ELSEVIER

Aquacultural Engineering Vol. 15, No. 1, pp. 1–11, 1996

Printed in Great Britain.
0144-8609/96

0144-8609(95)00001-1

Gas-phase Axial Dispersion in a Spray Tower

Brian J. Vinci,[a] Barnaby J. Watten[b] & Michael B. Timmons[a]

[a]Cornell University, Department of Agricultural and Biological Engineering, Riley Robb Hall, Ithaca, NY 14853, USA
[b]National Fishery Research and Development Laboratory, National Biological Service, R.D. # 4, Box 63, Wellsboro, PA 16901, USA

(Received 28 March 1994; accepted 30 December 1994)

ABSTRACT

Gas-phase axial dispersion (mixing of the composition of the gas phase along the longitudinal axis) was characterized in an enclosed spray tower for purposes of establishing reactor type for the solute–solvent pair oxygen and water. Test condition variables were spray tower height (TH), 1·52, 2·03 and 2·54 m; hydraulic loading (HL), 44·2, 66·3 and 88·4 kg/m^2*s; the ratio of volumetric oxygen injection to water flow rate (G/L), 1·0, 2·5 and 5·0%; the ratio of volumetric bulk tower gas recirculation flow rate to water flow rate (BG/L), 0, 500 and 700%; and bulk tower gas recirculation direction, counter-current to and co-current to the water flow. Gas composition measurements (% O*$_2$*) made across the long axis of the tower under steady-state conditions provided 1020 independent observations and 240 gas composition profiles. Factors showing a significant effect (*$P < 0{\cdot}05$*) on gas composition were TH, HL, G/L and BG/L. Sample location as a percentage of TH did not have a significant effect on gas composition and accordingly profile slopes were not different from zero (*$P > 0{\cdot}05$*). Profile data indicate a completely mixed gas phase within the tower. The dispersion observed was attributed to the lack of a significant pressure drop along the axis of the reaction vessel, forces due to nozzle operation, and to bulk tower gas recirculation.*

INTRODUCTION

Spray towers are commonly used in industrial operations for mass transfer between a dispersed liquid phase and a continuous gas phase

(Mehta and Sharma, 1970; Pinilla *et al.*, 1984). Typical applications include: absorption, desorption, humidification, cooling by evaporation, gas washing and spray drying (Perry and Green, 1984). These same applications can be performed with the packed tower at generally higher treatment efficiencies (Nirmalakhandan *et al.*, 1988; Watten and Boyd, 1989). However, lack of media within the contact chamber of a spray tower provides advantages over a packed column in applications where fouling or blockage within the packed media is a problem (Pigford and Pyle, 1951; Mehta and Sharma, 1970; Boyd and Watten, 1989). Spray towers also have the advantage of a low gas-phase pressure drop across the chamber, lower investment costs and mechanical simplicity (Pigford and Pyle, 1951; Mehta and Sharma, 1970; Pinilla *et al.*, 1984).

Aquacultural applications of the spray tower have focused on pure oxygen aeration systems either for oxygen addition or nitrogen removal (Colt and Watten, 1988). Here, influent water is directed through a spray nozzle positioned near the top of a sealed vertical chamber that receives pure oxygen (Boyd and Watten, 1989).

Spray tower design procedures require knowledge of the gas–liquid contacting mode within the reaction vessel, e.g. plug-flow or plug-flow with axial dispersion (mixing of the composition of the gas phase along the longitudinal axis). Contacting mode will vary with reactor geometry (Levenspiel, 1979) as well as liquid and gas throughputs (Keey and Pham, 1977; Pinilla *et al.*, 1984). When used as a gas absorber, dispersion of the gas phase is undesirable given the resultant drop in mean dissolved gas deficit (Levenspiel, 1979). Dispersion of the gas phase results from the absence of a stabilizing pressure drop such as that associated with tower packing or perforated plates. Non-uniform distribution of the liquid and varying droplet size encourage dispersion as does spray striking tower walls (Perry and Green, 1984).

