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Water delivery capacity of a vacuum airlift – Application to water recycling in aquaculture systems

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ABSTRACT

A study was undertaken to measure the water flow (Q_w) delivered by a vacuum airlift designed for recirculating aquaculture systems (RAS) in fresh (<1‰ of salinity) and sea water (35‰ of salinity). The vacuum airlift consists of two concentric tubes connected at their top to a depression chamber. The water rises in the inner tube as a result of air being injected in its lower section and flows back through the external downcomer tube. The vacuum airlift was adjusted at three different lengths: 2, 4 or 6 m and water discharge could be lifted from 0 to 30 cm. Air flow rate (Q_g) varied from 0 to 80 L min^{-1}. Different types of air injectors were tested, delivering different bubble sizes (0.1–5 mm) depending on porosity and functioning at low or high injection pressure. Results show an increase in water flow when pipe length and air flow were increased and lift height reduced. Water flow also depended on the type of water and ranged from 0 to 35 m^3 h^{-1} (0–580 L min^{-1}) for fresh water and only from 0 to 20 m^3 h^{-1} (0–330 L min^{-1}) for sea water (for a 6 m high vacuum airlift). This difference was attributed to the smaller bubble diameter and higher gas holdup (ε_g) observed in sea water (0–20%) compared to fresh water (0–10%). When bubbles were present in the downcomer tube, they created a resistance to flow (counter-current airlift) that slowed down liquid velocity and thus water flow. Increasing the vacuum made it possible to use low air injection pressures and high injection depths. Vacuum also increased bubble size and airflow (20 L min^{-1} at atmospheric pressure to 60 L min^{-1} at 0.3 barA) and thus water flow rates. With RAS, the presence of fish feed in water rapidly increased water flow delivered by the airlift because of changes of water quality and gas holdup. When working with low head RAS (under 0.3 m), vacuum airlift could save up to 50% of the energy required for centrifugal pumps. An empirical predictive model was developed and calibrated. Simulation shows a good correlation between predicted values and measurements (R^2 = 0.96).

1. Introduction

An airlift is obtained by introducing compressed gas (generally air) at the bottom of a pipe partially submerged in the liquid. It generates a vertical movement of the fluid (often water but sometimes a mixture of liquids and solids). The principle is that the presence of gas bubbles decreases the average gas–liquid density and creates the driving force of the pump (Awari et al., 2004). Airlift pumps are often used in difficult pumping operations such as deep-sea mineral mining, estuaries dredging, coal extracting or in oil, chemical or radiochemical industries, because they are reliable for lifting corrosive and/or toxic, explosive, volatile or viscous substances.

In recirculating aquaculture systems (RAS), water is usually circulated by pumps but airlifts are increasingly widely used (Mozes et al., 2004; Blancheton et al., 2007; Mamane et al., 2010). Airlifts are easy to build, simple to use and economical: energy costs of airlift pumps for water transport and aeration are 35% lower compared to standard pumps when used with low head systems (Reinemann, 1987; Awari et al., 2004; Kassab et al., 2009; Roque d'Orbcastel et al., 2009). In addition, in spite of their 80% efficiency, pumps have a limited lifetime and require more maintenance than airlift pumps (Kassab et al., 2007). Moreover, airlifts can combine different functions such as water transport, aeration, CO_2 stripping and foam fractionation in the same treatment device, which may decrease the occurrence of breakdown, reduce the need for technical supervision and space used (Roque d'Orbcastel et al., 2009; Barrut et al., 2011).

The main disadvantage of airlift pumping is the low water delivery height (*i.e.* lift height), limited to a maximum of around 0.3 m, which, in case of clogging, could reduce water flow by partial

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Nomenclature

A	cross sectional area of tube (m^2)
D	diameter of the tube (m)
Q_w	water flow rate ($m^3\,h^{-1}$)
Q_g	gas flow rate ($L\,min^{-1}$)
L	lift height (m)
H	pipe length or static height of water (m)
S_r	$S_r = H/(H+L)$ submergence ratio
ε_g	gas holdup (%)
ΔP	pressure drop between the two tapping ports (bar)
h	vertical distance between the two tapping ports (m)
ρ	density of the liquid phase ($kg\,m^{-3}$)
g	gravitational acceleration ($m\,s^{-2}$)
η	pumping efficiency (%)
p_1	injection pressure of air ($N\,kg^{-3}$)
p_2	pressure at the tube's top ($N\,kg^{-3}$)
U_L	liquid velocity ($m\,s^{-1}$)

obstruction. For acceptable water flow, head loss must be reduced in the water supply system and airlift must be designed with a large submergence ratio. The submergence ratio is defined as the average pressure gradient along the tube *i.e.* the ratio between the submergence (static height of water (H)) and the total length of the pipe (the sum of the static height of water (H) and the lift height (L)). This ratio has to be set above 0.7 to obtain an efficiency comparable to other pump types (Kassab et al., 2007). When the submergence ratio is too small (low immersion or high lift), water flow is almost null and the working cost of the pump is high (Parker and Suttle, 1987; Loyless and Malone, 1998; Awari et al., 2004).

