Chapter 2

Literature reviews

2.1 Backgrounds

Nitrification is an aerobic, autotrophic process which is basically the oxidation of ammonia to nitrite and to nitrate by autotrophic organisms which derive their energy solely from these oxidations and not from the oxidation of reduced carbon compounds [Wallace and Nicholas, 1969]. This type of microorganisms utilizes carbon dioxide as a carbon source for biosynthetic process and oxidation of reduced nitrogen compounds as an energy source [Strotmann and Windecker, 1997]. The first oxidation step, *i.e.* the conversion of ammonium ions to nitrite is carried out mainly by *Nitrosomonas* species, although other genera, including *Nitrosococcus*, and *Nitrosospira* may also complete the task. Some subgenera, *Nitrosolobus* and *Nitrosovibrio*, can also autotrophically oxidize ammonia [Watson *et al.,* 1981]. These nitrite-oxidizing bacteria oxidize ammonium to nitrite according to Equation (2-1).

$$NH_4^+ + 1.5\ O_2 \longleftrightarrow NO_2^- + H_2O \qquad (2\text{-}1)$$

In the second step of the process, nitrite-oxidizing bacteria oxidize nitrite to nitrate according to Equation (2-2).

$$2\ NO_2^- + O_2 \longleftrightarrow 2\ NO_3^- \qquad (2\text{-}2)$$

Nitrobactor is the most frequently identified genus associated with this second step, although other genera, including *Nitrospina*, *Nitrococcus*, and *Nitrospira* can also autotrophically oxidize nitrite [Watson *et al.,* 1981].

The overall nitrification which is the combination of the above two stoichiometries can then be expressed by

$$NH_4^+ + 2O_2 \longleftrightarrow NO_3^- + H_2O \qquad (2\text{-}3)$$

The overall nitrification reaction indicates that the oxygen requirement for the oxidation of ammonia is 4.57 g O_2/g NH_4^+-N, which consists of 3.43 and 1.14 g O_2 for the oxidations of ammonium and nitrite, respectively. Randall *et al.* (1992) found that the oxygen requirement was not significantly different from the above calculation and the reaction stoichiometry for the reaction with cell synthesis becomes:

$$NH_4^+ + 1.83O_2 + 1.98HCO_3^- \longrightarrow 0.98NO_3^- + 0.021cell + 1.88H_2CO_3 + 1.041H_2O \quad (2\text{-}4)$$

where approximately 4.2 g O_2/g NH_4^+-N is consumed for the oxidation of ammonia in this case. It is then concluded that this cell synthesis had only slight effect on the overall oxygen requirement for the nitrification and can be neglected. Hence, oxygen requirement from Equation (2-3) is usually considered for the nitrification reaction.

2.2 Factors controlling nitrification processes

Literature shows that nitrification was affected by a number of variables including dissolved oxygen concentration (DO), temperature (T), substrate concentration (S), and pH. The brief detail follows:

A. pH: Bulk water pH value is an important factor in nitrification activity. Nitrifying bacteria are very sensitive to pH as illustrated in Figure 2.1. *Nitrosomonas* has an optimal pH between approximately 7.0 and 8.0. During the nitrification step, pH of the bulk water tends to decrease because bicarbonate is consumed as a carbon source for these autotrophic microorganisms (*e.g. Nitrosomonas*) . It is important then, that pH is well controlled to ensure a proper growth of the nitrifying bacteria.

B. Temperature: The rate of nitrification is also strongly affected by temperature. Nitrification can occur in a wide range of temperature, *i.e.* from 4 to 45°C. Figure 2.2 shows that the rate of nitrification increased with temperature. In terms of reaction kinetics, the temperature has direct effects on the maximum specific growth rate of bacteria, μ_{max} (d^{-1}), for both *Nitrosomonas* and *Nitrobacter*. This relation follows Arrhenius equation as summarized in Tables 2.1 and 2.2, and Figure 2.3.

C. Dissolved Oxygen: The concentration of dissolved oxygen (DO) was also reported to strongly influence the growth rate of nitrifying bacteria. Figure 2.4 shows that nitrification could be achieved even at a very low DO level, *e.g.* 0.5 mg-O_2/L, but higher rate could be obtained at higher DO levels [Nagel and Haworth, 1969]. Table 2.3A summarize works done to investigate the effect of DO. Many found is follow Monod type kinetic. Table 2.3B shows some of the kinetic constant for the utilization of DO by nitrifying bacteria (assume Monod Kinetics). From table only two works support the claim though.

D. Ammonia concentration: The rate of ammonia or nitrite oxidation depends strongly on substrate concentrations (ammonium and dissolved oxygen). Figure 2.5 shows the effect of ammonia concentration on the growth rate where higher ammonium loading rate was found to provoke biomass concentration which nitrification rate increased with biomass concentration increase. With respect to dissolved oxygen and ammonia concentrations, the kinetics of nitrification process is usually reported in the form of Monod equation where both ammonium-nitrogen and dissolved oxygen are treated as essential substrates and the mathematical expression for this kinetics was given by Henze *et al.* (1987), as follows:

$$\mu = \mu_{max} \frac{NH_4-N}{K_{NH_4} + NH_4-N} \frac{DO}{(K_0 + DO)} \qquad (2\text{-}5)$$

where
- μ = Specific growth rate (d^{-1})
- μ_{max} = Maximum specific growth rate (d^{-1})
- NH_4-N = Ammonium concentration (mg NH_4-N/L)
- DO = Dissolved oxygen (mg O_2/L)
- K_{NH4-N} = Saturated constant of Ammonium-nitrogen (mg NH_4-N/L)
- K_o = Saturated constant of Dissolved oxygen (mg O_2/L)

Half-saturation constants (K_{NH4-N}) for ammonium of approximately 0.2-5 mg/L have been reported in Dincer (2000).

