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Airlift Technology Models for Aquaculture Applications with a Focus on Latin America: Predictive Tools for System Performance and Optimization

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Abstract

Aquaculture can be an important industry in the development and growth of economies. Chile is the second largest exporter of farmed salmon second to Norway. The aquaculture industry continues to grow and is a vital component of the country's economy. Air-lift devices can be a key element in the optimization of aquaculture systems, especially in the case of recirculating aquaculture processes. The effects of water height, draft tube diameter and air flow rate on the water flow rate generated in an airlift draft tube system were investigated. An experimental design approach was used to develop a multivariate model that could be used to estimate the water flow rate and accounted for 92% of the variability measured. Air flow rates between 5 and 15 SCFM were used. The range of draft tube diameters and liquid height were 1 – 4 in and 10-20 in respectively. A Box-Behnken experimental design was used to develop the model using 12 different experimental conditions. The distance between the liquid surface and the draft tube exit was found to not significantly affect the water flow rate generated for distances ranging between 1 and 6 in. Water flow rates as high as 66 lpm were generated in the system.

Introduction and Background

World-wide demand for seafood has doubled every 15 years in the recent past and is growing at a rate of 7.8% per year[1-3]. Chile has a unique opportunity for growth in aquaculture products, especially high-value products such as abalone. In order to become a world leader in aquaculture products, Chile must optimize its aquaculture industry so that the maximum profitability can be obtained in a cost-effective and ecologically responsible manner. This means increasing productivity while minimizing costs and optimizing animal health, growth and reproduction. Generating and maintaining appropriate liquid circulation in aquaculture sytems are important considerations. Air-lift devices can serve as inexpensive and effective means of liquid circulation, especially in recirculating systems. These systems use less water and can be more effective than single pass systems.

Air lift systems can be a reliable, efficient and cost effective way to create liquid circulation and minimize stratification in aquaculture operations. These systems can be used effectively in a wide range of operating scales. Air lift systems or pumps have been used since the late 1700's and theoretical principles governing airlift have been described in detail.[4,5] Airlift systems have been used to provide liquid circulation and to increase the oxygen concentration of water in systems ranging from small aquaria to large waste treatment facilities.[3] In the latter systems, design procedures have included solid suspension in waste treatment facilities. Airlift pumps are highly versatile units that can be used for a wide range of objectives associated with multiphase fluid flow. The simplicity of these systems and the lack of moving parts, make them particularly attractive for a wide range of operations. However, system stability and consistent water flow especially in multiple airlift pump systems connected to one compressor can present operational challenges, in part, due to the hydrodynamics associated with two-phase flow.[6-8] The objective of this work is to use an experimental design strategy to identify the critical parameters affecting the operation of airlift pump systems and to develop a predictive model for the water flow rate generated in these systems. These models can be used as part of a comprehensive design procedure for airlift pumps.

When air is pumped at the bottom of a pool of liquid, a two-phase region is developed above the injection site. The difference in density between this region and the surrounding liquid combined with the entrainment of liquid by the rising bubbles, generate a liquid circulation.[4,5] Depending on the application, air can be injected in the bottom of a draft tube in a larger system or directly into a contained liquid or pond. For low liquid height operations, as in aquaculture systems, high air volume at low inlet pressure have been found to be most effective.[9,10] Wurts et al. [10] obtained data for airlift pumps using a centrifugal blower. The airlift tube diameters ranged from 7.6 to 15.2 cm and the liquid heights used ranged from 50 to 80 cm. These workers found that for airflow rates ranging from 55 to 210 lpm, they could generate liquid to gas flow rate ratios of up to 1. These workers concluded that it was possible to generate significant water flow rates for large air flow rates. However, they also found that the high back pressures generated at high gas flow rates could cause problems with the airlift pump operation. They concluded that airlift pumps had great potential for applications in recirculating systems. Loyless and Malone[9] developed an empirical equation for the liquid flow rate as a function of gas injection rate for a 6 in. diameter airlift tube with a submerged height of 3 ft. Their flow rates ranged from 1 to 5 scfm. These workers found that the water flow rate increased with air injection rate but decreased as the distance between the liquid surface and the top center of the airlift tube was increased from 3 in to 12 in. A logarithmic model for the liquid flow rate as a function of air injection rate was developed for a limited set of operating variables. There was no methodology to extrapolate the results obtained to other configurations. Burris et al.[11] used an energy balance approach to develop a correlation for liquid flow rate in airlift systems as a function of gas flow rates. These workers varied the friction coefficient in the energy balance to develop their model. This work indicated that an energy balance approach was effective in modeling these systems, but only a very large scale airlift system was used. A water depth of 10 m was used for all tests and a diffuser was used to introduce the air into the system. Their airlift aerator was 1.1 m in diameter. The results of Felice[12] also confirm that an energy balance approach can be useful in modeling the liquid flow rate as a function of gas flow rate in airlift aerators. Felice[12] conducted experiments using two square columns with diameters of 50 and 100 mm and liquid heights of 1 and 2 m. Air flow rates of 0.1 to 0.8 m^3/ hr were used. The results indicated that there is approximately an exponential increase in liquid flow rate with increasing gas flow rate. The liquid flow rate also increased with liquid height. Liquid flow rates in airlift systems have been measured for a wide range of system scales. Blazej et al.[13] concluded that in airlift systems, the two-phase flow regime and the liquid flow rate generated for a specific gas injection rate depended on the scale of the system. In addition, Other workers have used Computational fluid dynamics (CFD) with