The design parameters of airlift water circulation systems must therefore be precisely defined (Kassab et al., 2007). The parameters of airlift pumps studied in the literature are rising tube diameter, water flow (or liquid circulation velocity), airflow (or superficial gas velocity) and submergence ratio (Nicklin, 1963; Parker and Suttle, 1987; Reinemann, 1987; Wurts et al., 1994). All these parameters directly affect airlift pump performance but few studies have been carried out on combined variations of these parameters, probably because of the large number of experiments required.

To determine the effects of water characteristics, Khalil et al. (1999) tested different types of fluids and showed that lower fluid surface tension could improve airlift pump efficiency by 30%. However, they did not characterize the effect of salinity on water flow rate. As bubble size distribution has a significant effect on the efficiency of airlift pumps and is decisive for their functioning, special attention was paid to bubble size distribution, which depends on the type of diffusers and water characteristics (Barrut et al., 2011).

Several models were investigated based on empirical studies (Loyless and Malone, 1998; Awari et al., 2004), but the accuracy of their predictive value is still limited and varies according to the specific configuration of each system (geometry, type of air injector), to the characteristics of the liquids (Loyless and Malone, 1998) and depending on what the airlift pump is used for (Wurts et al., 1994). Although the geometry of the airlift pump seems to be simple, the theoretical study of its performance appears to be complicated (Kassab et al., 2009). The technology is still under development and will require intensive field testing before models can be predictive (Kassab et al., 2009).

The vacuum airlift technology consists in (1) a vertical tube at the top of which a controlled vacuum is created by a vacuum pump to keep the water level stable, and at the bottom of which gas is injected similarly to a standard airlift, and (2) a downcomer tube to drive the water back to the pumping tank. The vacuum reduces air injection energy costs while maintaining a significant part of the pipe length above water level, thereby increasing the submergence ratio without the need of deep zones in the pumping area (Fig. 1). In addition, the risk of gas oversaturation is avoided by low air injection depths (Loyless and Malone, 1998). Use of a vacuum also allows the gas injected or removed from the fluid to be collected, for storage before treatment in the case of off-gas.

The aim of this study was to test the water transport capacity of a vacuum airlift with fresh water, sea water and fish rearing sea water. The specific objectives were to characterize the hydraulic capacity of a vacuum airlift and compare it to other pumping systems commonly used in RAS.

2. Materials and methods

2.1. Experimental setup and parameters tested

The experimental equipment used to study the transport function of the vacuum airlift pump is shown in Fig. 1. It comprised a 1000 L tank (1) connected to a vacuum airlift provided by COLDEP®; (2) composed of two concentric vertical transparent PVC pipes. The outer diameter (OD) of the internal pipe was 160 mm. The diameter of the external pipe was 315 mm (OD) along the first meter and 250 mm (OD) after the first meter and up to the top (Fig. 1). The top of the vacuum airlift was hermetically closed and connected to a vacuum pump (3) (BUSCH – Mink MM.1100.BV) with a maximal airflow of 60 $m^3\,h^{-1}$. The vacuum created by the pump allows water to rise in the internal pipe. A pressure gauge (4) ranging from −1 bar to 1 bar, connected to the frequency converter of the pump's electric motor, was used to control pressure level and regulate water height in the vacuum airlift. At the top of the vacuum airlift, the difference in height between the internal and external tubes was set at 0.2 m, to limit head losses when water flow passed from the internal to the external tube.

The positive role of injected air flow, bubble size and pipe length on airlift intensity in terms of pumping effect and conversely, the negative role of lift height have been extensively documented (Nicklin, 1963; Parker and Suttle, 1987; Loyless and Malone, 1998; Awari et al., 2004; Kassab et al., 2009; Moran, 2010b). Lift height (L) is defined as the distance from the water surface in the tank to the discharge pipe, *i.e.* the outlet of the vacuum airlift (Fig. 1). A lift of 0.3 m is usually selected as the maximum height for airlift water delivery (Loyless and Malone, 1998; Moran, 2010b).

The combination and the range of variations or values of each parameter tested to quantify water flow rate are given in Table 1.

Air was injected close to the bottom of the inner tube using an electric compressor (5) (BECKER DT4.40 K), which delivers a maximum of 40 $m^3\,h^{-1}$ at a pressure of 1 bar. Different types of injectors were used for air injection: an open tube diffuser which creates a swarm of large bubbles (>3 mm), an injector working at a pressure of 0.5 bar which creates fine bubbles (1 mm) and an injector working at a pressure of 1 bar which creates microbubbles (<1 mm).

The pressure of injected air was controlled by a pressure gauge and airflow was measured using a rotameter (Key Instrument MR 3000 Series Flowmeter ± 5 $L\,min^{-1}$). The water flow rate was

Table 1
Combination of all parameters tested to quantify water flow rate of the vacuum airlift.

Pipe length, H (m)	Depression (bar)	Type of injection	Air flow Q_g ($L\,min^{-1}$)	Lift height, L (m)
6	−0.5	Micro bubble	0–80	0–0.3
6	−0.5	Fine bubble	0–80	0–0.3
6	−0.5	Open tube	0–80	0–0.3
4	−0.3	Fine bubble	0–80	0–0.3
2	−0.15	Fine bubble	0–80	0–0.3