The objective of this study was to evaluate the extent of axial dispersion in the gas phase of a spray tower contacting water with commercial oxygen. Variables tested were: spray tower height; hydraulic loading rate; the ratio of volumetric oxygen injection to water flow (G/L); the ratio of volumetric bulk tower gas recirculation flow rate to water flow rate (BG/L); and bulk tower gas recirculation direction. Bulk tower gas was recirculated at different rates and direction given our intent, in future studies, to direct bulk tower gas through a packed tower scrubber for selective removal of carbon dioxide.

MATERIALS AND METHODS

Gas-phase axial dispersion was evaluated using a steady-state gas composition profile method similar to that described by Mathur and Wellek (1976) and Watten and Boyd (1989). Gas composition profiles were measured for all combinations of the independent variables: spray tower height, 1·52, 2·03 and 2·54 m; hydraulic loading rate, 44·2, 66·3 and 88·4 kg/m^{2}s; G/L, 1·0, 2·5 and 5·0%; BG/L, 0, 500 and 700%; and bulk tower gas recirculation direction, counter-current to the water flow and co-current to water flow, excepting those combinations with a tower height of 2·03 m and hydraulic loading rate of 88·4 kg/m^{2}s. The resulting combinations yielded 120 unique test conditions, each of which was duplicated providing 240 gas-phase profiles.

The test spray tower was constructed of 20·3 cm outside diameter, 0·6 cm thick, clear Plexiglas® tubing* in three sections. The main section 152·4 cm long could be connected with two smaller sections, each 76·2 cm in length, with a gasketed coupling to achieve the necessary tower height (Fig. 1). The tower was suspended within a 453 liter sump (61 × 61 × 122 cm) coupled with an external stand pipe that allowed for water level control. Various connections to the spray tower provided ports for oxygen injection, gas sampling and bulk tower gas circulation.

The spray tower received well water via two submersible pumps positioned in a sub-floor reservoir. Influent water entered the tower via a Spraying Systems Co. (Wheaton, Illinois, USA) DistriboJet® 2R BRASS 65 45 full cone spray nozzle. This nozzle is designed to deliver a coarse full cone spray. The water level within the tower, and thus the effective spray tower height, was held constant through adjustment of the external standpipe. Hydraulic loading was established by measuring effluent water flow from the standpipe with a barrel (approximately 40 liter), a stopwatch and an electronic scale (Toledo Scale, Model 8140, Worthington, Ohio, USA). Commercial oxygen ($O_2 > 99\%$) was routed through a pressure regulator and then a research grade rotameter (Cole-Parmer, Model 3216-45, Chicago, Illinois, USA) before being introduced to the tower at a point 15·2 cm above the sump water level. Off gas was vented from the spray tower through a 12·7 mm diameter riser pipe connected with a 5·1 × 10 cm demister. Bulk tower gas was circulated through an

---

*The mention of tradenames or manufacturers does not imply Cornell University or US Government endorsement of commercial products.