E. Organic carbon: Figure 2.6 demonstrates the effect of organic carbon/nitrogen ratio on nitrification rate. Nitrification processes were strongly inhibited in the presence of organic carbon. Organic matter in wastewater supports the growth of heterotrophic bacteria, which compete with the autotrophic nitrifiers. Heterotrophic bacteria typically have a maximum growth rate of five times and a yield of two to three times that of nitrifiers [Grady and Lim, 1980]. Bovendeur *et al.* (1990) observed a significantly decrease in nitrification rate for an increase in organic loading rate.

F. Toxics: It was reported that 10-20 mg/L of heavy metals could be tolerated by the bacteria because at the range of pH in the culture medium (7.5-8.0), most of the heavy metals exhibited low ionic concentrations. However, precipitated metals in the activated sludge could cause serious problems if the pH fell and the precipitate dissolved. High concentrations of ammonia or nitrite, between 1400-2500 mg N/L, could also be temporarily toxic to nitrifiers [US. EPA, 1975; Painter, 1977]. Table 2.4 shows concentration level of various compounds which could be toxic to nitrifying bacteria.

G. Salinity: Figure 2.7 depicts the variation of the rate of nitrification with salt concentration in the feed. Usually nitrification rate drops with an increase in salt concentration, and in this figure, as the salt content increases from 0 to 3 and 5% the rate of nitrification drops from 2.9 to 2.6 and 2.2 mgN/L.h, respectively.

H. Other essential requirements: Other requirements for growth of nitrifying bacteria include carbon dioxide, carbonate or bicarbonate, and ammonia or nitrite. Phosphate, magnesium, iron, and copper in small quantity are also essential for growth [Painter, 1977].

Table 2.5 summarizes previous investigation on the effect of these various parameters on the nitrification rates.

2.3 Nitrification systems

Nitrification was carried out in various closed seawater systems. Literature concerned with these systems is delineated as follows.

A. Trickling filters: A trickling filter is a wastewater treatment system that biodegrades organic matter and can also be used to achieve nitrification. The wastewater trickles through a circular bed of coarse stones or plastic material. A rotating distributor (a rotating pipe with several holes across it) evenly distributes the wastewater from above the bed. The microorganisms in the wastewater attach themselves to the bed (Fig. 2.8).

Treatment Detail Summary (see Table 2.6 for more detail)

Nitrification rate range	0.012-0.94 gN/m^2d
Volume	0.04-3 m^3
Specific surface area	18.3-480 m^2/m^3
DO	> 5.0 mgO_2/L
pH	6.7-8.5
Temperature	20-30 °C
Initial nitrogen concentration	0.5-15 mg NH_4-N/L

B. Submerged filters: Submerged filter or fixed bed filter is packed with filter media (coarse sand, gravel media, crushed rock media, plastic media and oyster shell) to support the growth of nitrifying bacteria. In the operation of this system, the wastewater is filled into column and air is pumped through the fixed film biofilter column to supply necessary oxygen for the microorganism (Fig. 2.9).

Treatment Detail Summary (see Table 2.6 for more detail)

Nitrification rate range	0.06-1.67 gN/m^2d
Volume	0.35-6 m^3
Specific surface area	80-1450 m^2/m^3
DO	>3.0 mgO_2/L
pH	6.0-9.0

Temperature	20-30 °C
Initial nitrogen concentration	0.2-10 mg NH_4-N/L

C. Airlift reactor: Airlift reactors are suitable for processes in which a good mixing and a close contact between phases are desired. Air is sparged into the inner cylinder, inducing a hydrostatic pressure difference between the riser and the downcomer. This pressure difference is the driving force for an internal circulation flow of liquid, particles and air bubbles (see Figs. 2.10 and 2.11) [Benthum *et al.*, 1999].

Treatment Detail Summary (see Table 2.6 for more detail)

Nitrification rate range	4.33 gN/m^2d
Volume	0.003-2.5 m^3
DO	> 3.0 mgO_2/L
pH	7.5-8.4
Temperature	25-30 °C
Initial nitrogen concentration	1.3-5 mg NH_4-N/L

D. Rotating filter: In this system, the biofilm develops on the surface of vertical disks that rotate within the liquid. The lower part of each rotating disking is periodically submerged in the liquid where the upper zone is in contact with air. The speed of rotation is adjustable. The attached growths are similar in concept to trickling filter, with the exception that the microbes are through the wastewater rather than the wastewater being passed over the microbes. (Fig. 2.12)

Treatment Detail Summary (see Table 2.6 for more detail)

Nitrification rate range	0.05-0.06 gN/m^2d
Volume	0.009-5.12 m^3
Specific surface area	18.3-278.80 m^2/m^3
DO	5.0-7.1 mgO_2/L
pH	6.0-8.0
Temperature	15-30 °C
Initial nitrogen concentration	7.95-10 mg NH_4-N/L

E. Fluidized bed reactor: In fluidized bed reactor, the particles move up and down in the bed while the expanded bed as a whole is kept within a well defined zone of the reactor. Fluidized bed configurations are characterized by very high volumetric rate of biological transformation, stable operation and self-cleaning effects over extended periods. A high surface loading in the biofilter is thus needed to ensure suspension of the media [Skjolstrup *et al.*, 1998].

Treatment Detail Summary (see Table 2.6 for more detail)

Volume	53-170 m^3
Specific surface area	178-1000 m^2/m^3
DO	5.3 mgO_2/L
pH	7-7.98
Temperature	17.6-30.4°C
Initial nitrogen concentration	2.2 mg NH_4-N/L

F. Immobilized in porous carriers: In immobilized system, the carriers with attached biofilm are left floating in the nitrifying column. These carriers might be conveyed through various parts of the reactor in airlift style, or can just be left floating on the top of the column. The immobilization of microorganisms can prevent them from being washed out and a high sludge age can be obtained.

