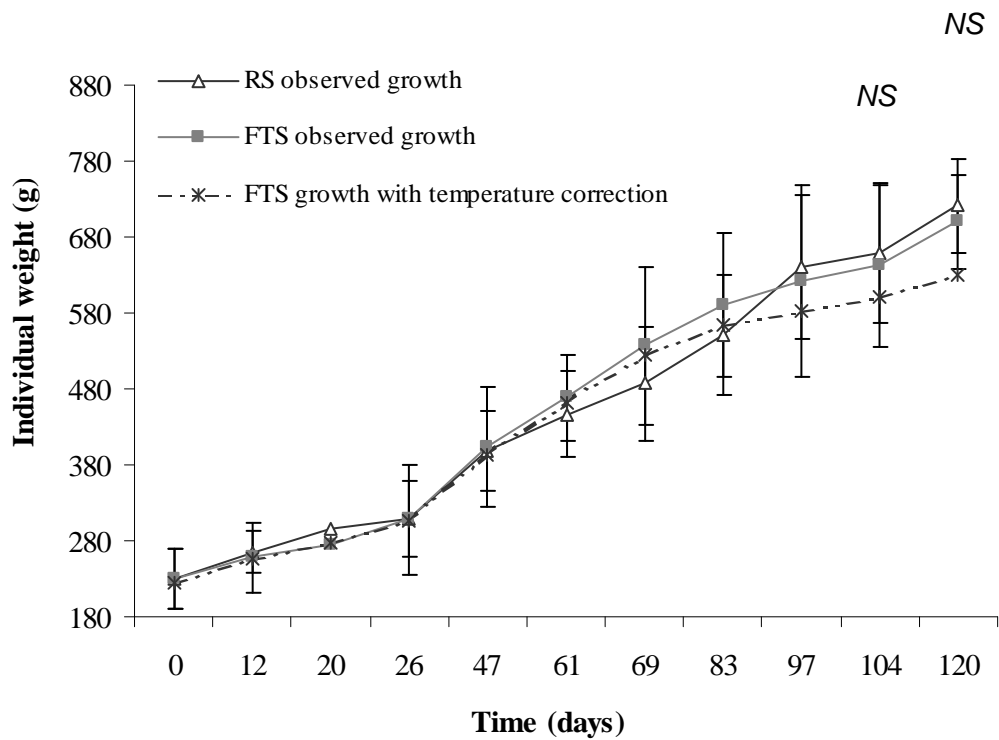

Figure 3. Changes over time in individual weight (mean ± SE) in RS (RS$_1$ period) and FTS. Statistical results are given for RS and FTS; NS, non significant difference ($P>0.05$); *, significant difference ($P<0.05$).
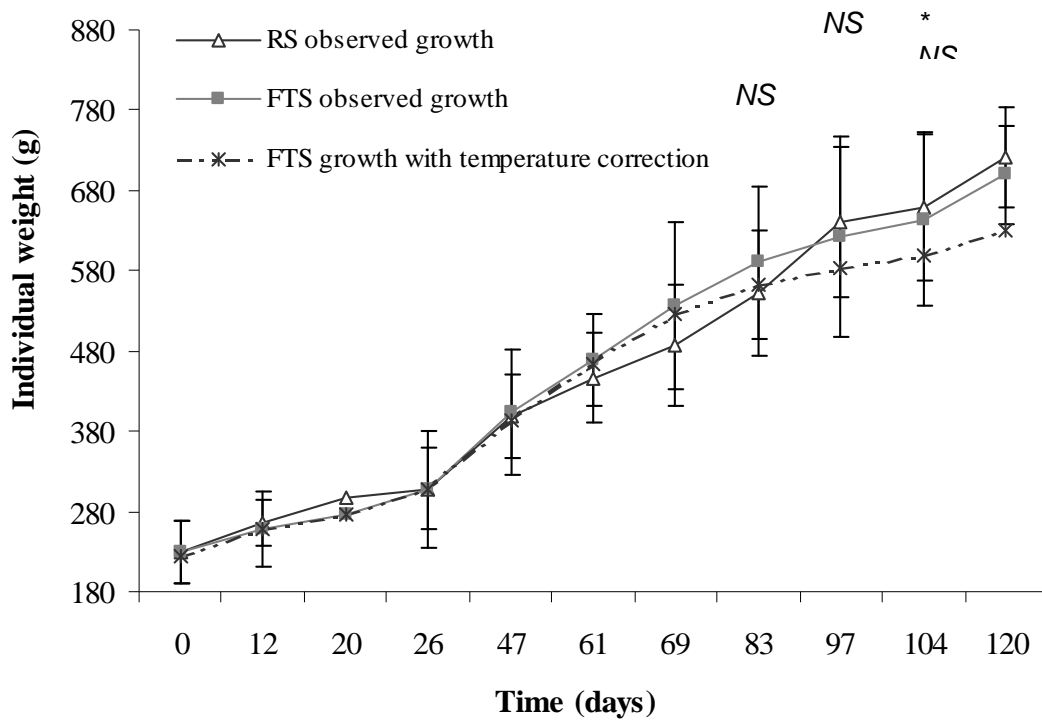
Figure 4. Changes over time in individual weight (mean ± SE) in RS (RS$_2$ period) and FTS. Statistical results are given for RS and FTS; NS, non significant difference (*P*>0.05); significant difference *, *P*<0.05.