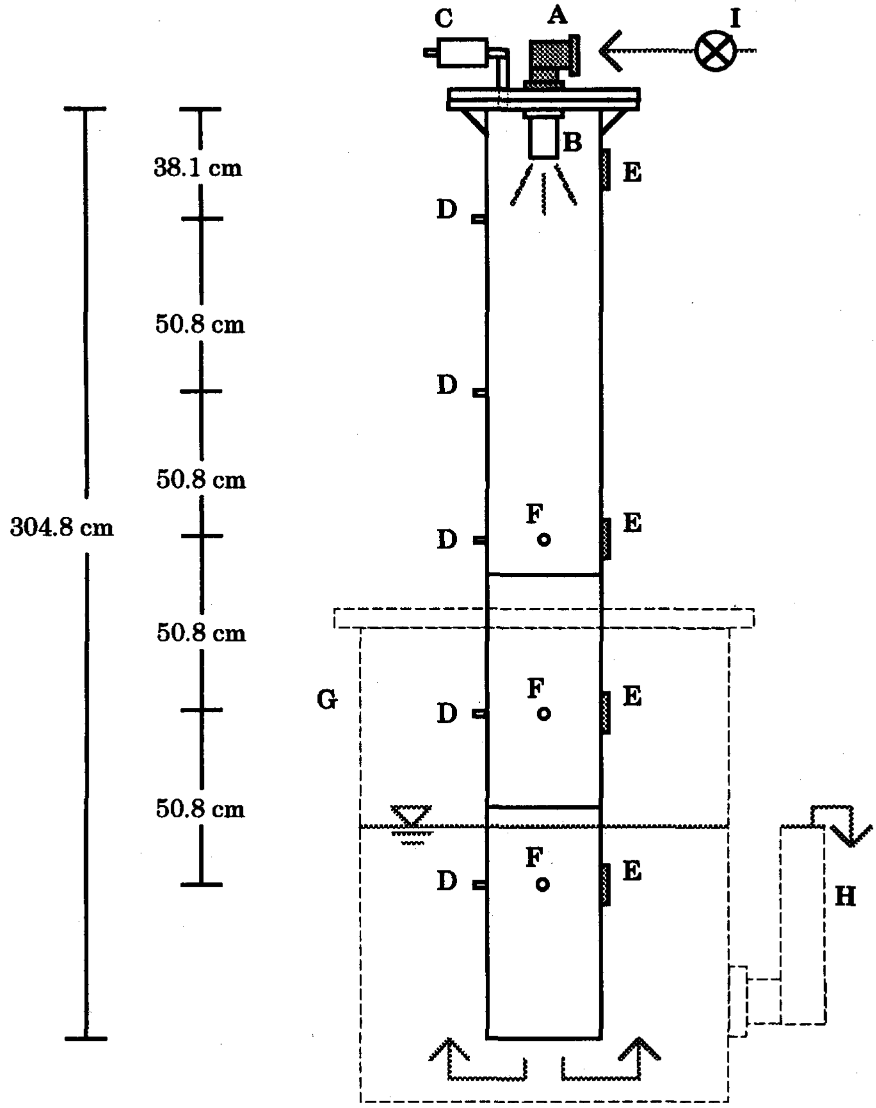

Fig 1. Detailed view of the 20·3 cm outside diameter spray tower. A, 5·1 cm water inlet; B, spray nozzle; C, demister and gas vent; D, gas sample ports; E, bulk gas circulation vents; F, oxygen injection ports; G, sump; H, external standpipe; I, water valve.

external loop of 5·1 cm diameter PVC with a gas tight blower (Rotron, Model DR303, Saugertis, New York, USA). The blower pulled bulk tower gas from the tower top or bottom and passed it through a 152 liter water trap. Bulk tower gas was then routed into the blower, through a 5·1 cm gate valve for regulation, and on to an orifice plate assembly for measuring gas flow rate. After passing the orifice plate assembly, the bulk tower gas was re-introduced to the spray tower, counter to where it had been extracted. The orifice plate assembly was designed and constructed based on ASME (1990). The assembly was constructed of two clear Plexiglas® plates, 30·5 × 30·5 × 1·9 cm, and a brass ASME orifice plate in a sandwich configuration. Two orifice plates with orifice diameters of 20·3 and 33·0 mm were used to establish test gas flows. Bulk gas flow rates were determined by measuring the pressure drop across the orifice assembly with a differential manometer (Solomat®, Model 2018, Stamford, Connecticut, USA). Bulk gas flow was then derived from traditional orifice plate flow meter calculations (Stearns *et al.*, 1951; Cusick, 1961; Ower and Pankhurst, 1966; ASME, 1990). A schematic of the relevant material flows in the test system are shown in Fig. 2.