Treatment Detail Summary (see Table 2.6 for more detail)

Nitrification rate range	8.2-70 gN/m^2d
DO	> 5.0 mgO_2/L
pH	6.0-8.0
Temperature	25-35 °C
Initial nitrogen concentration	10 mg NH_4-N/L

G. Membrane biofilm reactor: The membrane bioreactor is distinctively characterized by a complete retention of biosolids within the bioreactor brought by membrane separation. This enables control of sludge retention time (SRT) independent of hydraulic retention time [Huang *et al.*, 2001]. Recently, the use of bioreactors with an immersed membrane has been developed. The membrane replaces the secondary clarifier of a conventional system [Delgado *et al.*, 2002] (Fig 2.14).

Treatment Detail Summary (see Table2.6 for more detail)

Volume	170 m^3
DO	4.0-5.0 mgO_2/L
pH	6.8-8.5

The number of work performed on the nitrification process is numerous and it is considered too lengthy to include full detail of these investigations here. Hence, a clear description of each of the work on the nitrification systems are provided in a tabulated form in Table 2.6 which is considered to be adequately concise and descriptive. Advantages and disadvantages of each process are given in Table 2.7

2.4 Three-phase Airlift Reactor (TPAL): Introduction

A number of chemical and biological reactions and effluent treatment processes involve handling of gas-liquid-solid three-phase systems. The solids are either catalyst particles or microorganisms in the form of granules, supported enzymes or immobilized microbes. The biological aerobic systems essentially use air to supply the dissolved oxygen. The reaction takes place in aqueous phase containing gas, which is in intimate contact with the solid particles. For design and operating purposes, most of these papers focused on effects of various parameters, both geometrical and operational, on TPAL performance. These parameters include superficial gas-liquid velocities, cross-sectional area ratio between downcomer and riser, solid loading, solid density, sparger location, column diameter, draft tube height, etc. A mini review of these works is given in Table 2.7.

Past work on the hydrodynamics of TPALs includes the work of Fan *et al.* [1984] who reported that at low gas velocity the solids were not suspended in the liquid and formed a packed bed at the base of the reactor; they referred to this as "packed-bed mode". As the gas velocity increased they observed a "fluidized bed mode" in which substantial liquid recirculation occurred and served to suspend the solids in the riser zone. At adequately high gas velocity, this fluidized bed expanded to the top of the draft tube, and the solids began to recirculate with the liquid through the annular region the "circulating bed mode". Koide *et al.* [1984] investigated the critical gas velocity required

for solids suspension (equivalent to the gas velocity at the stall point) in a TPAL reactor, and also the overall gas holdup and gas-liquid mass transfer coefficient. The critical gas velocity was determined by supplying gas at sufficiently high velocity to suspend all solid particles in the recirculating bed mode, and then slowly decreasing gas velocity to the point where the reactor stalled. They concluded that the critical gas velocity increased with increasing particle settling velocity and solid concentration, and that solid particles were suspended at much lower gas velocities in the TPAL system than would be the case in an equivalent bubble column. Smita and Jo.Shi [1992] who found that an increase in gas velocity (in the range of 0.01-0.1 m s^{-1}) resulted in a higher liquid circulation rates even at 50% solid hold up. Lu and Hwang [1995] observed that the ratio between gas hold-ups in downcomer and riser decreased from 0.88 to 0.68 with an increase in the solid hold-up from 0 to 30% v/v. This experiment was performed with the solid phase with a similar density to water (alginate beads with density of 1030 kg/m^3). Benthum *et al.* [2000] described that the gas hold-up decreased with increasing solid hold-up, irrespective of the density and diameter of the particles and the solid hold-up. At high solid hold-ups (more than 20%) the gas hold-up decreased considerably due to increased air bubble coalescence.

In terms of gas-liquid mass transfer, Nikov and Delmas [1987] reported that the mass-transfer coefficient in TPALs increased with the gas flow rate. This influence was more obvious for light particles at liquid velocities close to the minimum fluidization conditions. Nikov and Delmas [1992] demonstrated that superficial gas-liquid velocities caused changes in the velocity gradient close to the particle surface. In this case, each sphere was surrounded by a gas-liquid mixture, of lower homogeneous density, thus increasing the particle terminal velocity, which in turn affected positively the liquid-solid mass transfer coefficients. Nicolella *et al.*[1998] observed that the gas-liquid mass transfer coefficient of oxygen (k_La) in a three-phase biofilm airlift suspension reactor decreased proportionally with an increase in solid hold-up.

Turning now to other aspects of TPALs, Smita and Jo.Shi [1992] showed that ALFR (airlift fluidized bed reactor) was very much more attractive than the conventional three-phase fluidized bed because of its low power requirements and low levels of shear stresses. The power requirement of the ALFB was very low (less than 0.5 kW/m^{-3}) compared to that of the Three Phase Reactor or TPR (4-10 kW/m^{-3}) for a similar solid-

liquid interfacial area. The level of shear stress in the ALFB was found to be two to three times lower than those generated in the TPR. Hence, the ALFB is expected to be a promising multiphase contactor for handling biological reactions.