Tables

Table 1. System metrics: make up water renewal rate and flow rate (r, q), water circulation flow rate (Q), time required for make up water to exchange the system volume (T1), time required for recirculated water flow to exchange the rearing volume (T2) and volumetric fraction of water reused in the system (R); air flow rates and airlift compressor (SF 700 / 1PC) characteristics.

Parameters / metrics	RS$_1$ period	RS$_2$ period	RS average value (whole experiment)	FTS average value (whole experiment)
Motor speed (round min^{-1})	2687	2015	2350	
Frequency (Hz)	40	30	35	
Air flow rate (m^3.h^{-1})	88	60	71 ± 17	
Water flow rate Q (m^3.h^{-1})^a	1175 ± 207	870 ± 94	913 ± 171	309 ± 98
r (m^3.kg of feed^{-1})	9 ± 3	8 ± 1	9 ± 2	58 ± 10
r (m^3.kg of fish produced$^-$	12	7	9	63

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$^{1)}$				
q ($m^3 \cdot h^{-1}$)	17	12	14	309
T1 (h)	11	17	14	From 0.03 to 0.15[b]
T2 (h)	0.06	0.08	0.08	= T1
R	0.99	0.99	0.98	

[a]: including make-up water flow rate
[b]: according to the FTS volume which varied with the commercial constraints of the farm (45 m^3 for the first period and 10 m^3 for the second period)

Table 2. Average make up water quality concentrations (mg l^{-1}) (N=18)

	pH	T°C	O_2	TSS	TAN	PO_4-P	Urea-N	NO_2-N	NO_3-N
Mean value	7.3	11.9	8.3	0.0	0.0	0.01	0.01	0.00	7.37
SD	0.4	1.1	1.1	0.0	0.0	0.03	0.01	0.00	1.07

Table 3. Water physico-chemical quality of the two rearing systems (NS, non significant difference; significant difference *, $P<0.05$; ***, $P<0.001$).

		TSS	TAN	NO_2-N	NO_3-N	Urea-N	PO_4-P
Period	N° days	Concentrations in mg.l^{-1}					
RS (N = 18)	200 d	7.3±7.1	0.29±0.09	0.11±0.05	8.56±0.99	0.07±0.02	0.04±0.03
FTS (N = 13)		3.9±2.7	0.89±0.08	0.02±0.00	7.51±0.70	0.13±0.01	0.05±0.01
P		NS	***	***	***	***	NS
RS_1 (N = 7)	94 d	4.8±1.8	0.26±0.14	0.13±0.10	8.06±0.99	0.06±0.02	0.03±0.03
RS_2 (N = 11)	106 d	8.0±7.9	0.29±0.07	0.10±0.03	8.68±0.96	0.07±0.02	0.04±0.03
P		NS	NS	NS	NS	NS	NS

Table 4. Gas concentration, pH and temperature of the rearing waters (NS, non significant difference; significant difference *, $P<0.05$; ***, $P<0.001$).

Period	N° days	pH	T (°C)	O_2 outlet concentration (mg l^{-1})	CO_2 concentration (mg l^{-1})	N_2 saturation (%)
RS	200 d	7.36 ± 0.21	11.2 ± 1.4	7.94 ± 1.1	8.5 ± 2.6	107.5 ± 2.5
FTS		6.86 ± 0.32	11.6 ± 0.5	6.62 ± 0.8	18.8 ± 4.2	< 100
P		***	***	***	***	***
RS_1	94 d	7.35 ± 0.17	12.6 ± 0.8	7.97 ± 1.01	9.0 ± 2.8	107.1 ± 2.4
RS_2	106 d	7.36 ± 0.23	10.2 ± 0.7	7.93 ± 1.11	8.3 ± 1.6	108.5 ± 2.1
P		NS	***	NS	NS	NS

Table 5. Water treatment system efficiency, under a maximal water recirculation (period RS_1) and water recirculation decrease (period RS_2).