k-ε and Kolmogorov entropy models and frequency analyses to describe the two-phase flow in airlift systems.[14,15] These analyses have been important in understanding airlift systems and are the foundation of process design procedures. However, much of the available work does not include designed experiments or statistical engineering data analysis that can provide a comprehensive multivariate model development and a quantitative understanding of the effect of process variables on the liquid flow rate.

Experimental Design

The design of experiments has become more widely used in the last decade. As the cost of experimental work has increased and more computing power and software have become available, experimental design has been recognized as an important tool for laboratory and industrial scale. There are numerous experimental designs and much has been written on the subject.[16-19] Design of experiments uses statistical analyses to develop experimental programs that allow the selection of experimental conditions to minimize the number of experiments and eliminate unplanned dependence between independent variables. Experimental design techniques yield the maximum information for the minimum number of experiments and allow for more effective model development. These techniques have been used in optimization of aquaculture systems.[20] The Box-Behnken experimental design was selected for this work. This is a response surface design that allows for the computation of main effects and interactions between variables. It has been used extensively in a wide range of applications to account for nonlinear responses.[21, 22] Experimental variables are coded +1 and -1, for the largest and smallest value of the variable respectively. Middle values of variables are coded as 0. Table 1 is a listing of the experiments (coded) that comprise a Box-Behnken experimental design for three variables. Figure 1 is a graphical representation of the design. A three variable Box-Behnken design was the experimental program selected for this investigation.

Experiment	X_1	X_2	X_3
1	1	0	1
2	-1	0	1
3	1	0	-1
4	-1	0	-1
5	0	1	1
6	0	1	-1
7	0	-1	1
8	0	-1	-1
9	1	1	0
10	1	-1	0
11	-1	1	0
12	-1	-1	0

Table 1: Coded Variables for a three variable Box-Behnken experimental design

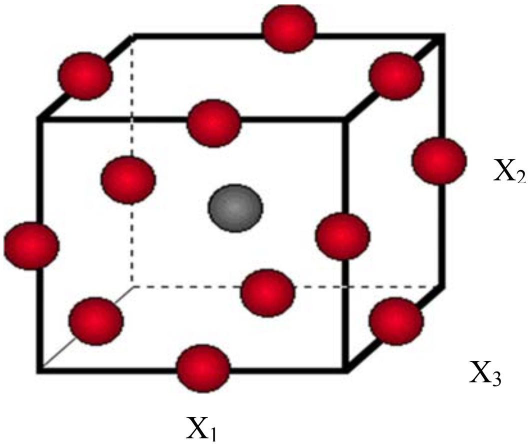

Figure 1: Box-Behnken experimental design for three variables in a unit cube

Experimental Equipment, Procedure and Conditions

The experimental equipment consisted of an acrylic rectangular tank (3.3ft X 2.6 ft) and PVC airlift pipes (draft tubes) with inside diameters of 1”, 2” and 4”. A custom aluminum stand for a single draft tube was constructed. The stand consisted of a circular base and a rectangular shaft. Figure 2 is a schematic of the experimental assembly. Each draft tube was drilled and tapped near the bottom end at the same location for air hose fittings of 3/8” and 3/4”. This was the air injection port and polyethylene tubing with internal diameters of 0.125” and 0.75,” depending on the draft tube, was connected to the draft tube . The building air supply was used for all experiments (60psi). The air injection rate was controlled using a flow meter.