Table 2.1 Specific growth rate of nitrifiers in various systems (ammonium oxidizers, except where stated)

Sewage-sludge (pH 7.5-8)			
20 ^{0}C		10 ^{0}C	
μ_{max} (d^{-1})	Reference	μ_{max} (d^{-1})	Reference
>0.5	Lawrence and Brown (1976)	0.3	Hall (1974)
0.42-0.59	Hall (1974)	0.25	Lawrence and Brown (1976)
0.46	Cole (1983)	0.14	Hall (1974)
(0.19-0.23)			
<0.37	Boon and Burgess (1974)		
0.34(0.5)	Hall and Murphy (1980)		
0.25-0.42	Painter and Loveless		
(0.19-0.32)	(1983)		
Enriched system			
0.3	Stover *et al.* (1976)		
0.56	Stensel *et al.* (1976)		

Table 2.2 Effect of temperature on specific growth rate of nitrifying microorganisms

	Ammonium oxidizers		Nitrite oxidizers	
	μ_{max} (d^{-1})	Reference	μ_{max} (d^{-1})	Reference
20°C	0.5	Hall and Murphy (1980)	0.56	Hall and Murphy (1980)
	0.65	Jones and Paskins (1982)		
	0.94	Buswell *et al.* (1954)		
25°C	0.69-0.88	Loveless and Painter (1968)		
	1.5	Engel and Alexander (1958)		
30°C	1.51	Skinner and Walker (1961)		
32°C			1.3	Boon and Laudelout (1962)

Table 2.3A Dependency of nitrification on dissolved oxygen

Concentration of dissolved oxygen (mg/L^{-1})	Extent of nitrification in activated sludge	Reference
0.2	None	Downing and Scragg(1958)
0.3	≈50% nitrification	
0.5	Full	
1, 4, 7	Full, at 8 days SRT	Wuhrmann (1963)
4, 7	Full, at 4 days SRT	
7	None, at 0.8 days SRT	
0.9	60% at 6 days SRT	Jones *et al.* (1969)
0.9	80-90% at 8 and 11 days SRT	
1.8, 3.6, 7.2	≈90% at 6, 8 and 11 days SRT	
1-2	Full, at 10 days SRT	Lee and Johnson (1979)
<1.5	None SRT not stated	Case (1984)
>3	Full	

SRT = sludge retention time (sludge age)

Table 2.3B Saturation constant* for dissolved oxygen utilization by nitrifying bacteria

Saturation constant for DO, $K_{s\,(DO)}$ (mg/L^{-1})	Remarks	Reference
0.25-0.3	Pure culture, *Nitrosomonas*	Loveless and Painter (1968) Peeters *et al.* (1969)
0.3-0.7	Pure culture, *Nitrobacter*	See Stenstrom and Poduska (1980)
0.8-2.5	*Pure culture, Nitrobacter*	Peeters *et al.* (1969)
0.3	Activated sludge	Loveless and Painter (1968)
0.4	Activated sludge	Stankewich (1972)
2.0	Activated sludge	Nagel and Haworth (1969)

*Assume Monod kinetics

Table 2.4 Compounds giving substantial inhibition of ammonium oxidation by activated sludge in batch tests [Tomlinson *et al.*, 1966 ; *Wood et al.*, 1981; Hockenbury and Grady, 1977; King and Painter, 1985]

≈1 mg/L	≈10 mg/L	≈20 mg/L	20-100 mg/L	>100 mg/L
Thiourea	Methyl thiuronium sulphate	Na dimethyldithiocarbamate	Piperidinium cyclopenta Methylene dithiocarbamate	Dicyandiamide
Allylthiourea	Aniline	Tetramethylthiuramthiocarbamate	Benzyl thiouronium chloride	Trimethylamine HCl
Thiosemicarbazide	1-Naphthylamine	Na cyclopentamethylene-thiocarbamate	Tetramethylthiuram disulphide	Triethylamine
Thioacetamide	Ethylene diamine	Na cyclopentamethylene-dithiocarbamate	Benzthiazole disulphide	Benzylamine
Na methyldithiocarbamate	Quinoline	Guanidine carbonate	Diguanide	Ninhydrin
Dithio-oxamide	Skatole	Naphthyl ethylenediamine	Hydrazine	Benzocaine
Methyl isothiocyanate	Phenol	Pyridine	Hexamethylene diamine	Strychnine HCl
Mercaptobenzthiazole	*P*-Benzoquinone	2,2-Bipyridine	*P*-Nitraniline	2,4,6-Tribromophenol
Allyl isothiocyanate		*o*-,*p*-,*m*-Cresols	*P*-Amino propiophenone	K thiocyanate[300]
Dodecylamine		Allyl alcohol	*P*-Phenyl azoaniline	Methylene blue[100]
N-methyl aniline		Chloroform	Benzidine dihydrochloride	EDTA[350]
Na cyanide		Cetyl trimethyl ammonium	2-Chloro-6 (trichloromethyl)pyridine	Streptomycin[400]
			8-Hydroxy-quinoline	Methylaniline HCl[1550]
			Cetyl pyridinium chloride	
			Diallyl ether	
			Na azide	
			Carbon disulphide	
			P-Nitrobenzaldehyde	
			Dichlorophen	

Table 2.5 Optimal level of various parameters for nitrification

Factors	Reference	Optimal Value
pH	Shammas, 1986	8.5
	Shrestha *et al.*, 2002	7.0-8.0
	Wild *et al.*, 1971	7.8-8.9
	Skadsen *et al.*, 1996	7.0-8.0
Temperature	Watson and Valos, 1981	25-35 °C
	Wild *et al.*, 1971	35 °C
	US. EPA, 1994	35-42 °C
	Focht and Verstraets, 1977	25-30 °C
	Buswell *et al.*, 1954	35 °C
	Nelson, 1980	35-42 °C
	WEF, 1998	30-36 °C
Dissolved oxygen	Shammas, 1986	2 mg/L
	Skadsen *et al.*, 1996	1 mg/L
	Wild, 1971	>1 mg/L
	Dincer, 2001	2.5 mg/L
Ammonia concentration	US. EPA, 1975	>2.5 mgNH_4Cl/L
Organic carbon (C/N)	Dincer *et al.*, 2001	<0.25
	Shammas, 1986	<1.5
	Zhu and Chen, 2001	0
Toxic	WEF, 1998	NH_4 < 1000 mg/L
		NaCl < 35000 mg/L
		H_2S < 50 mg/L
		Chlorine < 1 mg/L
		Ethanol < 2400 mg/L
		Methanol < 160 mg/L
Salinity	Dincer, 2001	< 3%
	Nihof and Bovendeur, 1990	< 34 ppt

