A note on oxygen supply in RAS: The effect of water temperature

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\textbf{A B S T R A C T}

Two methods of supplying oxygen to recirculating aquaculture systems (RAS) are considered. One is aeration, here by means of airlifts, and the other is pure oxygen, here by liquid oxygen (LOX). Simplified steady-state models are used to compare the performance of these two methods over a range of water temperatures. Biological information for Mediterranean seabreams, as well as engineering and economic information, was obtained from the literature and from practice in Israel. The results, to a first approximation, are: (1) the feed and oxygen consumed by a fish to grow to a certain size are independent of temperature. (2) Supply of oxygen by aeration is controlled by its (minimal) required concentration in the water. As the temperature increases, this concentration approaches the saturation value, thus reducing the driving gradient. (3) Data of required oxygen concentration as a function of temperature are not consistent. Here we assume that for seabreams it is a constant absolute concentration, independent of temperature. (4) The optimal air discharge of an airlift does not depend on the gas to be transferred (oxygen or carbon dioxide), nor on temperature. (5) In operation mode, all available oxygen supplying airlifts should be operated simultaneously at the same air discharge, which together satisfy the oxygen demand. (6) At high temperatures, oxygenation with pure oxygen has a relative advantage over airlifts (aerators), and vice versa. The advantage of airlifts is larger for lower (safer) permissible carbon dioxide levels in the water.

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1. Introduction

Intensive aquaculture requires oxygen supplementation. Airlifts may be installed to deliver atmospheric oxygen, or else, pure oxygen may be used for that purpose (Timmons et al., 2002, Section 8.3). Here we focus on the effect of temperature on the supply of oxygen by these two means. The former is common in low head (LH) systems, such as driven by airlifts, while the latter is common in high head (HH) systems, generally driven by centrifugal pumps. Simplified models of the two oxygen supply systems are developed, and qualitative conclusions are drawn. Interaction with \(CO_2\) stripping is considered. The main hardware element to be modeled is an airlift developed at the National Center for Mariculture (NCM) in Eilat, Israel. Additional information is obtained from other local sources and from the literature. Characteristic behavior of Mediterranean seabreams is used to describe the fish.

The formulation of the model, intended mainly for the design phase of a project, assumes idealized steady-state conditions, where temperature is kept constant throughout the residence time of the fish, and feeding is to satiation. A virtual RAS module is analyzed, where each day one fingerling is introduced into the module and one marketable fish is removed (harvested). Fish mortality is ignored, but can be accounted for if so desired (Seginer and Ben-Asher, 2010, Section 3.4). The results are given in terms of amounts (such as feed) required to produce one fish, and as it turns out, several of these are, to a first approximation, independent of temperature.

2. Model

2.1. Fish growth

On the assumption that oxygen requirement is a function of feed consumption, the required feed to grow one fish to its marketable size is calculated first. To do that, a growth function and a feed function are required.
Here $M$ is live body biomass (BM = ‘weight’) of a single fish (in g[BM]/fish), $t$ is time (in days), $T$ is water (and fish) temperature (in °C), and $\alpha_M$, $\beta_M$ and $\gamma_M$ are positive coefficients (Table 1). Other growth functions for gilthead seabream are also available (Petridis and Rodgakis, 1996; Hernández et al., 2003; Seginer and Ben-Asher, 2010), but these have been found not to satisfy the needs of the current study. Eq. (1) is obviously only an approximation within the practical range, because (1) for sufficiently large fish, $M$ as a function of time must have an inflection point (sigmoid function), and (2) at a sufficiently high temperature, growth rate must decrease with increasing temperature (Hernández et al., 2003, Fig. 3; Pörtner and Knust, 2007, Fig. 1B).

Integration of Eq. (1) with respect to time, assuming constant temperature, produces the mass of a single fish at time $t$:

$$M = \left[ M_1^{1-\beta_M} + (1 - \beta_M) \alpha_M \exp(\gamma_M T) \right]^{1/(1-\beta_M)},$$

(2)

where $M_1$ is initial mass (stocking mass) of a single fish. Time to grow from $M_1$ to the final (marketable) size $M_f$ is the residence time, which for constant temperature is

$$t_f = \frac{M_f^{1-\beta_M} - M_1^{1-\beta_M}}{(1 - \beta_M) \alpha_M \exp(\gamma_M T)},$$

(3)

and the standing-stock biomass required to produce, at steady-state, one marketable fish per unit time (one module), is

$$\Phi = \int_0^{t_f} Mdt = \int_0^{t_f} \left[ M_1^{1-\beta_M} + (1 - \beta_M) \alpha_M \exp(\gamma_M T) \right]^{1/(1-\beta_M)} dt$$

$$= \frac{M_f^{2-\beta_M} - M_1^{2-\beta_M}}{(2 - \beta_M) \alpha_M \exp(\gamma_M T)},$$

(4)

where $\Phi$ is in g[BM]/(fish/d).