For a typical experiment, the draft tube was selected and the tubing connecting the pipe to the building air supply was attached to the draft tube. This assembly was secured to the pipe stand at the selected height on the pipe. This set the water height and the distance between the center exit of the draft tube and the liquid surface. After securing the draft tube on the stand, the flow meter was set at the desired flow rate. The liquid flow rate

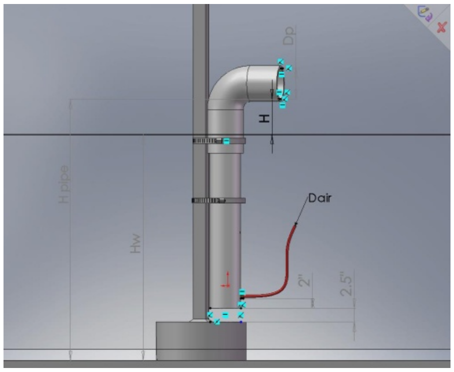

Figure 2: Experimental Draft Tube Assembly

generated was measured by collecting the liquid in a container as it exited the draft tube for a specified amount of time. The liquid collected was weighed and the flow rate was computed by using a constant water density at 20^0 C. A total of four replicate measurements were made at each experimental condition.

Results and Discussion

The draft tube diameter, air flow rate and water height were the variables investigated in this work. The distance between the liquid surface and the center exit of the draft tube was held constant (6"). Preliminary experiments indicated that the distance between the liquid surface and the draft tube exit did not affect the liquid flow rates for distances ranging between 1 and 6 in. Other workers have found this distance to be a significant factor in determining water flow rates, when varied from 3 to 6 in.[7] Table 2 lists the experimental conditions used in this work along with the liquid flow rate generated by the airlift and the standard deviation for each average measurement. The average measurements were obtained from the four measurements taken at each experimental condition. The coded value for each variable in parenthesis is also included in the table.

Draft tube diameter (in)	Air flow rate (CFM)	Water height (in)	Measured Liquid Flow rate (lpm)	Standard deviation (lpm)	Skewness, kurtosis
4 (1)	15 (1)	15 (0)	65.6	2.97	-0.48, -1.06
4 (1)	10 (0)	20 (1)	61.3	2.35	-0.23, 0.52
4 (1)	10 (0)	10 (-1)	2.8	0.35	-1.24, 0.98
4 (1)	5 (-1)	15 (0)	17.1	0.42	-0.89, 0.56
2.5 (0)	15 (1)	20 (1)	78.7	4.02	0.93, 0.28
2.5 (0)	15 (1)	10 (-1)	6.9	0.32	-0.48, 0.23
2.5 (0)	10 (0)	15 (0)	33.2	2.18	-0.82, 0.42
2.5 (0)	5 (-1)	20 (1)	59.4	3.92	-0.33, -1.41
1 (-1)	5 (-1)	10 (-1)	2.64	0.25	1.37, 1.22
1 (-1)	15 (1)	15 (0)	14.1	0.15	0.69, 0.75
1 (-1)	10 (0)	10 (-1)	15.9	0.24	-1.21, 1.01
1 (-1)	5 (-1)	15 (0)	7.05	0.25	0.47,0.20

Table 2: Liquid flow rates generated at 12 Box-Behnken experimental design conditions

Table 2 also includes the standardized skewness and kurtosis values for each measurement. The standardized skewness and kurtosis values, computed from the third and fourth moment of the distribution, are standard indicators of data normality.[14-17] Data are considered normal when these values are in the range of -2 to +2. The data for this work were analyzed using Statgraphics® software (Statpoint, Inc.).