Table 2.6 Detail on the operation of various types of nitrification processes

References	Nitrification rate (gN/m^2-d)	Type volume (m^3)	Packing	Flow rate (L/min)	Retention time (min)	DO (mgO_2/L)	Specific surface area (m^2/m^3)	pH	Temperature (°C)	Salinity (%)	$NH_4 - N$ ($mgNH_4$-N/L)
Trickling filter											
Greiner and Timmons (1998)	0.94 -3.92	0.06	Commercial	b.		>5.0	164	6.7	26.4		
Arbiv and Rijn (1995)	0.149	2		250	0.02	5.8-7.2	200	7.0-7.9	22.5-27		2
Lakang and Kleppe (2000)	0.1-0.2		Finturf articial glass Kaldnes rings Plastic rings Leca (Clay)	0.5	2.98	6.7-10.7	248 500 220 500 -1000	6-7	14-16		1.5
Knosche (1994)	0.4			b.			200	7	25		5
Kamtra (1998)	0.24-0.55			b.		7.0-8.0	100-150	7	22-24		
Singh and Ebeling (1999)		2	Polyethylene	150	0.005	5.75-6.92			23.19		
Nijhof (1995)	0.22(38.2%)	3.0	Sieve screen	3458.33	2.49*10-5	7.4-8.2	200	7.0-7.5	25		0.5-5
Otte and Rosenthal (1979)	0.75	1.06	Plastic foil fiter	83.33	2.5*10-5	6.0-7.5	480	8.2	20	8	15
Rogers (1985)	0.012	0.04	Slag	0.16	0.342	5.0-6.0	18.3	7.1-8.5	25.5-30.0	20	9.3
Submerged filter											
Menasveta et al. (2001)	0.068	6	Plastic ball	b.				7.5			2
Bower (1982)	91%	3	Limestone	b.				8.32	25.3	30	6.23

Table 2.6 (cont.)

References	Nitrification rate (gN/m^2-d)	Type volume (m^3)	Packing	Flow rate (L/min)	Retention time (min)	DO (mgO_2/L)	Specific surface area (m^2/m^3)	pH	Temperature (°C)	Salinity (%)	$NH_4 - N$ ($mgNH_4$-N/L)
Strotmann and Windecker (1997)	19mg/L h (100%)	1.5	Raschig ring	6.25	240	3		7			
Shanableh and Hijazi (1998)	1.5		Polypropylene	b.		5.0-7.0	115				8.0-9.0
Abeysinghe et al. (1996)							141				
MacMillan et al. (1994)	0.083	2.3	Polyester&charcoal	7	328.57			8.0-8.4	22	27-31	10
Davis and Arnold (1998)	0.59	0.72	Poiypropylene	280	25.714	10.2	223.1				
Nijhof and Bovendeur (1990)	0.28	3.5	Plastic	b.			200		24	17-34ppt	
Tschui et al. (1994)	0.48		Biocarbon	3.0-4.0			1450		10		
	1.43		Polystyrenr	6.0-7.0	1.97*10-5		1050		10		
	1.67		Plastic	>10	1.47*10-5		240		10		
Zhu and Chen (2001)		2.5	Plastic	0.11	22.3	6	623	7.7	20		
Tseng (1998)	0.23	0.72	Plastic	b.	20	3.6	150	7.48-7.96	32	33ppt	3.64
Koller and Avtalion (1985)			Gravel	0.09	3.0-5.0	3.4-5.6		6.9-7.5	26-28		3
MacMillan et al. (1994)		0.35	Activated carbon	7				8-8.4	22-24	26-30	
Yang et al. (1989)	0.69		Crush oyster shell	81				8	30	34-36	
Yang et al. (2001)			Plastic&carbon	70	150	5	80-300	6.0-9.0	0	0	1

Table 2.6 (cont.)

References	Nitrification rate (gN/m^2-d)	Type volume (m^3)	Packing	Flow rate (L/min)	Retention time (min)	DO (mgO_2/L)	Specific surface area (m^2/m^3)	pH	Temperature (°C)	Salinity (%)	NH_4 – N ($mgNH_4$-N/L)
Menasveta (1991)			Plastic	b.		5.0-6.0		7.0-8.0	27-29	30	
Millamena et al. (1994)		0.1	Sand, gravel & rock	b.	1.6	>4		7.8-8.3	28-31	30-32.5	
Tseng et al. (1998)		0.72		36	20	5.4-6.9		7.5-8.0	29-33	33	
Sastry et al. (1999)			Polyethylene	30-41		>2.0			26-30		
Wickins (1985)	0.43		Plastic	0.083			160-200		28	20-34	0.2
Airlift reactor											
Benthum et al. (1998)	1.25	0.003	Basalt	0.465l/h	240	>3.0		7.5	30		5
Sakairi et al. (1996)	1.3	0.0157	Polyethyleimine	b.		5		8.1-8.4	28		1.3
Millamena et al. (1994)						3.6					
Seo and Kim (2001)	2	2.5		0.1vvm.	48h	5.2		7.8-8.2	25		
Benthum et al. (1999)	4.33	1.7	Basalt	7.0-8.0							4.37
Fluidized-bed filter											
Reyes and Lawson (1996)		170	Polyethylene			5.3	178	7.98	30.4		
Skjolstrup et al. (1998)		53					1000	7	17.6		2.2

Table 2.6 (cont.)

