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HYPOLIMNETIC AERATION: PRACTICAL DESIGN AND APPLICATION

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Abstract—Hypolimnetic aeration is becoming increasingly important as a fisheries management and water quality improvement technique, however its application has been restricted by a paucity of practical reference material. Hypolimnetic aeration includes partial and full lift designs and several air/oxygen injection systems. Positive displacement compressors flanged to three phase electric motors are the preferred air supply and power for most lake aeration projects. Internal combustion power is adequate for short term use and wind power is in the developmental stage. Rubber compressed air hose is recommended for lake aeration applications. Free air delivery is the air volume taken into the compressor at standard temperature and pressure however actual output volume is regulated by discharge pressure. Performance specifications of full lift hypolimnetic aerators are based on water:air ratios, oxygen increase, transfer efficiencies and oxygenation capacity. An empirical sizing method is proposed using hypolimnetic volume, hypolimnetic oxygen consumption, water flow, air flow and inflow tube radius. Outflow tube radius should equal or exceed inflow tube radius to achieve high flow rates and allow efficient removal of residual bubbles. Floatation requirements are calculated from the total weight of the separator box, inflow and outflow tubes and the theoretical water head.

Key words—hypolimnetic aeration, air compressors, air line, transfer efficiencies, aerator design, oxygenation capacity, oxygen consumption

NOMENCLATURE

v = bubble–water velocity (m s^{-1})
K_L = entrance constant (dimensionless)
f = friction factor (dimensionless)
Q_w = water flow (m^3 s^{-1})
g = acceleration of gravity (m s^{-2})
L = depth of air release (m)
Γaw = density of air:water mixture (kg m^{-3})
Γw = density of water (kg m^{-3})
ΔH = entrance, exit and friction losses (m)
Γa = density of air (kg m^{-3})
$\bar{Q}_a$ = mean volumetric air flow (m^3 s^{-1})
Q_a = volumetric air flow (m^3 s^{-1})
ΔP = pressure drop across orifice (kg cm^{-2})
h = pressure drop in supply system (kg cm^{-2})
Q_w/Q_a = volumetric ratio of water to air flow
r = radius of inflow tube (m)
d = diameter of inflow tube (m)
PR = pressure required in compressor (kg cm^{-2}).

INTRODUCTION

Hypolimnetic aeration is becoming increasingly important as a fisheries enhancement and water quality improvement technique. Since its development in the late 1940s (Mercier and Perret, 1949), more than twenty scientific papers have appeared describing various hypolimnetic aeration projects (see Taggart and McQueen, 1981 for review). The majority of these projects were concerned with assessing its effect on the lake ecosystem and developing new technology. However, the more practical aspects of hypolimnetic aeration such as aerator design, sizing and installation have not been well documented in the literature. This results in a "re-invention of the wheel" each time a hypolimnetic aeration project is undertaken.

The purpose of this paper is to examine specific design, equipment and operational components of hypolimnetic aeration systems which I believe are inadequately documented in the scientific literature.

AIR SUPPLY

An important component of a well engineered hypolimnetic aeration system is the air supply. This topic can be divided into four sections: compressors, power source, power transmission and air lines.

Compressors

Compressors suitable for lake aeration applications are displacement types: reciprocating piston, rotary screw and rotary vane. In reciprocating compressors air is compressed by a piston following a reciprocating motion within a cylinder. They are generally designed for intermittent operation and should be run into a receiving pressure tank for maximum efficiency. Rotary screw compressors use two parallel screws joining on a thin oil film as a compression seal. Rotary screw compressors are suitable for continuous operation and could be used in aeration systems where high power (>45 kW) is required. Rotary vane compressors operate via radially moveable vanes turning eccentrically in a circular compression chamber. Advantages of this design include vibration free operation, few moving parts and a non-pulsating air supply. Rotary vane compressors are designed for continuous operation and are well suited for lake aeration applications in the 1.5–37 kW (2–50 h.p.) range.

An important option which should be ordered on any compressor design is a high air/oil temperature cutout switch which turns off the compressor if mechanical problems cause it to overheat.

Power source

There are basically three different power sources for air compressors: internal combustion, electric and wind. Internal combustion engines are generally fueled by gasoline or diesel fuel. Gasoline or diesel power is only useful for short term (1–2 month) use due to the frequency of maintenance (i.e. daily), noise/odour problems and increasing fuel costs.