The data indicate that each four replicate run yielded data that were within the normal range for the distribution of liquid flow rates at each experimental condition. In addition, the relative standard deviations ranged from 1.5% to 10.4% . These results indicate that the data are well behaved and repeatable. Figures 3 and 4 show the residuals and Box and Whisker plots for each run respectively. Box and Whisker plots are used to identify outliers in data.[14-17] Figure 3 confirms the standard deviation results from Table 2. The precision of the measurements is quite high and there appear to be no pattern in the residuals. The Box and Whisker plots in Figure 4 indicate that none of the samples contained any outliers. Some of the boxes in the figure are small in order to accommodate all of the data in one plot. However, the results clearly indicate that there are no outliers present.

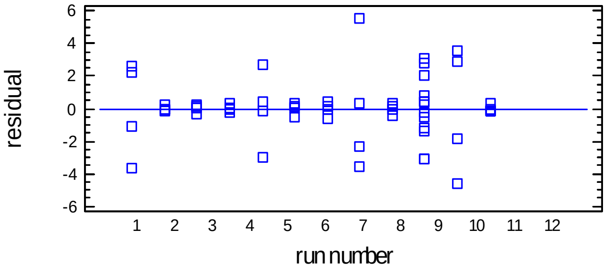

Figure 3: Residuals for each experir

Outliers would appear as points outside the box and outside of the range of the whiskers. These results indicate that all of the data can be used for model development.

The data were analyzed and a multivariate regression was performed using Statgraphics.® Figure 5 is a normality plot for the design. The Figure confirms the normality of the data for all experimental conditions. A straight line indicates data normality.

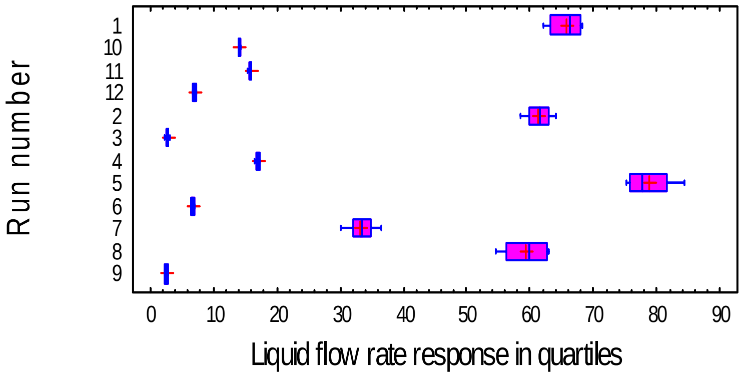

Figure 4: Outlier detection: Box and Whisker plots

Figure 4: Box and Whisker plots – outlier determination

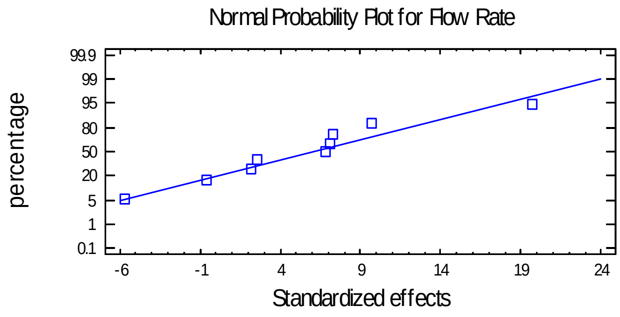

Figure 5: Normality plot

Figure 6 is a Pareto Chart showing the standardized effects for each variable and all possible variable interactions. This standard analysis technique[14-17] computes the effect of each variable relative to the experimental error. It compares this value to the minimum value that would indicate a statistically significant effect (shown by vertical line on the chart