References	Nitrification rate (gN/m^2-d)	Type volume (m^3)	Packing	Flow rate (L/min)	Retention time (min)	DO (mgO_2/L)	Specific surface area (m^2/m^3)	pH	Temperature (°C)	Salinity (%)	$NH_4 - N$ ($mgNH_4$-N/L)
Activated sludge											
Campos et al. (1999)					13h				20		7.5
Campos et al. (2002)								7.6	20		
Batch CSTR						>2		7.8	20		3.3
Kim et al. (2000)	0.82		Ba-algenated		18	7.5-7.9			25		20
			Ca-algenated								
			Carageenan								
			Agar bead								
Sequency batch reactor											
Sliekers et al. (2002)	0.15	2			24h			7.8	30		14
Shrestha et al. (2002)								7.0-8.0	30		
Rotating biofilter Contactor (RBC)											
Rogers (1985)	0.06	0.04		0.08		5.0-6.0	18.3	7.8	25-30	20	10
Wortman and Wheaton (1991)								7.5-8.5	25		

Table 2.6 (cont.)

References	Nitrification rate (gN/m^2-d)	Type volume (m^3)	Packing	Flow rate (L/min)	Retention time (min)	DO (mgO_2/L)	Specific surface area (m^2/m^3)	pH	Temperature (°C)	Salinity (%)	$NH_4 - N$ ($mgNH_4$-N/L)
Reyes and Lawson (1996)		5.12	Polyethylene			5.3	178	7.98	30.4		
Schuster and Stelz (1998)		0.12						6.0-7.0	15		
Biodrum											
Wortman and Wheaton (1991)		0.009				5.8-7.1	278.83	8	25		7.95
Rogers (1985)	0.05	0.04	Slag	0.08		5.0-6.0	18.3	7.8	25-30	20	10
Ponds											
Gross et al. (2000)	0.7										5.9
Immobilized in porous carrier											
Sakairi and Yasuda (1996)		0.0157	Cellulose carrier	0.052		5		8	28		
Greiner and Timmons (1998)						>5		6.0-7.0	26.4		
Kim et al. (2000)	8.2		Alginate		0.3h				55		
Seo and Kim (2001)	70				12h				25		10
Membrane biofilm reactor											
Huang et al. (2001)					5h	4.0-5.0		6.8-7.2			
Delgado et al. (2002)		170						8.5			

b. operated batch type

Table 2.7 Disadvantages and advantages of various nitrification processes.

Reactor type	Disadvantage	Advantage
Trickling filter	1. High pumping cost for tall and narrow trickling filter [Nijhof, 1995]. 2. Strict control flow rate influent[Metcalf and Eddy, 1991]. 3. Relatively high incidence of clogging [Metcalf and Eddy, 1991].	1. Low maintenance. 2. Cheap installation. 3. Great tolerance of differences in hydraulic and organic loads. 4. Encourage oxygenation and removal of carbon. 5. Simple, reliable for a treatment system [Metcalf and Eddy, 1991]. 6. Moderate level of skill and technical expertise to manage and operate. 7. Appropriate for small-to medium-sized communities and onsite systems [Metcalf and Eddy, 1991; Nijhof, 1995]. 8. Trickling biofilter maintained higher DO levels as compared to the systems with bead biofilters.[Singh *et al.*, 1999]
Submerged filter	1. Solids collection and poor gas exchange in the submerged thin film filter [Metcalf and Eddy, 1991]	1. Decreased pumping costs. 2. Easient application of aerated biofilters. 3. Low area.
Airlift reactor		1. Good mixing and close contact between three phase , liquid , gas and solid [Benthum *et al.*, 1999]. 2. Sufficiently high oxygen transfer from the gas to the liquid [Benthum *et al.*, 1999]. 3. Well -mixed aerobic compartment [Benthum *et al.*, 1999]. 4. Low area. 5. Decreased pumping costs.

Table 2.7 (cont.)

Reactor type	Disadvantage	Advantage
Immobilized cell	1. High experience operate	1. Short start-up time [Kim *et al.*, 2000]. 2. Small reactor volumes and high flow rate.
Membrane reactor	1. Material was expensive 2. Needed to regenerate membrane 3. Higher maintenance	1. High pollutant removal and low sludge production[Delgado *et al.*, 2002]. 2. Membrane reactor lower than in a conventional activated sludge process [Huang *et al.*, 2001].
Rotating reactor	1. High pumping costs.	1. Selective nitrifier population [Strotmann *et al.*, 1997]. 2. Good drain off data and very stable operating mode [Wortman and Wheaton, 1991].
Activated sludge	1. Very large area 2. Needed to treated water being separated from the sludge in a setter.	1. Robust and easy to operate technology.
Fludised-bed reactor	1. Lower retention time. 2. High power pump.	1. Stable operation [Skjolstrup *et al.*, 1998]. 2. Self-cleaning effects over extended periods [Skjolstrup *et al.*, 1998]. 3. High specific surface area.

Table 2.8 Summary of hydrodynamic and mass transfer of three-phase internal airlift reactor

Reference	Equation	Packing		Media	Parameter	
		ρ(kg/m^3)	d_p(mm.)		Solid loading	Parameter ranges
F. Carla(2001)	$\frac{C^* - C_L}{C^* - C_{L0}} = 1 - E = \left(\frac{e^{-tk_L a}}{t_E} - k_L a e^{-(t/t_E)} \right) \frac{t_E}{1 - t_E k_L a}$	1023 and 1048	2.131and 2.151	Water, ethanol solution and Ca-alginate beads	0, 5, 10, 15, 20 and 30%	u_{sg} = 0.01-0.5 m/s
	$E = \frac{C_L - C_{L0}}{C^* - C_{L0}}$					
	$1 - E = \frac{e^{-tk_L a}}{1 - t_E k_L a} \qquad t >> t_E$					
	Water / high density solids :					
	$k_L a = \left(-0.33 u_{gr}^2 + 0.43 u_{gr} - 0.0064\right)$					
	$\times \left(-0.000080\ \varepsilon_s^2 - 0.0056\ \varepsilon_s + 0.17\right)$					
	Water / low density solids :					
	$k_L a = \left(-0.93 u_{gr}^2 + 1.33 u_{gr} - 0.012\right)$					
	$\times \left(-0.0000016\ \varepsilon_s^2 - 0.00099\ \varepsilon_s + 0.054\right)$					
	Ethanol / low density solids :					
	$k_L a = \left(-0.95 u_{gr}^2 + 1.34 u_{gr} - 0.021\right)$					
	$\times \left(-0.000072\ \varepsilon_s^2 + 0.00079\ \varepsilon_s + 0.075\right)$					
	Ethanol / high density solids :					
	$k_L a = \left(-0.78 u_{gr}^2 + 1.20 u_{gr} - 0.021\right)$					
	$\times \left(-0.000074\ \varepsilon_s^2 - 0.0035\ \varepsilon_s + 0.081\right)$					