Period	Nb days	Oxygenation yield (% pass^{-1})	Oxygenation yield (g of O_2 kWh^{-1})	$[CO2]_{inlet}$ (mg l^{-1})	$[CO2]_{outlet}$ (mg l^{-1})	CO2 degassing yield (% pass^{-1})	TSS removal rate (% day^{-1})
RS	200	7.4 ± 6.4	392 ± 132	8.6 ± 2.5	6.7 ± 2.3	23.3 ± 11.9	59.6 ± 27.7
RS_1	94	6.8 ± 7.6	459 ± 200	8.8 ± 1.2	7.0 ± 1.7	21.4 ± 12.1	40 ± 18.5
RS_2	106	6.3 ± 7.1	342 ± 21	8.4 ± 3.6	6.3 ± 3.0	25.6 ± 12.7	80 ± 11.9
P		*NS*	*NS*	*NS*	*NS*	*NS*	*

Table 6. TAN inlet and outlet concentrations, NO_2-N residual concentration, TAN removed per single pass and TAN oxidation kinetic of the biofilter, under (1) maximal recirculation condition (RS_1), (2) decrease recirculation condition (RS_2) and (3) average conditions of the 200 day experiment. Biofilter is working with 11 m^3 of air injected h^{-1} m^{-3} of media

Period	N° days	Inlet TAN biofilter concentration (mg l^{-1})	Outlet TAN biofilter concentration (mg l^{-1})	NO_2-N residual concentration (mg l^{-1})	TAN removal efficiency of the biofilter per single pass (g pass^{-1})	TAN removal efficiency of the biofilter (% TAN removed pass^{-1})	Oxidation kinetic (g of TAN m^{-3} of media d^{-1})
RS	200	0.27 ± 0.05	0.19 ± 0.05	0.10 ± 0.03	8.6 ± 3.0	27.7 ± 6.0	34.5 ± 13.9
RS_1	94	0.21 ± 0.06	0.14 ± 0.04	0.10 ± 0.04	8.0 ± 2.9	33.2 ± 7.5	35.9 ± 12.8
RS_2	106	0.29 ± 0.07	0.21 ± 0.05	0.10 ± 0.03	8.8 ± 3.0	26.3 ± 4.5	34.3 ± 14.2
P		*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

Table 7. Net change of inorganic nitrogen (TAN, NO_2-N and NO_3-N) concentrations produced across the RS (outlet – inlet mass balance).

Period	Inlet concentrations (mg l^{-1})			Outlet concentrations (mg l^{-1})			Outlet – inlet mass balance (mg l^{-1})
	TAN	NO_2-N	NO_3-N	TAN	NO_2-N	NO_3-N	
RS_1	0.0	0.0	7.60 ± 0.61	0.27 ± 0.12	0.22 ± 0.17	8.81 ± 0.77	1.69
RS_2	0.0	0.0	7.44 ± 0.76	0.28 ± 0.07	0.11 ± 0.03	9.45 ± 0.92	2.44

Table 8. Waste fluxes of the two systems, measured with the hydrobiological method and calculated with the nutritional method (nm = non measured parameters)

	RS measured waste fluxes (200d average)	FTS measured waste fluxes	RS and FTS calculated waste fluxes
	$g\ kg^{-1}\ feed\ d^{-1}$	$g\ kg^{-1}\ feed\ d^{-1}$	$g\ kg^{-1}\ feed\ d^{-1}$
Method	Hydrobiological	Hydrobiological	Nutritional
TSS	68.6 ± 48.4	226.2 ± 117.9	147.0 ± 0.2
Total nitrogen	Nm	38.5 ± 7.1	42.6 ± 0.4
TAN	3.6 ± 3.4	22.5 ± 5.3	28.3 ± 0.3
Urea-N	0.8 ± 0.7	7.6 ± 1.8	nm
NO_2- N	1.7 ± 2.0	0.8 ± 0.1	nm
NO_3 - N	91.9 ± 56.8	15.8 ± 15.1	nm
Total phosphorus	Nm	9.7 ± 2.5	4.5 ± 0.1
PO_4 - P	0.5 ± 0.8	2.8 ± 0.1	nm

Table 9. Biological indexes in the RS with a maximal recirculation (RS_1) and a reduced recirculation (RS_2) in comparison with the FTS indexes (NS: non significant difference, $P>0.05$).

Period	System	Stocking density ($kg.m^{-3}$)	Cumulative mortality rate over the period (%)	SGR (%)	TGC	FCR
From 23.08.06 to 23.11.06	RS_1	71	0.2	1.45	0.22	0.83
	FTS	33	0.1	1.15	0.19	1.06
	P		NS	NS	NS	NS
From 23.11.06 to 06.03.07	RS_2	59	0.1	1.26	0.21	0.82
	FTS	60	0.1	1.24	0.21	0.94
	P		NS	NS	NS	NS