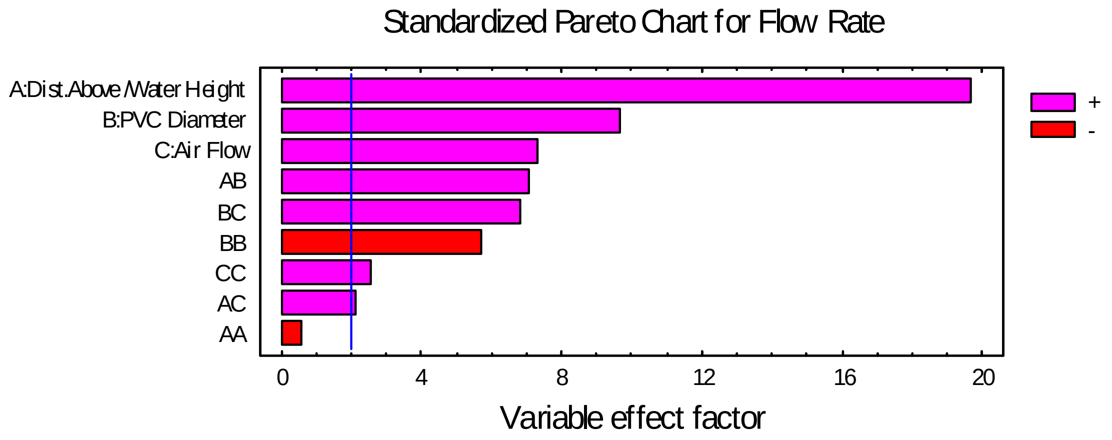

Figure 6: Pareto Chart indicating variable relative significance

The Figure clearly indicates that the most significant variable is the height of liquid in the system followed in relative significance by the draft tube diameter and the air flow rate. The data also indicate that all but one of the possible interactions are significant in determining the liquid flow rate generated in the draft tube. All of the factor effects for the interactions are greater than the minimum significant factor effect as shown on

Figure 6. The data indicate that increasing the water height and the air flow rate increases the liquid flow rate generated. All interactions except for the second order terms for draft tube diameter and the water height also increase the liquid flow rate generated in the draft tube.

A multivariate regression resulted in the coded model given by Equation 1 below.

$$Q_l = 33.3267 + 12.0609*D + 9.10313*Q_g + 24.4953*H_L - 10.4558*D^2 +$$
$$11.9669*D*Q_g + 12.4425*D*Q_g + 4.66104*Q_g^2 + 3.78063*Q_g*H_L - 1.10458*H_L^2 \quad (1)$$

Where D= draft tube diameter (all variables in coded values)
Q_g = gas flow rate
H_L = water height

The model has an R^2 value of 0.92. Thus, it accounts for 92% of the variability observed. The model was validated using additional experimental runs and agreement between the liquid flow rate generated and the model predictions were within 10%.

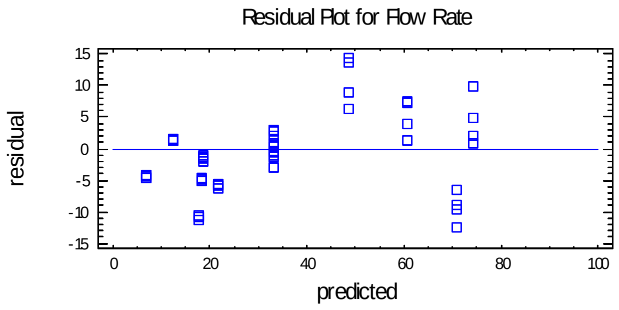

Figure 7: Residuals for predicted values

Figure 7 shows the residuals for each of the predicted values. This figure indicates that there appear to be no serial correlation among the residuals. Thus, the residuals can be considered independent of the order in which the data were obtained.

Figure 8a is the estimated response surface for the system for the mid-value of liquid height. The plot depicts the nonlinearities of the system. The maximum liquid flow rate is generated in the draft tube for large air flow rates and tube diameters near the maximum value of 4 in. The analysis indicates that there is a maximum in the dependence of the liquid flow rate to the draft tube diameter. Figure 8b shows the same response surface for the mid-level value of draft tube diameter. This plot indicates that, at a constant mid-level value of draft tube diameter, the water flow rate increases with water height and air flow rate for the range of operating variables used in this investigation. Figures 8 a and b are developed on a coded values basis.

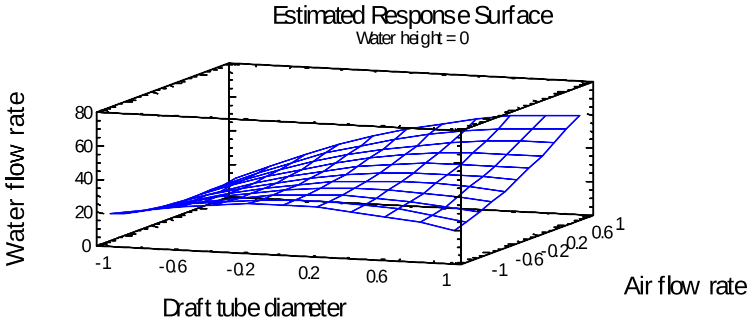

Figure 8a: Response surface – for mid-level water height

The model was used to develop a contour plot to show graphically the effect of the variables investigated on the liquid flow rate. The contour plot is shown in Figure 9.