Gas samples were taken from the spray tower in either four or five places along its longitudinal axis following the establishment of

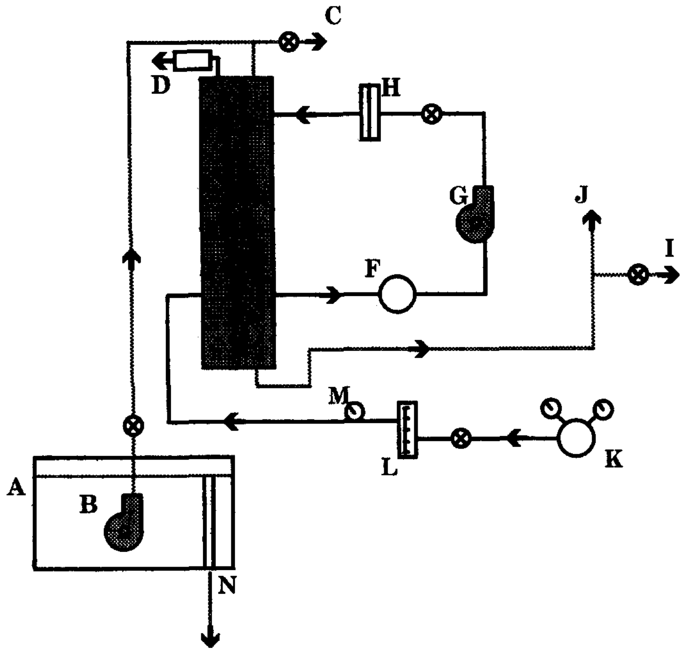

Fig. 2. Schematic of relevant material flows in the test system used to study gas-phase axial dispersion in a spray tower. A, sub-floor water reservoir; B, submersible water pumps; C, influent water sample point; D, off-gas vent with demister; E, spray tower; F, water trap; G, gas blower; H, orifice plate assembly; I, effluent water sample point; J, discharge line; K, pressure regulator; L, rotameter; M, manometer; N, reservoir standpipe.

steady-state conditions. Oxygen gas analysis was performed as bulk tower gas was pulled into a sampling apparatus that contained a fuel cell (Bio-Tek, Model 74223 oxygen sensor, Winooski, Vermont, USA). Water and bulk tower gas temperatures upstream of the flange tap were measured with a thermocouple. Tower influent and effluent dissolved oxygen concentrations were determined with a polarographic oxygen probe (YSI, Model 57, Yellow Springs, Ohio, USA) and barometric pressures were determined with a pressure transducer (Solomat®, Model 2018, Stamford, Connecticut, USA). Tower effluent total dissolved gas pressures were established with a saturometer (Common Sensing, Model TBO, Bainbridge Island, Washington, USA) while influent total dissolved gas pressure was measured with a Bouck-type gasometer (Bouck, 1982).

Least-squares regression was used to correlate gas composition to tower height, sample location as a percentage of the tower height, hydraulic loading, BG/L, bulk gas direction and G/L. Gas composition profile slopes, derived from regressions performed for each set of operating conditions ($N = 240$), were also correlated to test variables. Statistical significance for factor effects was evaluated with Student's t-test at the 95% confidence level (Lide, 1991).

RESULTS

Results of the least-squares regression for the 1020 gas composition observations are shown in Table 1. Overall, the regression yielded a

TABLE 1

Results of Least-squares Regression for Gas Composition (% Oxygen) as a Function of Tower Height (m), Sample Location, Hydraulic Loading (kg/m^{2}s), the Ratio of Bulk Tower Gas Recirculation Flow Rate to Water Flow Rate (BG/L), Bulk Gas Direction, and the Ratio of Volumetric Oxygen Injection to Water Flow Rate (G/L)

Parameter	*Coefficient*	*Standard error*	t *statistic*
Intercept	73·9	0·62	120·1[1]
Tower height	−6·2	0·21	−29·6[1]
Sample location	−0·00061	0·0026	−0·24
Hydraulic loading	−0·12	0·0054	−22·2[1]
BG/L	−0·10	0·034	−2·94[1]
Bulk gas direction	−0·043	0·10	−0·43
G/L	585·4	5·43	107·8[1]