Electric motors are available in single phase or three phase. Three phase motors are preferred as they are manufactured in a wide range of power sizes and are less expensive to purchase, operate and repair than single phase motors. However many rural districts do not have three phase electricity available. In this situation, single phase motors are perfectly acceptable. This is an important distinction as it determines the number, size and cost of the compressors, electrical contracting fees and operating costs. Single phase motors are generally restricted to a 5.6 kW (7.5 h.p.) maximum size. If more than 5.6 kW in single phase power is required then multiple units are necessary. It is advisable to check with the local power company on the type and capacity of their electrical system before purchasing any equipment.

Wind power is still in the developmental stage, however it should eventually become a viable alternative for small isolated lakes as conventional energy costs continue to rise. Reider (1977) concluded small wind powered compressors were technically and economically comparable with electric compressors in small scale applications.

Power transmission

Most compressors are available with one of three drive mechanisms: flange-mounted motors, v-belt drive and direct flexible coupling (Atlas Copco, 1978). In flange-mounted designs the motor shaft is coupled directly to the compressor shaft and the motor housing is flanged to the compressor body. Advantages of this design include no transmission power loss, reduced maintenance through absence of power transmission parts, reduced unit size and simplified installation. Direct flexible couplings are the second choice and used where flange mounting is not possible. This method retains most of the advantages of flange-mounted motors. v-Belt drives are the least compact form of drive mechanism. This type of power transmission entails a power loss of approx. 4% and requires a more expensive foundation and larger floor space than the other methods (Atlas Copco, 1978). However, v-belts offer more flexibility in adjusting compressor speeds and are reliable if properly maintained.

Air line

The choice of air line material is an important consideration as it influences capital costs, operating costs, and potential problem areas. Air line materials include rigid metal or plastic pipe, flexible polyethylene pipe and standard rubber compressed air hose. Although rubber air hose is more expensive (2 ×) than other types of air lines, its ease of installation, durability and strength compensate for the initial purchase price.

The internal diameter of air lines is an important factor. Small lines restrict air flow on long sections, whereas using overly large pipe on short runs is an unnecessary expense. Air line diameter is selected on the basis of minimizing pressure loss and cost for each installation which is a function of the internal diameter, length, and construction of the air line (Atlas Copco, 1978). Most compressor manufacturers publish tables or nomograms of pressure loss based on air flow, pressure, internal hose diameter and length (e.g. Ingersoll-Rand, 1971). In practice the British Columbia Fish and Wildlife Branch has achieved satisfactory results with compressors under 2.8 $m^3 min^{-1}$ free air delivery (100 $ft^3 min^{-1}$) using the following guidelines:

0.76 m (0–250 ft)	1.9 cm (0.75 in.) i.d.
76–152 m (250–500 ft)	2.5 cm (1.0 in.) i.d.
152–457 m (500–1500 ft)	3.8 cm (1.5 in.) i.d.
457–914 m (1500–3000 ft)	5.1 cm (2.0 in.) i.d.

RATED AND ACTUAL AIR FLOW

A confusing concept in lake aeration is the difference between the rated output and the actual volume of air delivered by a compressor. Air compressors are rated by the manufacturer in terms of free air delivered (FAD) at specific operating temperatures and pressures. Free air delivered is the volume (usually expressed in standard cubic feet per minute, i.e. SCFM) at 1.0 kg cm^{-2} and 21°C (14.7 lb in^{-2} and 70°F) which a compressor with the intake open to the atmosphere *takes in*, compresses and delivers at the stated delivery pressure. For example, a 5.6 kW (7.5 h.p.) compressor operating at 7.0 kg cm^{-2} (100 lb in^{-2}) may be rated for 0.8 $m^3 min^{-1}$ (28 SCFM) free air delivery. The actual output of this compressor is 0.1 $m^3 min^{-1}$ (3.6 $ft^3 min^{-1}$) at 7.0 kg cm^{-2} (100 lb in^{-2}). After leaving the compressor this volume of air expands back to 0.8 $m^3 min^{-1}$ (28 $ft^3 min^{-1}$) at normal sea level atmospheric pressure 1.0 kg cm^{-2} (14.7 lb in^{-2}) i.e. 8.1 kg cm^{-2}/1.0 kg cm^{-2} × 0.1 $m^3 min^{-1}$ = 0.8 $m^3 min^{-1}$. In theory, the discharge volume decreases as the discharge pressure increases in accordance with Boyle's Law ($P_1V_1 = P_2V_2$ at constant temperature), and the discharge volume (V_2) expands back to the original intake volume (V_1) at standard conditions (1.0 kg cm^{-2} and 21°C).