The size distribution of the fish population in each module whose total biomass is $\Phi$, is independent of temperature. However, while the smallest fish is always of size $M_1$ and the largest is of size $M_f$, the number of fish (equal to the number of days in residence), and (as Eq. (4) shows) also the total biomass, are smaller at higher temperatures. This means that for any given biomass density (carrying capacity; in kg[BM]/m³[water]), less rearing space is required as the temperature increases.

2.2. Feed consumption

Feed intake (consumption) to satiation of a single (gilthead seabream) fish is also given by Lupatsch and Kissil (1998) as a function of fish size and temperature. Specifically,

$$\frac{dF}{dt} = \alpha_F M^{\beta_F} \exp(\gamma_F T)$$

(5)

where $dF/dt$ is feed intake rate (in g[feed]/(fish/d)), and $\alpha_F$, $\beta_F$ and $\gamma_F$ are positive coefficients (Table 1). Eq. (5) is also an approximation, because at a sufficiently high temperature, feed consumption must decrease with increasing temperature.

Substituting from Eq. (2) into Eq. (5), yields

$$\frac{dF}{dt} = \alpha_F \exp(\gamma_F T) \left[ M_1^{1-\beta_M} + (1 - \beta_M) \alpha_M \exp(\gamma_M T) \right]^{1/(1-\beta_M)},$$

(6)

which, by integration with respect to time, and substituting for $t_f$ from Eq. (3), gives the feed consumed by a single fish throughout its residence in the system:

$$F_f = \frac{1}{1 + \beta_F - \beta_M} \cdot \frac{\alpha_F \exp(\gamma_F T)}{\alpha_M \exp(\gamma_M T)} \left[ M_f^{1+\beta_F-\beta_M} - M_1^{1+\beta_F-\beta_M} \right].$$

(7)
Table 1
Growth, feed intake, and respiration coefficients for gilthead seabream (Lupatshc et al., 2003, p. 245; personal communication). The values are valid for water temperature ranging from 19 to 27 °C and for fish sizes from 1 to 450 g(BM)/fish. The coefficients are to be used in Eqs. (1) and (5), in conjunction with M in g(BM)/fish, F in g(feed)/fish, T in °C and t in days.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Growth</th>
<th>Feed intakea</th>
<th>Growth respiration</th>
<th>Maintenance respiration</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>0.024</td>
<td>0.029</td>
<td>0.0072</td>
<td>0.0018</td>
</tr>
<tr>
<td>β</td>
<td>0.51</td>
<td>0.60</td>
<td>0.60</td>
<td>0.82</td>
</tr>
<tr>
<td>γ</td>
<td>0.060</td>
<td>0.057</td>
<td>0.060</td>
<td>0.074</td>
</tr>
</tbody>
</table>

* In the calculations: α = 0.027, γ = 0.06.

This is also the daily amount of feed consumed by the steady-state fish population, \( \Phi \), required to produce one marketable fish per day (one module). Thus

\[
F_\Phi = F_t. \quad (8)
\]

Note that if

\[
\gamma_f = \gamma_M, \quad (9)
\]
as it approximately is (Table 1), the feed consumed to grow a fish to its final size (Eq. (7)) is independent of temperature.

The feed conversion ratio (FCR), \( \eta \) (in g(feed)/g(BM)), is obtained by dividing Eq. (5) with Eq. (1), to result in

\[
\eta = \frac{dF}{dM} = \frac{\alpha_F}{\alpha_M} M^{\beta_f-\beta_M} \exp((\gamma_f - \gamma_M) T). \quad (10)
\]

which for \( \gamma_f = \gamma_M \) is also independent of temperature. It increases significantly, however, with the size of fish, because \( \beta_f \) is significantly larger than \( \beta_M \) (Table 1). For the steady-state fish population as a whole, the FCR is

\[
\eta_\Phi = \frac{F_\Phi}{M_f-M_l} \approx \frac{F_\Phi}{M_f}. \quad (11)
\]

2.3. Oxygen consumption and carbon dioxide excretion

The respiration rate of fish, usually measured in terms of oxygen consumption, may be divided into maintenance respiration and growth respiration (Lupatshc and Kissil, 2005). For feeding to saturation, both depend on body size and temperature, similarly to growth and feed consumption (Eqs. (1) and (5)). If the body size and temperature coefficients of maintenance and growth respiration are similar to those of feed intake, as they roughly seem to be (Table 1), the ratio of oxygen-consumption to feed-consumption is approximately constant, independent of size and temperature. Making this assumption, oxygen demand to produce one marketable fish (or to support the population \( \Phi \)), may be written as

\[
Q_\Phi = Q_t = \theta F_\Phi, \quad (12)
\]

where \( Q_t \) (in g(O2)/fish) is the amount of oxygen required to grow one fish to harvest size. In practice, \( \theta \) should be corrected for the oxygen consumption of micro-organisms in the system.