[1] Significant at the 0·05 level.

coefficient of determination, r^2, of 0·93, and a standard error of 2·87. Factors showing a significant effect on gas composition were tower height, hydraulic loading, BG/L and G/L. Increases in tower height, hydraulic loading and BG/L resulted in lower levels of oxygen in the gas phase, whereas an increase in G/L resulted in higher levels of oxygen. Sample location did not have a significant effect on gas composition value (Fig. 3). Accordingly, gas composition profile slopes were not significantly different from zero (average slope = −0·02%, standard error = 0·04%; range = −1·6 to +2·0%). Results of the least-squares regression for all gas composition profile slopes derived are shown in Table 2. Overall, the regression yielded a coefficient of determination, r^2, of 0·003, and a standard error of 0·006. Factor effects on profile slope were not significant.

DISCUSSION

Oxygen composition of the gas phase within the spray tower did not vary significantly with sample point over the range of operating conditions tested. Moreover, the mean gas composition slope was negligible, averaging just −0·02%. These data support the hypothesis that the gas phase within the tower is completely mixed and hence axial dispersion is extensive. The extensive dispersion in the gas phase observed is consistent with the lack of a change in oxygen transfer noted by Dwyer *et al.* (1991) when oxygen flow was redirected from the bottom to the top of a test tower measuring 1·25 m in length, i.e. performance of a reactor with a homogeneous gas phase will not be influenced by the point of oxygen injection (Levenspiel, 1979). Extensive dispersion in the gas phase of spray tower equipment has also been reported for applications involving solute and solvent components other than water and oxygen (Mehta and Sharma, 1970; Pinilla *et al.*, 1984).

The dispersion observed in our tests without bulk tower gas recirculation no doubt reflects the lack of a significant pressure drop across the long axis of the reaction vessel. Pressure drop is related to system geometry and will increase with gas and liquid throughput. During tests G/L was held at or below 5%. This low range is typical of commercial oxygen absorption equipment applications given the need to minimize loss of oxygen due to off-gas venting (Colt and Watten, 1988). Over our range of tested liquid irrigation rates (44·2–88·4 kg/m^{2}s), resultant superficial gas velocities were less than $4{\cdot}42 \times 10^{-3}$ m/s. Hence the progression of gas from the injection