PERFORMANCE SPECIFICATIONS

Hypolimnetic aerators exhibit a wide range in size and operational efficiencies (Taggart and McQueen, 1982). The criteria used to evaluate hypolimnetic aerators are based mainly on hydraulic efficiency and ability to add oxygen to water pumped through the system.

Water:air ratios

Water:air ratios (Q_w/Q_a) are the volumetric ratio of water to air flow (compressor free air delivery) in the riser tube. Aerators with higher water:air ratios circulate more water per unit air volume (and energy), hence are more efficient at generating large volume water flows. Water:air ratios for full lift hypolimnetic aerators range from 7 (Hess, 1975) to 31 (Bernhardt, 1974).

Oxygen increase and transfer efficiency

Oxygen flow to an aerator is determined by the volume of air supplied by the compressor. Since air is approx. 21% oxygen by volume (Davis, 1975), initial oxygen input is restricted to 21% of compressor output at any fixed flow rate. Oxygen input may be increased by injecting pure oxygen, however this procedure may be impractical in remote areas or for large lakes. Transfer efficiencies for full lift aerators range from 5% (Bengtsson *et al.*, 1972) to 50% (Bernhardt, 1967), and oxygen increases per cycle range from 0.7 mg l^{-1} (Ashley, 1983) to 9.0 mg l^{-1} (Fast, 1971). Most aerator designs have relied on high hydrostatic pressure as the driving force for oxygen transfer. The co-current method of bubble–water transport in the inflow tube becomes progressively less efficient at oxygen transfer in shallow depths. Declining hydrostatic pressure is mainly responsible for this drop, however the decreasing oxygen content of rising air bubbles also contributes to poor oxygen transfer efficiency in shallow water (Speece, 1974).

Additional factors influencing oxygen transfer efficiency are oil content of air and bubble size. Most air compressors are oil lubricated and release a small quantity of oil (28 g/1416–2124 m^3) in the compressed air. All oil should be removed before it reaches the aerator as oil contamination of air bubbles inhibits oxygen transfer at the air–water interface and reduces overall transfer efficiency (Lorenzen and Fast, 1977).

The influence of air bubble size on oxygen transfer efficiency is related to the mechanics of oxygen diffusion at the bubble–water interface and efficiency of air-lift pumps. The oxygen transfer process occurs in three stages (Eckenfelder and Ford, 1968). Initially oxygen molecules from the gas phase are rapidly transported to the liquid surface, resulting in saturation conditions at the interface. This liquid interface or film is approximately three molecules thick and composed of water molecules oriented with their negative sides (i.e. oxygen) facing the gas phase. In the second phase, oxygen molecules pass through this film by molecular diffusion, and in the third stage oxygen is mixed into the water by diffusion and convection currents. At low mixing levels the rate of oxygen absorption is regulated by molecular diffusion through the undisturbed liquid film, however as turbulence levels increase the surface film is disrupted and renewal of the film becomes responsible for transferring oxygen to the liquid (Eckenfelder, 1969).

To maximize transfer efficiency bubble velocity should be high in relation to water velocity, i.e. large bubbles. Unfortunately large bubbles and higher velocities decrease air–bubble contact time in the aerator and reduce air-lift pump efficiency (Andeen, 1974). Small bubbles (<0.5 mm) have lower rise velocities and provide a higher surface area to volume ratio which enhances oxygen exchange (Andersen and Hurd, 1971), however small bubbles require small diffusor orifices which can lead to clogging problems. Therefore bubble size in the range of 2.0–2.5 mm (dia.) is recommended for hypolimnetic aeration (Speece, 1974). However, since bubbles tend to rise in "clouds" and coalesce during ascent it may be difficult to accurately control bubble size.

Oxygenation capacity and cost

Oxygenation capacity is defined as the amount of oxygen transferred to the water per unit work effort (Symons *et al.*, 1967). Literature values range from 0.18 to 1.09 kg O_2 kWh^{-1} (Lorenzen and Fast, 1977).