To a first approximation, the excretion of carbon dioxide by the fish is also proportional to metabolism, and hence to oxygen consumption and to feed. Thus,

\[
D_\Phi = \kappa_\Phi Q_\Phi = \kappa_\Phi F_\Phi, \quad (13)
\]

where \( D_\Phi \) (in g(CO2)/fish), is carbon dioxide produced by a single fish throughout its residence in the system, and \( \kappa \) (in g(CO2)/g(O2)) is the ratio of carbon dioxide production to oxygen consumption.

2.4. Required oxygen concentration in water

When oxygen is supplied by means of aerators, the economically optimal level of dissolved oxygen in the water, \( C_0 \) (in g(O2)/m³/water), is the lowest permissible, because this produces the largest driving gradient from air to water. The limiting value is obtained experimentally by gradually reducing the oxygen level until a reduction in the relevant fish performance (growth in our case) is observed. For most fish (the ‘regulators’) normal performance is maintained down to a critical oxygen concentration and then drops rapidly off, exhibiting a break-point (Brett, 1979, Fig. 15; Pedersen, 1987, Table 2; Jobling, 1994, Fig. 10.7; Zakharstev et al., 2003, Fig. 2A; Cerezo-Valverde et al., 2006, Fig. 4).

While growth is the relevant process for aquaculture (Jobling, 1994, Chapters 9–11, Brett, 1979), most available data are related to processes which are measurable over shorter periods of time. The critical point for each of these processes may be different, as is clearly shown in Fig. 1 by results of Cerezo and Garcia (2004) and Cerezo-Valverde et al. (2006), for two Mediterranean seabreams (Diplodus puntazzo and Dentex dentex). Three separate critical points are shown: one, where ventilation frequency starts to increase (‘Ventilation’ in figure); second, where oxygen consumption starts to fall off (‘Oxygen’); and third, where half the fish die (‘Lethal’). The ‘oxygen’ critical point which is measured most often and is usually called just ‘the critical point’, is considered by the authors not to ensure stress-free conditions. They suggest, instead, that the ventilation critical point be used as the operating level for aquaculture. Fig. 1 shows (1) that the two fish behave in a similar manner (probably also similarly to the gilthead seabream), (2) that all three critical concentrations are independent of temperature, and (3) that the constant oxygen level based on practice...
Goldfish, from eelpout, for pressure of water. Critical and concentrations (left critical our other literature. There possibly first approach, and to critical curve (2 or 3) eventually reaches the saturation curve (empty circles in Fig. 3, where the oxygen gradient from air to water vanishes), which indicates the onset of anaerobic metabolism and eventual death (Pörtner and Knust, 2007, Fig. 1E). As this point is approached, an ever increasing aeration capacity is required to supply the necessary oxygen, increasing thereby the relative advantage of pure oxygen, which cost is independent of temperature (as will be shown below).

For lack of accepted criterion and in view of the recent detailed results of Cerezo and Garcia (2004) and Cerezo-Valverde et al. (2006), and our Fig. 1 for Mediterranean seabreams, we choose in this paper to calculate for line 2 of Fig. 3 (constant absolute critical concentration at 5.5 g O₂/L m² [water]). This is somewhat safer (higher) than the ‘Ventilation’ line of Fig. 1. This choice predicts, by extrapolation, a maximum feasible temperature of 36°C, not very different from the lethal temperature of Hernández et al. (2003) for seabream, where, incidentally, the actual cause of death may be other than lack of oxygen. Furthermore, at such a high temperature, Eqs. (1) and (5) may no longer approximate the actual processes sufficiently well.