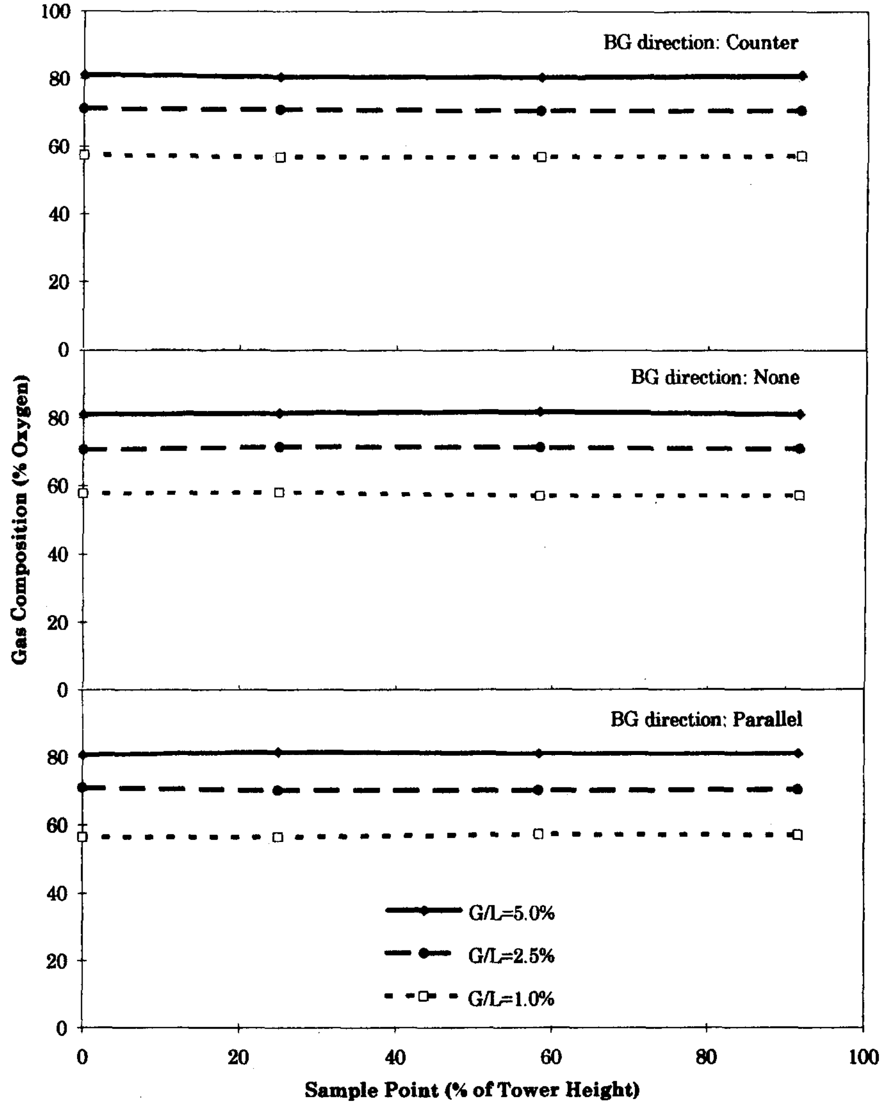

Fig. 3. Gas composition vs sample point established with and without bulk gas recirculation using oxygen injection to water flow rate ratios (G/L) of 1·0, 2·5 and 5·0%. The tower was 1·52 m high and received water at a rate of 88·4 kg/m^{2}s. When operating with bulk gas recirculation (counter-current or co-current to water flow) the ratio of gas circulation flow rate to water flow rate was 700%.

point to the release point was very slow and apparently masked by extensive mixing forces associated with operation of the liquid nozzle.

Dispersion observed with bulk tower gas recirculation can be attributed, in part, to a change in reactor type (Levenspiel, 1979).

TABLE 2

Results of Least-squares Regression for Gas Composition (% Oxygen) Profile Slope as a Function of Tower Height (m), Hydraulic Loading (kg/m^{2}s), the Ratio of Bulk Tower Gas Recirculation Flow Rate to Water Flow Rate (BG/L), Bulk Gas Direction and the Ratio of Volumetric Oxygen Injection to Water Flow Rate (G/L). The *t* statistic values indicate factor effects were not significant

Parameter	*Coefficient*	*Standard error*	t *statistic*
Intercept	−0·00047	0·00027	−0·17
Tower height	0·00022	0·00093	0·24
Hydraulic loading	−0·0000020	0·000024	−0·082
BG/L	0·000052	0·00016	0·33
Bulk gas direction	−0·00028	0·00046	−0·62
G/L	−0·012	0·025	−0·48

Bulk G/L ratios here ranged from 500 to 700% providing an increase in gas throughputs of 100–700 times throughputs maintained without recirculation. The effective gas recirculation rates in all cases exceeded 99%. The high rate of recycle and associated blending of the oxygen feed with previously treated bulk gas acts to lower the oxygen level in the gas as well as its concentration gradient along the axis of the reactor — the net result being the development of a homogeneous gas phase.

Regardless of the mechanisms involved in creating the dispersion observed, mixing of the gas phase will reduce tower mass transfer rates to levels below those possible with plug-flow contacting (Levenspiel, 1979). Under these conditions a higher mean gas–liquid-phase concentration gradient can be established, for improved performance, through repeated contacting of tower off-gas with the untreated liquid. This method has been used successfully to accelerate mass transfer in packed column equipment shown also to have a mixed gas phase when used for commercial oxygen–water contacting (Watten and Boyd, 1989, 1990). Further, knowledge of dispersion within spray-tower oxygen absorption equipment allows development of performance algorithms needed to address oxygen transfer rates as well as total gas pressure limits and predicted changes during treatment (Watten, 1990).