Oxygenation cost is the energy cost required to dissolve 1 kg of oxygen in water. Although few comparative figures are available, oxygenation costs are usually less in full lift hypolimnetic aerators. Fast *et al.* (1976) compared oxygenation costs for full lift, partial lift and oxygen injection systems and concluded full lift hypolimnetic aerators were almost twice as efficient as the other systems.

DESIGNING AND SIZING HYPOLIMNETIC AERATION SYSTEMS

One of the most important aspects of hypolimnetic aeration is developing methods for sizing compressors and hypolimnetic aerators to lakes. Lorenzen and Fast (1977) and Taggart and McQueen (1982) recently reviewed this topic and proposed two methods for sizing hypolimnetic aeration systems. In this section I will outline an empirical method derived from the aforementioned papers and experience with the Black Lake hypolimnetic aeration system (Ashley, 1983). This procedure contains some unproven assumptions which are noted in the text and assumes the reader is familiar with the literature. A complete example of the sizing procedure is given in the Appendix.

Step 1. Estimate hypolimnetic volume

Hypolimnetic volume can be estimated using an accurate bathymetric map and a series of summer temperature profiles. One must be careful to obtain the largest estimate of hypolimnetic volume to avoid undersizing the system.

Step 2. Estimate hypolimnetic oxygen consumption

Hypolimnetic oxygen consumption can be estimated by observing the rate of oxygen depletion following spring stratification. The spring stratification period is preferable to inverse winter stratification as oxygen and temperature conditions will approximate those encountered during actual aeration. Total hypolimnetic oxygen content is then plotted against time, and the depletion rate (in $kg\ day^{-1}$) calculated from the maximum slope of the regression line (Lorenzen and Fast, 1977).

Step 3. Calculate water flow

The amount of water required to balance daily oxygen consumption is the total daily oxygen consumption ($mg\ day^{-1}\ O_2$) (Step 2) divided by the input rate of the aerator ($mg\ l^{-1}$). Theoretically this daily water flow should balance daily oxygen consumption. This is an important assumption of this procedure.

The critical factor in this calculation is the input rate of the aerator which can range between 0.7 and 9.0 $mg\ l^{-1}$ (average = 4.6 $mg\ l^{-1}$), and are difficult to predict (Taggart and McQueen, 1982).

Step 4. Calculate inflow and outflow tube size

One of the most important criteria involved in designing a hypolimnetic aerator is determining the size (i.e. length and diameter) of the inflow and outflow tubes. To optimize oxygen transfer efficiency inflow and outflow tube lengths should be as long as practically possible in shallow lakes (< 10 m max. depth), and extend well into the hypolimnion in deeper lakes. Inflow tube radius is derived from the formula for calculating flow, i.e.

$$Q_w = \pi r^2 \times v$$

rearranging:

$$r = \sqrt{Q_w/v\pi}$$

where:

r = radius of inflow tube (m),
v = bubble–water velocity ($m\ s^{-1}$) and
Q_w = water flow ($m^3\ s^{-1}$).

Q_w was calculated in Step 3 and v was estimated at 1.2 $m\ s^{-1}$. Taggart and McQueen (1982) used this formula to derive inflow tube radius and concluded that the actual inflow tube radius should not exceed the calculated radius.

Outflow tube radius should equal or exceed the inflow tube radius. If the total cross-sectional area of the outflow tubes is less than the inflow tubes a buildup of water will occur in the separator box and reduce flow rates.

Increased outflow tube area also decreases outflow current velocity relative to inflow velocity. Low current speeds reduce the risk of sediment disruption (Smith *et al.*, 1975) and allow more efficient degassing in the separator box. The outflow tube should also be fitted with a 45 or 90 degree elbow to prevent immediate recirculation of aerated water and minimize sediment disruption.

Inflow and outflow tubes have been built from a variety of materials including fibreglass, steel plate, polyethylene, reinforced neoprene/wire mesh and galvanized sheet metal. The basic requirements are that the pipes are air-tight, water-tight and strong enough to withstand installation and positioning within the lake.

Step 5. Determine entrance, exit and friction losses

These losses are calculated with equation (5) (Appendix) and are used to estimate the total head loss for the system. The effect of the air bubbles interspersed with the water in the inflow tube is assumed to have a negligible effect on the head loss calculations (Lorenzen and Fast, 1977).