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		$\rho(kg/m^3)$	d_p(mm.)		Solid loading	Parameter ranges
Livingston and Zhang (1993)	$U_{LR}=\left(\frac{2gH_D(\varepsilon_{GR}-\varepsilon_{GD})}{\frac{K_T}{(1-\varepsilon_{GR})^2}+K_B\left(\frac{A_R}{A_D}\right)^2\frac{1}{(1-\varepsilon_{GD})^2}}\right)^{0.5}$	1000-2950	0.11-0.155	Water and glass beads		H = 1and 2 m. u_{sg} = 0.07-0.09 m/s u_t=0.0089-1.193
	$\rho_{HD}=\frac{(1-\varepsilon_{GD}-\varepsilon_{SD})\rho_L+\varepsilon_{SD}\rho_S}{(1-\varepsilon_{GD})}$					
	$=\rho_L+\frac{Wf_D}{V_D(1-\varepsilon_{GD})}\left(1-\frac{\rho_L}{\rho_S}\right)$					
	$P_{available}=gH_D\{[\rho_{HD}(1-\varepsilon_{GD})+\rho_G\varepsilon_{GD}]-[\rho_{HR}(1-\varepsilon_{GR})+\rho_G\varepsilon_{GR}]\}$					
	$if \quad \rho_{HD},\rho_{HR}>>\rho_G$					
	$P_{available}=gH_D[\rho_{HD}(1-\varepsilon_{GD})-\rho_{HR}(1-\varepsilon_{GR})]$					
	$P_{loss}=\frac{1}{2}\rho_{HD}K_BV_{LD}^2+\frac{1}{2}\rho_{HR}K_TV_{LR}^2$					
	$V_{LD}=\frac{U_{LR}}{(1-\varepsilon_{GD}-\varepsilon_{SD})}\frac{A_R}{A_D}$					
	$V_{LR}=\frac{U_{LR}}{(1-\varepsilon_{GR}-\varepsilon_{SR})}$					
	$U_{LR}=\left(\frac{2gH_D[\rho_{HD}(1-\varepsilon_{GD})-\rho_{HR}(1-\varepsilon_{GR})]}{\frac{\rho_{HD}K_T}{(1-\varepsilon_{GR}-\varepsilon_{SR})^2}+\rho_{HD}K_B\left(\frac{A_R}{A_D}\right)^2\frac{1}{(1-\varepsilon_{GD}-\varepsilon_{SD})^2}}\right)^{0.5}$					

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		$\rho(kg/m^3)$	$d_p(mm.)$		Solid loading	Parameter ranges
	$V_{SD}=\frac{U_{LR}}{(1-\varepsilon_{GD}-\varepsilon_{SD})}\frac{A_R}{A_D}+U_t$					
	$V_{SR}=\frac{U_{LR}}{(1-\varepsilon_{GR}-\varepsilon_{SR})}-U_t$					
	$t_R=\frac{H_D}{V_{SR}},\ t_D=\frac{H_D}{V_{SD}}\ ;\ t_{total}=t_R+t_D$					
	$f_R=\frac{t_R}{t_{total}},\ f_D=\frac{t_D}{t_{total}}\ ;\ f_R+f_D=1.0$					
	$\frac{f_R}{1-f_R}=\frac{V_{SD}}{V_{SR}}=\frac{\left(\frac{U_{LR}}{(1-\varepsilon_{GD}-\varepsilon_{SD})}\frac{A_R}{A_D}+U_t\right)}{\left(\frac{U_{LR}}{(1-\varepsilon_{GR}-\varepsilon_{SR})}-U_t\right)}$					
	$U_{LR}=\frac{(1+\phi)U_t}{\left(\frac{\phi}{(1-\varepsilon_{GR}-\varepsilon_{SR})}-\frac{1}{(1-\varepsilon_{GD}-\varepsilon_{SD})}\frac{A_R}{A_D}\right)}$					
	$\varepsilon_{GR}=\frac{U_{GR}}{U_{bo}+f(U_{LR})}\ ,\ U_{LR}=\frac{4V_T}{t_r\pi d_D^2}\ ,\ \varepsilon_{GR}=\frac{U_{GR}}{0.45+1.1(U_{GR}+U_{LR}+U_{SR})}$					

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		$\rho(kg/m^3)$	d_p(mm.)		Solid loading	Parameter ranges
Calvo E. et al (1999)	$\bar{V}_{LR} = \frac{(1-\varepsilon_{SD})A_D}{(1-\varepsilon_G-\varepsilon_{SR})A_R} V_{LD}$ $\varepsilon_G = \frac{J_{GM}}{U_s + 0.5V_{LC} + V_{LR}}$ $V_{LC} = \frac{\left(V_{LO} - \bar{V}_{LR}\right)}{(1-\varepsilon_G-\varepsilon_{SR})}\left(\frac{N}{N+2}\right)$ $\varepsilon_{SR} = \varepsilon_S^0 \frac{V_{LD}+U_t}{V_{LD}+V_{LR}}$ $\varepsilon_{SD} = \varepsilon_S^0 \frac{A_R}{A_D}\frac{V_{LR}+U_t}{V_{LD}+V_{LR}}$ $\varepsilon_G - \left(\frac{\rho_s}{\rho_L}-1\right)(\varepsilon_{SR}-\varepsilon_{SD}) \geq 0$	2550-3700	0.1-3	Water and glass beads	40, 70 and 100 kg/m3	D_r = 0.172m A_D/A_r=1.06 H = 0.7 m.
Benthum et al (2000)		1050 and 2485	1.2and0.29	Water and polystyrene micro-granulate , silver sand	2.1-10.1% v/v	u_{sg} = 0.0124-0.061 m/s u_t=0.33 and 0.016 m/s