ACKNOWLEDGEMENTS

We thank the United States Department of Agriculture, Agricultural Research Service, grant £59-32U4-8-15, and the Conservation Fund's

Freshwater Institute for funding this work. We also thank Bill Ridge for his assistance with the test system construction, and the New York Co-operative Fish and Wildlife Research Unit, Cornell University, for administrative support.

REFERENCES

ASME (1990). Measurement of fluid flow in pipes using orifice, nozzle, and venturi. ASME MFC-3M-1989. American Society of Mechanical Engineers, New York.

Bouck, G. R. (1982). Gasometer: An inexpensive device for continuous monitoring of dissolved gas and supersaturation. *Trans. Am. Fish. Soc.*, **111**, 505–16.

Boyd, C. E. & Watten, B. J. (1989). Aeration systems in aquaculture. *CRC Crit. Rev. Aquatic Sci.*, **1**, 425–72.

Colt, J. & Watten, B. J. (1988). Applications of pure oxygen in fish culture. *Aquacult. Engng*, **7**, 397–441.

Cusick, C. F. (1961). *Flow Meter Engineering Handbook* (3rd edn). Minneapolis–Honeywell Regulator Company, Brown Instruments Division, Philadelphia.

Dwyer, W. P., Kindschi, G. A. & Smith, C. E. (1991). Evaluation of high- and low-pressure oxygen injection techniques. *Am. Fish. Soc. Symp. Series*, **10**, 428–36.

Keey, R. B. & Pham, Q. T. (1977). Residence-time distribution of air in a tall-form spray chamber. *J. Engng Sci.*, **32**, 1219–26.

Levenspiel, O. (1979). *The Chemical Reactor Omnibook.* Oregon State University, Corvallis, Oregon.

Lide, D. R. (1991). *CRC Handbook of Chemistry and Physics* (72nd edn). CRC Press, Boston, Massachusetts.

Mathur, V. K. & Wellek, R. M. (1976). Effect of axial dispersion on interphase mass transfer in packed absorption columns. *Can. J. Chem. Engng*, **54**, 90–6.

Mehta, K. C. & Sharma, M. M. (1970). Mass transfer in spray columns. *Br. Chem. Engng*, **15**, 1440–4.

Nirmalakhandan, N., Lee, Y. H. & Speece, R. E. (1988). Optimizing oxygen absorption and nitrogen desorption in packed towers. *Aquacult. Engng*, **7**, 221–34.

Ower, E. & Pankhurst, R. C. (1966). *The Measurement of Air Flow.* Pergamon Press, New York.

Perry, R. H. & Green, D. (1984). *Chemical Engineer's Handbook* (6th edn). McGraw-Hill, New York.

Pigford, R. L. & Pyle, C. (1951). Performance characteristics of spray-type absorption equipment. *Ind. Engng Chem.*, **43**, 1649–60.

Pinilla *et al.*, 1984Pinilla, E. A., Diaz, J. M. & Coca, J. (1984). Mass transfer and axial dispersion in a spray tower for gas–liquid contacting. *Can. J. Chem. Engng*, **62**, 617–22.

Stearns, R. F., Johnson, R. R., Jackson, R. M. & Larson, C. A. (1951). *Flow*

Measurement with Orifice Meters. Van Nostrand, New York.

Watten, B. J. (1990). Design of packed columns for commercial oxygen addition and dissolved nitrogen removal based on effluent criteria. *Aquacult. Engng*, **9**, 305–28.

Watten, B. J. & Boyd, C. E. (1989). Gas phase axial dispersion in a packed column oxygen absorber. *Aquacult. Engng*, **8**, 421–34.

Watten, B. J. & Boyd, C. E. (1990). Gas transfer within a multi-stage packed column oxygen absorber: Model development and application. *Aquacult. Engng*, **9**, 33–59.