Step 6. Determine the density of the air–water mixture

The density of the air–water mixture in the inflow tube is estimated using equation (6) (Appendix) which assumes that the theoretical head generated (ΔH) is a result of the density difference between the air–water mixture in the inflow tube and the outside water. It is also assumed that one-half of the theoretical head is used to pump water up the inflow tube and an equivalent amount is used to pump water back down the outflow tube (Lorenzen and Fast, 1977).

Step 7. Calculate air flow requirements

Equation (7) is used to estimate the air flow required to pump water through the aerator at the design specifications. As a design check, this volume is compared to the theoretical air volume calculated from Step 2. The Step 7 volume must equal or exceed the theoretical volume to satisfy the measured hypolimnetic oxygen demand.

Step 8. Estimate compressor pressure and power requirements

The last step involving air flow is determining the pressure and power requirements of the air compressor. Pressure requirements are estimated from the sum of the pressure drops in the air supply system (Lorenzen and Fast, 1977):

$$PR\ (kg\ cm^{-2}) = \Delta P + h + L\ (1.0/10.1)$$

where:

PR = pressure required,
ΔP = pressure drop across diffusor orifice (approx. 0.4–0.7 $kg\ cm^{-2}$),
L = depth of air release (m) and

h = pressure drop in air line, valves, elbows etc. (from tables; e.g. Ingersoll-Rand, 1971; in $kg\,cm^{-2}$).

This relationship establishes a general pressure requirement for a given installation and indicates whether a low pressure blower, single stage compressor or double stage compressor is required. One then selects a compressor with an operating pressure 0.7–1.4 $kg\,cm^{-2}$ (10–20 $lb\,in^{-2}$) above that estimated from the formula.

Compressor power is then calculated from standard engineering formulae (e.g. Horton, 1959) or obtained from compressor manufacturer's specifications for the required pressure and volume output.

Step 9. Calculate separator box size and floatation requirements

A separator box is required to position the inflow and outflow tubes and provide a waterproof degassing area for the aerated water. The box should be well insulated to minimize warming of hypolimnetic water. The size of the box is not critical however its minimum size is determined by the diameter of the inflow and outflow tubes. The Black Lake separator box was 2.4 × 1.2 × 0.9 m and housed two 0.76 m dia tubes. I believe a similar ratio of length, width and height to inflow tube diameter will form a suitable separator box size for any tube diameter.

Floatation requirements of the separator box are estimated from the total weight of the separator box, tubes and water head. Waterproof floatation foam will support approx. 27 kg (60 lb) per 0.028 m^3 (1.0 ft^3) of foam volume. The floatation should be constructed around the outside perimeter of the separator box and securely attached. A weight factor which is often overlooked is the weight of the water head in the separator box when the system is operating. This can be estimated from $\Delta H/2$ (Step 5) × area of the separator box = cubic meters of water × 1000 $kg\,m^{-3}$ = total weight (kg) of water head. I believe the best strategy is to design the floatation requirements as described, and operate the system with the separator box partially (one-third to one-half) submerged. The system should be operating efficiently in this position and generating higher flows than if the separator box remained at the surface (Smith *et al.*, 1975). If too much air (and water) is supplied the separator box may submerge completely and begin destratifying the lake.

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REFERENCES

Andeen G. B. (1974) Bubble pumps. *Compress. Air Mag.* **79,** 16–19.

Andersen D. R. and Hurd M. (1971) Study of a complete mixing activated sludge system. *J. Wat. Pollut. Control Fed.* **43,** 422–432.

Ashley K. I. (1983) Hypolimnetic aeration of a naturally eutrophic lake: physical and chemical effects. *Can. J. Fish. Aquat. Sci.* **40,** 1343–1359.

Atlas Copco Manual, Third Edition (1978) Stockholm, Sweden.

Bengtsson L., Berggren H., Meyer O. and Verner B. (1972) Restauerering av sjor med kulturbetingat hypolimniskt. Limnolgiska Institutionen, Lund Universitet, Centrala Fysiktaboratoriet, Atlas Copco AB. (In Swedish).

Bernhardt H. (1967) Aeration of Wahnbach Reservoir without changing the temperature profile. *J. Am. Wat. Wks Ass.* **59,** 943–964.