2.5. Oxygen supply by airlifts

In an airlift (or any other aerator), the flux of oxygen from atmospheric air to water is proportional to the oxygen concentration difference between the equilibrium-with-air level (‘saturation’), \(C_o(T)\), and the bulk concentration in the water, \(C_o\) (required, critical level), defined by the needs of the fish. Thus

\[
S = \ln(C_o(T) - C_o),
\]

Fig. 3. Three different schematic formulations of the minimum oxygen concentration for aquaculture (in sea water): (1) constant saturation fraction; (2) constant absolute concentration; (3) absolute concentration increasing with temperature. The solid arrows indicate the direction of oxygen transfer, from air to water. The crossings of the minimum permissible oxygen curves with the saturation curve are indicated by empty circles. In the background, in dashed lines, the transfer of CO₂ from water to air is indicated. A range of permissible CO₂ concentrations is indicated at the top of the frame.
where $S$ is the discharge of oxygen delivered by a single airlift (in g/$[O_2]/[airlift\, d]$), and $h$ is the oxygen transfer coefficient of the airlift (in m$^3$/water/$[airlift\, d]$). The transfer coefficient increases with air discharge through the airlift, $A$ (in m$^3$/airlift/$[airlift\, d]$), and to some extent with temperature. Thus, $h\{A, T\}$.

Indicating by $f$ (in airlift$/[fish]/[d]$) the number (or fraction) of airlifts required to support the fish population $\Phi$, the oxygen requirement of the fish, $O_\Phi$ (in g/$[O_2]/[fish]$), becomes

$$O_\Phi = fs.$$  \hfill (15)

There is a trade-off between $f$ and $A$, namely between investment (capital) and operating costs. The best combination of $f$ and $A$ is selected as follows: Given the cost of capital for one airlift, $u_c$ (in $\$/[airlift\, d]$), the power required to operate the airlift, $p\{A\}$ (in $\$/[airlift\, d]$), and the cost of electricity, $u_e$ (in $\$/m$^3$)), the cost of providing the necessary oxygen for the population $\Phi$ by means of the airlifts ($K^\text{lift}_O$, in $\$/[fish]$), is

$$K^\text{lift}_O = f (u_c + u_e p\{A\}),$$  \hfill (16)

which, utilizing Eqs. (15) and (14), becomes

$$K^\text{lift}_O = \frac{u_c + u_e p\{A\}}{h\{A, T\}} \cdot \frac{O_\Phi}{C_0(T) - C_0}.$$  \hfill (17)

The oxygen transfer coefficient $h\{A, T\}$ may be written as a product

$$h\{A, T\} = h\{A\} \exp[\gamma_0(T - T_r)],$$  \hfill (18)

where the exponential function is a temperature correction (Tchobanoglous et al., 2003, p. 427) relative to a reference temperature, $T_r$. It is convenient to incorporate the temperature correction into $f$, which may be expressed as

$$f = \frac{f_0 \exp[\gamma_0(T - T_r)]}{\exp[\gamma_0(T - T_r)]}.$$  \hfill (19)

where $f_0$ is the required number of airlifts at the reference temperature (at which the calibrating data are collected). Hence, Eq. (17) may be written as

$$K^\text{lift}_O(T) = \frac{1 + (u_c/u_e)p\{A\}}{h\{A\}} \cdot \frac{1}{\exp[\gamma_0(T - T_r)]} \cdot \frac{u_c O_\Phi}{C_0(T) - C_0}.$$  \hfill (20)

The cost $K^\text{lift}_O$ can be minimized with respect to the air discharge $A$, irrespective of the temperature and of the oxygen demand, which are restricted to the square bracketed factor. For a given airlift design and operating head, therefore, the optimal discharge depends only on the price ratio $u_c/u_e$.

The number of oxygen-supplying airlifts to produce one fish per day (from Eqs. (16)–(18)),

$$f_0 = \frac{O_\Phi}{h\{A\} \exp[\gamma_0(T - T_r)](C_0(T) - C_0)},$$  \hfill (21)

depends very much on the difference (gradient) $\dot{C}_0(T) - C_0$. For the chosen Scheme 2 (constant absolute $C_0$; Fig. 3), the concentration gradient approaches zero as the temperature increases, and therefore $f_0$ increases indefinitely with temperature. With this scheme, proper oxygen supply by means of airlifts (and aerators in general) may become economically unviable at sufficiently high temperatures.