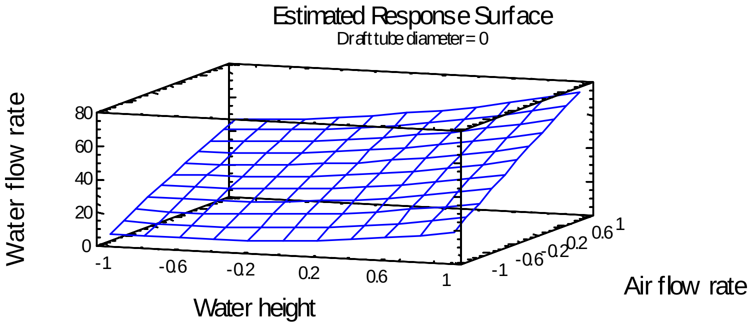

Figure 8b: Response surface – for mid-level draft tube diameter

The plot shown is for the middle value of water height and the range of draft tube diameters and air flow rated studied. The nonlinear nature of the process is clearly shown in the figure. These types of plots can be used to obtain a general idea of how operating parameters affect water flow rate in the system and to specify operating conditions to obtain a specific liquid flow rate. For example, it is possible to obtain 24 lpm of water flow rate in the system investigated for large draft tube diameters and relatively low flow rates or small draft tube diameters and larger flow rates.

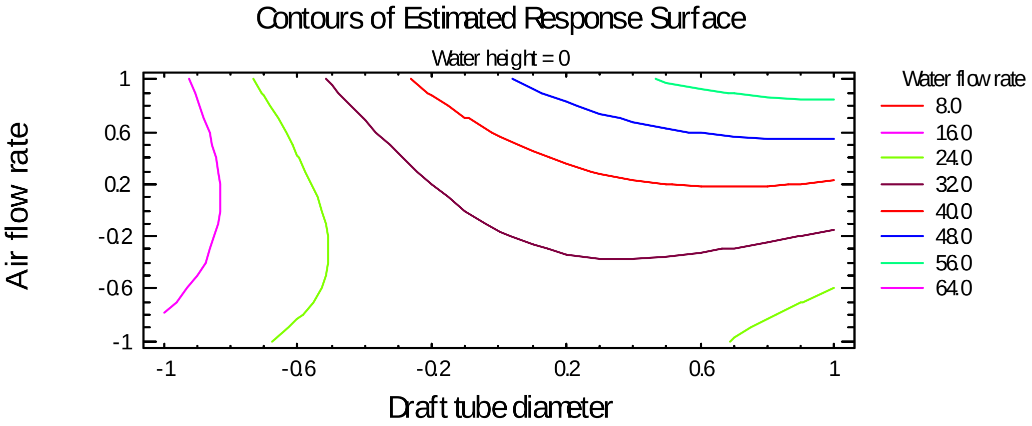

Figure 9: Contour diagram – mid-level value water height value

Conclusions and Recommendations

An experimental design strategy was used to investigate the liquid flow rate generated in an airlift draft tube as a function of water height, draft tube diameter, and gas flow rate. A Box-Behnken experimental program was designed and implemented and a multivariate model that can account for 92% of the variability observed was developed. The data indicate that, for the range of variables studied, the most significant variable is the liquid height, followed by the draft tube diameter and air flow rate. The importance of this work is in that the model developed is multivariate and can be used to predict liquid flow rates for all combinations of variables within the range for which the model was developed. The coded model eliminates the effect of different variable magnitudes and ranges in the determination of coefficients. Additional data analysis is necessary to combine these results with an energy- balance based model, complete additional comparisons to available data, and refine the existing model. Finally, developing a model that can be used for multiple draft tubes connected to a single compressor would be an important contribution to the development of design criteria for aquaculture applications of airlift technology.

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