Bernhardt H. (1974) Ten years experience of reservoir aeration. *Prog. Wat. Technol.* **7,** 483–495.

Davis J. C. (1975) Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review. *J. Fish. Res. Bd Can.* **32,** 2295–2332.

Eckenfelder W. W. (Ed.) (1969) Oxygen transfer and aeration. In *Manual of Treatment Processes*, Vol. 1. Environmental Science Services Corp., U.S.A.

Eckenfelder W. W. and Ford D. L. (1968) New concepts in oxygen transfer and aeration. In *Advances in Water Quality Improvement* (Edited by Gloyna E. F. and Ekenfelder W. W.). Water Resource Symposium No. 1.

Fast A. W. (1971) The effects of artificial aeration on lake ecology. E.P.A. Water pollution Control Research Series 16010 EXE 12/71.

Fast A. W., Lorenzen M. W. and Glenn J. H. (1976) Comparative study with costs of hypolimnetic aeration. *J. envir. Engng Div. Am. Soc. civ. Engrs* **102,** 1175–1185.

Hess L. (1975) The effects of the first year of artificial hypolimnetic aeration on oxygen, temperature and depth distribution of rainbow trout (*Salmo gairdneri*) in Spruce Knob Lake. West Virginia Department of Natural Research F-19-R-3.

Horton H. L. (Ed.) (1959) *Machinery's Handbook*, 16th Edition. Industrial Press, New York.

Ingersoll–Rand (1971) *Compressed Air and Gas Data* (Edited by Gibbs C. W.). Ingersoll–Rand, New York.

Lorenzen M. and Fast A. W. (1977) A guide to aeration/circulation techniques for lake management. EPA 600/3-77-004. U.S. Environmental Protection Agency, Washington, DC.

Mercier P. and Perret J. (1949) Aeration station of Lake Bret, Monastbull, Schwiez. *Ver. Gas. Wasser-Fachm* **29,** 25.

Reider W. G. (1977) Wind powered artificial aeration of northern prairie lakes. Research Report No. WI-222-014-77. Department of Mechanical Engineering, N. Dakota State University, Fargo, ND.

Smith S. A., Knauer D. R. and Wirth T. (1975) Aeration as a lake management technique. Wisconsin Department of Natural Research, Technical Bulletin No. 87.

Speece R. E. (1974) Ten years experience of reservoir aeration: Reply to H. Bernhardt. *Prog. Wat. Technol.* **7,** 483–495.

Symons J. M., Irwin W. H., Robinson E. L. and Robeck G. G. (1967) Impoundment destratification for raw water quality control using either mechanical or diffused air pumping. *J. Am. Wat. Wks Ass.* **59,** 1268–1291.

Taggart C. T. and McQueen D. J. (1981) Hypolimnetic aeration of a small eutrophic kettle lake: physical and chemical changes. *Arch. Hydrobiol.* **91,** 150–180.

Taggart C. T. and McQueen D. J. (1982) A model for the design of hypolimnetic aerators. *Water. Res.* **16,** 949–956.

APPENDIX

Example of Sizing a Hypolimnetic Aeration System

Step 1. Hypolimnetic volume = 1,000,000 m^3.

Step 2. Maximum hypolimnetic oxygen consumption = 0.2 mg l^{-1} day^{-1}. Total consumption = 1,000,000 m^3 × 0.2 mg l^{-1} day^{-1} = 2 × 10^8 mg day^{-1} or 2 × 10^2 kg day^{-1}.

Step 3. Water flow. 2 × 10^8 mg day^{-1}/2 mg l^{-1} (aerator input rate) = 1 × 10^8 l day^{-1} or 1 × 10^5 m^3 day^{-1} or 1.16 m^3 s^{-1}.

Step 4. Calculate inflow and outflow tube size.

$$\text{Tube radius} = \sqrt{\frac{\text{water flow}}{\pi \times v}} = \sqrt{\frac{1.16\ \text{m}^3\,\text{s}^{-1}}{\pi \times 1.2\ \text{m s}^{-1}}} = 0.55\ \text{m}$$

Tube diameter = 0.55 m × 2 = 1.1 m

where:

v = bubble–water velocity (estimated).