The airlift power requirement, $p\{A\}$, and the transfer coefficient, $h\{A\}$, may be conveniently approximated by power expressions:

$$p\{A\} = \chi A^\mu,$$  \hfill (22)

and

$$h\{A\} = \sigma A^\nu,$$  \hfill (23)

which, when introduced into Eq. (20) yields

$$K^\text{lift}_O(T) = 1 + (u_c/u_e)p\{A\} \cdot \frac{1}{\exp[\gamma_0(T - T_r)]} \cdot \frac{u_c O_\Phi}{C_0(T) - C_0}.$$  \hfill (24)

### 2.6. Operational considerations

Once a system is constructed, its operation must be considered. The appropriate scaling in the design phase (as in the preceding analysis), is with respect to production rate (e.g., $f$ in airlifts per fish$/d$). System operation, on the other hand, is more naturally scaled with respect to the (already) installed capacity of the system (e.g., $S$ in g/$[O_2]/$per airlift-/day). Suppose that, for one reason or another, the oxygen demand per airlift, designed to be $S = O_\Phi/f$ (Eq. (15)), changes. If it increases, the only solution is to increase, at an additional cost per unit oxygen, the air discharge of the airlifts. If the oxygen demand falls below the design value, however, there is a choice between operating all the airlifts at a reduced air discharge, or a smaller number of airlifts at the previously obtained optimal discharge. As the capital cost, $u_c$, is no longer relevant, setting it to zero in Eq. (24) yields the operating cost

$$K^\text{lift}_O(T) = u_0 \frac{X A^{(a - \nu)}}{\exp[\gamma_0(T - T_r)]} \cdot \frac{O_\Phi}{C_0(T) - C_0}.$$  \hfill (25)

As will be shown below, $\mu - \nu > 0$. Hence the operating cost is minimal at the lowest air discharge $A$ which supplies the required oxygen. In other words, all available airlifts should be operated all the time, varying the air discharge to exactly match the demand for oxygen. Note that if in practice the load of the various fish tanks is not the same, all the airlifts supplying a given tank should operate at the same discharge, suitable for the particular load of that tank.

### 2.7. Oxygen supply by pure oxygen

Just as with aerators, there is also a range of designs for oxygenation with pure oxygen, whether in the liquid phase (LOX) or as pressurized gas (Timmons et al., 2002, p. 275). For our purpose two main properties, common to all variants, are important, namely (1) that a bulk saturation level (in water) of 100% (the maximum permissible) is achievable, which is impossible with airlifts, and (2) that the cost of supplying the oxygen is, to a first approximation, independent of temperature, due to the high concentration at the source.

As a result, the cost of supplying pure oxygen may be formulated simply as

$$K^\text{pur}_O = u_0 O_\Phi = u_0 f\Phi,$$  \hfill (26)

where $u_0$ (in $\$/[g]/[O_2]$) is the unit price of oxygen actually consumed by the fish (including costs of generation and pressurization and considering dissolving efficiency). The cost is proportional to the feed consumed (by Eq. (12)) and hence, from this point of view as well, practically independent of temperature.

### 2.8. Carbon dioxide stripping by airlifts

Carbon dioxide stripping is usually effected by (atmospheric) aeration, whether with airlifts, trickling nitrification biofilters or stripping columns (Timmons et al., 2002, Section 8.4). The mechanism for stripping excess CO$_2$ is analogous to that of supplying oxygen, except in the opposite direction. To a first approximation, the production of carbon dioxide is proportional to the consumption of oxygen (Eq. (13)) and the transfer coefficients of the two gasses are proportional to each other over the relevant range of air-discharge and temperature. Hence, the cost of CO$_2$ stripping...
Example only, as there is a wide variety of RAS facilities, and estimates are obtained in different ways and to a different accuracy by the various sources.

3.1. Fish characteristics

Assuming, as already mentioned, that the temperature coefficients, \( \gamma \), of growth and feed consumption are the same, the coefficients of the feed column of Table 1 have been slightly modified by refitting (these values apply to the particular feed used in the original experiments). The final coefficient values are

\[
\alpha_F = 0.027 \frac{\text{g[feed]}}{\text{g[O2]/kg[feed]}^{1/2} \text{d}}; \quad \beta_F = 0.60; \quad \gamma_F = 0.061/K
\]

\[
\alpha_M = 0.024 \frac{g^{1-\beta_F}[\text{BM}]}{\text{fish}^{1-\beta_F} \text{d}}; \quad \beta_M = 0.51; \quad \gamma_M = 0.061/K
\]

From practice

\[
M_i = 2 \text{g[BM]/fish}; \quad M_f = 400 \text{g[BM]/fish}.
\]

With these values, one obtains

\[
F_M = 706 \text{g[feed]/fish} (= F_J; \quad \text{Eq. (7)})
\]

and the FCR (Eq. (11)) becomes

\[
\eta_F \equiv 1.8.
\]

There is a wide range of experimental results for \( \theta \) in the literature, depending on species, fish size, feed composition and ration. Timmons et al. (2002, pp. 99–100) quote a representative value of \( \theta = 0.25 \). A more recent study (Merino et al., 2009, Table 4) suggests, for halibut of similar size and feeding ration as our seabream, a mean value of \( \theta = 0.5 \text{kg[O2]}/\text{kg[feed]} \). Measured values of \( \kappa \) are rare. Timmons et al. (2002, p. 287) suggest a theoretical value of 1.38 kg[CO2]/kg[O2].