Step 5. Determine entrance, exit and friction losses.

$$\text{Entrance loss} = \frac{K_L \times 8Q_w^2}{\pi^2 D^4 g};$$

$$\text{Exit loss} = \frac{8Q_w^2}{\pi^2 D^4 g}$$

$$\text{Friction loss} = \frac{fL \times 8Q_w^2}{\pi^2 D^5 g}$$

$$= \left[\frac{4Q_w^2}{\pi^2 g}\left(\frac{1}{D^4} + \frac{2}{D^4} + \frac{2fL}{D^5}\right)\right] \times 2 = \Delta H$$

$$= \left[\frac{4(1.16^2)}{\pi^2(9.8)} \times \left(\frac{1}{1.1^4} + \frac{2}{1.1^4} + \frac{2(0.02)(12.2)}{1.1^5}\right)\right] \times 2 = 0.26\ \text{m}$$

where:

K_L (entrance constant) = 0.5,

f (friction factor) = 0.02,

Q_w = water flow (m^3 s^{-1}),

D = pipe diameter (m),

g = acceleration of gravity (m s^{-2}),

L = depth of air release (m)

Step 6. Calculate density of air–water mixture.

$$\Gamma aw = \frac{L \times \Gamma w}{L + \Delta H} = \frac{12.2 \times 1000}{12.2 + 0.26} = 979\ \text{kg m}^{-3}$$

where

Γaw = density of air:water mixture (kg m^{-3}),

Γw = density of water (kg m^{-3}),

L = depth of air release (m) and

ΔH = entrance, exit and friction losses (m).

Step 7. Calculate air flow.

$$\bar{Q}_a = \frac{10.4\,Q_a \ln\dfrac{L + 10.4}{10.4}}{L}$$

$$= \frac{10.4\,Q_a \ln\left(\dfrac{12.2 + 10.4}{10.4}\right)}{12.2}$$

$$= 0.661\,Q_a$$

$$\text{Then } Q_a = \frac{(Q_w \times \Gamma_w) - (Q_w \times \Gamma aw)}{(\Gamma aw \times 0.661) - \Gamma_a}$$

$$= \frac{(1.16 \times 1000) - (1.16 \times 979)}{(979 \times 0.661) - 1.06}$$

$$= 0.04\ \text{m}^3\,\text{s}^{-1}$$

or

2.4 m^3 min^{-1}.

$$\text{Compare to theoretical demand} = \frac{\text{Step 2}}{\text{g}\,O_2\,\text{m}^{-3}} = \frac{2 \times 10^5\ \text{g day}^{-1}}{300.14\ \text{g m}^{-3}} = 0.46\ \text{m}^3\,\text{min}^{-1}$$

2.4 m^3 min^{-1} > 0.46 m^3 min^{-1} → air flow is O.K.

where

$\bar{Q}_a$ = mean volumetric air flow rate (m^3 s^{-1}),

Q_a = volumetric air flow rate (m^3 s^{-1}),

Q_w = water flow rate (m^3 s^{-1}),

Γ_a = density of air (kg m^{-3}),

Γ_w = density of water (kg m^{-3})

Γ_{aw} = density of air:water mixture (kg m^{-3})

Step 8. Estimate compressor pressure and power requirements.

Pressure required = $\Delta P + h + L(1.0/10.1)$

= 0.35 (est) + 0.35 (est) + 12.2 (1.0/10.1) = 1.9 kg cm^{-2}

= 1.9 + 1.4 (est) = 3.3 kg cm^{-2} maximum pressure required

where

ΔP = pressure drop across orifice (kg cm^{-2}, estimated),

h = pressure drop in supply system (kg cm^{-2}, estimated) and

L = depth of air release (m).

Compressor power (from manufacturer's specifications) for 3.3 kg cm^{-2} and air flow of 2.4 m^3 min^{-1} is 15 kW (e.g. Hydrovane SR6600)

Step 9. Calculate separator box size and floatation requirements.

Ratio of length to width to height to tube diameter is 3:16:1.58:1.18:1

Length = 3.16 × 1.1 m = 3.5 m

Width = 1.58 × 1.1 m = 1.7 m

Height = 1.18 × 1.1 m = 1.3 m

where: 1.1 m = tube diameter.

Floatation requirements = ΔH/2 × area of box = 0.26 m/2 × (3.5 m × 1.7 m) = 0.774 m^3 × 1000 kg m^{-3} = 774 kg + weight of tubes and box.