Here we choose to use values obtained from the detailed empirical model of Lupatsch for seabream (Lupatsch, personal communication). On average, for the range of temperatures 20–70°F, the following equivalents are obtained

\[
\theta = 0.63 \text{kg[O2]}/\text{kg[feed]}, \quad \kappa = 1.14 \text{kg[CO2]}/\text{kg[O2]}.
\]

In practice, the supply of oxygen is augmented to offset inefficiencies and to provide for oxygen-consuming micro-organisms in the system. Hence, the value of \( \theta \) for the subsequent calculations (for both configurations) is increased to

\[
\theta = 0.75 \text{kg[O2]}/\text{kg[feed]}.
\]

This value is supported by bulk data obtained recently at Ein Hamifrats: Over a period of one year a total of 203 (metric) tons of feed and 157 tons of liquid oxygen have been purchased, resulting in a very similar ratio: \( \theta = 0.77 \text{kg[O2]}/\text{kg[feed]} \).

3.2. Capital cost of airlifts

The pilot plant at Eilat has 208 oxygen-supplying airlifts, which cost $196,000, including blowers, to construct and install. At a return rate of 0.15/y, the capital cost of an airlift is determined as

\[
u_1 = 0.39 \text{$/airlift \cdot d}$
3.3. Optimal air discharge through the airlifts

The optimal air discharge through an airlift is obtained by minimizing Eq. (24), namely by minimizing \[ 1 + (u_\ell/u_t)\gamma A(t)^2/|\sigma A^2| \] with respect to \( A \). For the installation under consideration (NCM data)
\[ u_\ell = 0.10 \text{ $\frac{kWh}{M/J}$} \]
\[ \chi = 0.00543 \text{ and } \mu = 1.134 \text{ for } A \text{ in } m^3[air]/h \text{ and } p \text{ in kW} \]
(Eq. (22))
\[ \sigma = 7.8 \text{ and } \nu = 0.675 \text{ for } A \text{ in } m^3[air]/h \text{ and } h \text{ in } m^3[water]/h \]
(Eq. (23))
Hence, the optimal air discharge is
\[ A = 29.2 m^3[air]/[airlift \cdot h], \]
which is about a third of the maximum air discharge for which the airlifts have been tested.

3.4. Oxygen supply and CO₂ stripping by means of airlifts

Whether supply of oxygen or carbon dioxide stripping is the limiting factor of the airlift operation, can be decided by evaluating Eq. (28). For our conditions (sea bream in red sea water) the design (limiting) concentration of oxygen is considered to be around
\[ C_0 = 5.5 g[O_2]/m^3[water] \]
which is represented by the ‘Const’ lines of Figs. 1 and 2, and by line 2 of Fig. 3.

There is considerable uncertainty regarding the limiting carbon dioxide concentration, so here we consider the range
\[ 10 \leq C_0 \leq 20 g[CO_2]/m^3[water]. \]
The limiting oxygen and carbon dioxide concentrations are shown by horizontal lines in Fig. 3.

At the low end of the sea bream temperature range, 20 °C, and for salinity of 40 g[salts]/kg[water], the gas concentration equilibrium with a standard atmosphere (based on Weiss, 1970, 1974), are
\[ \hat{C}_0(20^\circ C) = 7.2 g[O_2]/m^3[water] \text{ and } \hat{C}_D(20^\circ C) = 0.50 g[CO_2]/m^3[water]. \]

These points lie on the corresponding saturation curves of Fig. 3. It should be clear from the figure that while the oxygen gradient of line 2 decreases rapidly with increasing temperature (vanishing at 36.3 °C), the carbon dioxide gradient is large and essentially constant with temperature.

There are only a few carbon dioxide transfer data. It seems that the value of \( \omega \) (Eq. (27)) depends on the aerating equipment and may differ significantly from the theoretical value of \( \omega \approx 0.9 \) (Summerfelt et al., 2000; Eshchar et al., 2003; Aitchison et al., 2007). Unpublished NCM data for the airlifts in question indicate a value as low as
\[ \omega \approx 0.3. \]

Even for this low value and the lowest maximum permissible CO₂ concentration \( C_0 = 10 g[CO_2]/m^3[water] \), the cost ratio, \( \varepsilon \), is considerably larger than 1:
\[ \varepsilon(20^\circ C) = \frac{f_D}{f_0} = 1.50 > 1. \]

This implies that for the ranges of temperature and carbon dioxide concentrations considered here, oxygen supply by airlifts is more limiting than the stripping of carbon dioxide, and that the cost of operation needs to be calculated by means of \( K_0^{ pur } \) (Eq. (24)), not \( K_0^{ lift } \) (Eq. (27)). To determine \( K_0^{ lift } \) via Eq. (24), \( O_\varphi \) and \( \gamma_0 \) are required. \( O_\varphi \) is evaluated with Eq. (12) as
\[ O_\varphi = 530 g[O_2]/fish. \]

and \( \gamma_0 \) is set, following Tchobanoglous et al. (2003, p. 427) to
\[ \gamma_0 = 0.024 1/K \text{ at } T_r = 23 \degree C \]

With these values, \( K_0^{ lift } \) (T) varies between 20 and 30 °C from 0.18 to 0.43 $/fish, indicating a considerable increase with temperature, as expected.

3.5. Oxygenation by means of liquid oxygen

The cost of \( K_0^{ pur } \) depends on the system used to deliver the oxygen. Here we use the cost of liquid oxygen determined from the actual expenses at Ein Hamifrat, namely
\[ \mu_0 = 0.43 $/kg[O_2]. \]
of which about 10% is attributed to the cost of the required equipment, 5% to imperfect dissolving efficiency and about 0.15 $/kg[O_2] to the cost of electricity for the water pressurizing pumps. Incidentally, the cost of generating oxygen on location is lower in terms of energy for generation, higher in capital cost and about the same in terms of dissolving efficiency and pressurization costs. Altogether, possibly somewhat less expensive.

Multiplying \( \mu_0 \) by \( \theta \) and \( F_0 \), the cost of oxygenation with pure oxygen is calculated via Eq. (26) to be
\[ K_0^{ pur } = 0.23 $/fish, \]
independent of temperature.

The cost \( K_0^{ lift } \) (T) is calculated, with the already specified parameters, via Eq. (27). It decreases between 20 and 30 °C from 0.123 to 0.095 $/fish for the lower permissible CO₂ concentration of 10 g[CO₂]/m³[water], and from 0.060 to 0.047 $/fish for the upper permissible CO₂ concentration of 20 g[CO₂]/m³[water].

If oxygen is supplied by pure oxygen, the airlifts duty is mainly CO₂ stripping, which requires a considerably lower airlift capacity (number of airlifts). On the assumption that the bulk oxygen concentration in the water for this configuration is 100% saturation, the total cost of oxygen supply and carbon dioxide stripping is \( K_0^{ pur } + K_0^{ lift } \) (sum of Eqs. (27) and (26)).

4. Results, discussion and conclusions

4.1. Constant temperatures

Costs of supplying oxygen and stripping of carbon dioxide for the set of parameters of Section 3, are compared in Fig. 4. The cost of effecting these two processes simultaneously by means of the same airlifts, is represented by the increasing curve (empty circles, Eq. (24)). It is tagged with \( K_0^{ lift } \), and approaches infinity (impossibility) at about 36.3 °C. The cost of supplying oxygen by means of pure oxygen (here LOX), is independent of temperature and is represented by the horizontal line (diamonds, Eq. (26)) tagged with \( K_0^{ pur } \). Utilizing pure oxygen reduces the required capacity of the airlifts, which now are needed for just CO₂ stripping. When the cost of stripping, \( K_0^{ lift } \), is added to the cost of oxygenation, the result is a curve, tagged with \( K_0^{ pur } + K_0^{ lift } \), which decreases slowly with temperature and which level depends on the permissible CO₂ concentration (here between 10 and 20 g[CO₂]/m³[water]).

In summary: Fig. 4 shows (1) that the cost of supplying oxygen by means of airlifts increases ‘exponentially’ with temperature;
(2) that the cost of CO₂ stripping decreases slightly with temperature, and (3) that the cost of CO₂ stripping decreases when the permissible ('design') CO₂ concentration increases. As a result, the temperature where the optimal design switches from one configuration to the other increases (1) with decreasing permissible CO₂ concentration, and (2) with increasing relative cost of pure oxygen.

With the parameter values of this study, and selecting the low (safer) bound of CO₂ concentration, namely 10 g[CO₂]/m³[water], the broken curve with filled circles in Fig. 4 indicates that Configuration 1 (airlifts) has the advantage at temperatures lower than 27.7°C, while Configuration 2 (mixed) is more economic for higher temperatures. If the CO₂ concentration is allowed to increase to 20 g[CO₂]/m³[water], the switching temperature goes down to just 26°C, and pure oxygen becomes the better choice over a wider temperature range. The difference in cost between systems is of the order of 0.05 $/fish (0.12 $/[kgBM]).

There is considerable uncertainty regarding several of the assumptions and parameter values, even for the selected species (seabream). As an example, if the value of \( \omega \) (Section 3.4) is closer to its theoretical value (higher than assumed), CO₂ stripping is more efficient (less expensive), and the switching temperature is diminished. The same effect is obtained by reducing the cost of pure oxygen. It should also be clear that the relative advantage of pure oxygen increases as the slope of the oxygen curves of Fig. 3 increases (Curve 1 to 2 to 3). Our choice of Curve 2 (zero slope), based on Fig. 1, is, in this respect, an intermediate choice.

Future changes in energy prices may also affect the relative advantage of the alternatives. For example, the current trend in European aquaculture seems to be that “pumps become more efficient or replaced by airlifts” (Martins et al., 2010, Section 3.1.3). If this trend (to reduce energy costs) persists, 'mixed' systems with airlifts for stripping (and for submerged nitrification biofilters), and liquid oxygen for oxygenation, may become more popular, especially for warm water RAS. When the approach suggested here is to be applied to another species, installation and/or economic environment, a new set of parameters must be obtained.

4.2. Variable temperatures

The approach described so far and illustrated in Fig. 4, is suitable for making choices regarding constant-temperature systems. If, however, the temperature varies significantly over the annual cycle (e.g., 20–28°C as at Eilat), the steady-state analysis of Section 2 is no longer strictly valid (Seginer and Halachmi, 2008; Seginer, 2009). Furthermore, the cost curves of Fig. 4 also do not strictly apply, because each point on these curves represents a (physically) different system (e.g., more airlifts at higher temperatures). When the temperature fluctuates, proper integration of the seasonal costs requires that a particular rearing system, as well as a particular stocking and harvesting policy, are specified. In addition, capital and operating costs should be treated separately: while the former stays constant with time, the latter varies in response to the changing temperature. All this can be done by simulation, but may not be justified as long as the accuracy of key parameters is questionable. At the present time it would seem that as a rule of thumb, if the mean seasonal water temperature is below the switching temperature, Configuration 1 (airlifts) should be preferred over Configuration 2 (mixed), and vice versa.

If the temperature distribution is wide and nearly uniform (e.g., as resulting from a sinusoidal variation with time; Seginer et al., 2008, Fig. 4), a 'hybrid' system may be contemplated. Such a system utilizes the airlifts for oxygen supply at low temperatures and switches to pure oxygen at a temperature selected to minimize the operational costs (pure oxygen as a backup system). Such a combination would reduce the capital cost of the airlifts (fewer than required to cover the needs at higher temperatures), but, on the other hand, would add the expense of installing the pure oxygen equipment. A more detailed analysis of such a hybrid system is possible, but is beyond the scope of the present paper.

4.3. Conclusions

The first-order analysis presented in the preceding sections may be summarized as follows:

1. For seafish fed to satiation, and probably for some other fish as well, growth rate, feed consumption, and oxygen consumption, all increase with temperature at the same rate (about 6%/K in the low temperature range). As a result, the quantities of feed and oxygen consumed by a fish to grow to a certain size (F and O₂), are, to a first approximation, independent of temperature (Eqs. (7) and (12)).

2. The factor which limits the transfer of oxygen into the water by means of aeration, is the (absolute) bulk concentration of oxygen below which a reduction in fish growth occurs. As temperature increases, this limiting concentration approaches the oxygen saturation curve (Fig. 3), resulting eventually in hypoxia.

3. For seabream in the practical range, the limiting (absolute) oxygen concentration is most likely independent of temperature (Fig. 1).

4. Any given airlift (operating at a given head) has an optimal air discharge which depends only on the cost ratio of electricity to capital, \( u_{e}/u_{t} \), not on the gas to be transferred, nor on temperature (Eq. (27)).

5. In operation mode, all oxygen-supplying airlifts available to a certain fish tank, should be operated simultaneously at the same air discharge which together satisfies the oxygen demand (Eq. (25)).

6. The cost of oxygenation with liquid oxygen is, to a first approximation, independent of temperature (Eq. (26)), and hence, this method may have a relative advantage over airlifts (aerators) at high temperatures (Fig. 4).

![Fig. 4. Cost of supplying oxygen and stripping carbon dioxide to produce one fish of 400 g [BM] (left scale) or one kilogram of BM (right scale).](image-url)
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References


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