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		ρ(kg/m^3)	d_p(mm.)		Solid loading	Parameter ranges
Tobajas et al(1999)	$\bar{V}_{LR} = \frac{(1-\varepsilon_{SD})A_D}{(1-\varepsilon_G-\varepsilon_{SR})A_R} V_{LD}$ $\varepsilon_G = \frac{J_{GM}}{U_s + 0.5V_{Lc} + \bar{V}_{LR}}$ $V_{LC} = \left(\frac{\left(V_{L0} - \bar{V}_{LR}\right)}{1-\varepsilon_G-\varepsilon_{SR}}\right)\left(\frac{N}{N+2}\right)$ $\varepsilon_{SR} = \varepsilon_s^0 \frac{V_{LD}+U_t}{V_{LD}+V_{LR}}$ $\varepsilon_{SD} = \varepsilon_S^0 \frac{A_R}{A_D}\frac{V_{LR}-U_t}{V_{LD}+V_{LR}}$ $K_L = \frac{2}{\sqrt{\pi}}\sqrt{\frac{D_L}{\theta}}$ $a = \frac{6\varepsilon_G}{d_b(1-\varepsilon_G)}$ $K_L a = \frac{2}{\sqrt{\pi}}\sqrt{D_L}\left(\frac{U_s\rho_L g\varepsilon_G}{\mu}\right)^{1/4}\frac{6\varepsilon_G}{d_b(1-\varepsilon_G)}$	2200		Seawater and marine sediment	5-25%	A_D/A_r=1.0-0.65 H = 1.5 m. u_{sg} = 0.02- 0.1 m/s
Smita and Jo Shi (1992)	$Ga = \{d_p^3\rho_L(\rho_L-\rho_s)g\}/\mu^2$ $\mathrm{Re}_\infty = Ga/18$ $= (Ga/18)^{0.8}$ $= 0.45Ga^{0.61}$ $= 1.732Ga^{0.5}$	700	3	Water		A_D/A_r = 0.25-2 H/D = 5-80 u_{sg} = 0.01-0.1 m/s L_R/L = 0-0.4 $Ga < 1.8$ $1.8 < Ga < 2600$ $2600 < Ga < 3.3\times10^5$ $Ga > 3.3\times10^5$

Table 2.8(cont.)

Reference	Equation	Packing ρ(kg/m^3)	Packing d_p(mm.)	Media	Parameter: Solid loading	Parameter: Parameter ranges
	$n = (4.6 + 19.5 d_p / D)$					$Re_\infty < 0.2$
	$= (4.35 + 17.5 d_p / D)\,Re_\infty^{-0.03}$					$0.2 < Re_\infty < 1.0$
	$= (4.45 + 18.0 d_p / D)\,Re_\infty^{-0.1}$					$1.0 < Re_\infty < 200$
	$= 4.45\,Re_\infty^{-0.1}$					$200 < Re_\infty < 500$
	$= 2.39$					$Re_\infty > 500$
	$V_{hin} = V_\infty (1-\epsilon_s)^n$					
	$Sh = 0.5(Re)^{2/3}(Sc)^{1/3}$					$Re_\infty > 500$
	$Sh = 1.2(Re)^{1/2}(Sc)^{1/3}$					$1 < Re_\infty < 500$
	$Re = d_p u' \rho_L / \mu$; $u' = 0.33 V_\infty$					
	$Sc = \mu / \rho_L D_M$					
	$Sh = k_{SL} d_p / D_M$					
	$\alpha = \frac{1}{2[1/k_L A + 1/2Q_L]}$					
	$\beta = \frac{1}{2[1/K_{SL} A_p - 1/2Q_L]}$					
	$V_{GC} = 5.73 U_\infty^{0.52} \epsilon'^{\,s\,0.54}$					
	$u' = 1.5 U_h \epsilon_s / (1-\epsilon_s)$					

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		ρ(kg/m^3)	d_p(mm.)		Solid loading	Parameter ranges
Nikov and Delmas (1987)	$K = \frac{I}{n_e F S C_A}$	1.34, 2.52, 2.56 and 8.15	10000 and 3000	$2*10^{-3}$M in potassium ferricyanide and potassium ferrocyanide in 0.5N sodium hydroxide solution and plastic spheres, glass spheres		Sc = 1540 V_L = 11 and 20 $*10^{-2}$ m/s
	$Sh = \frac{Kd}{D} = \frac{Id}{n_e F S C_A D}$					
	$Sh = 0.253\ \mathrm{Re}^{0.004} Ga^{0.319} Mv^{0.299} Sc^{0.400}$					$1.6 < \mathrm{Re} < 1316$
	$Sh = 0.31 (GaMvSc)^{1/3}$					$2740 < Ga < 4.42\times10^6$
	$Sh = Sh_0 \left(1 + A_2 Mv^{\alpha 2} \left(U_G^2 / gd\right)^{\beta_2}\right)$					$0.27 < Mv < 1.14$
	$Sh = Sh_0 \left(1 + A_1 Mv^{\alpha 1} \left(U_G / U_L\right)^{\beta_1}\right)$					$305 < Sc < 1450$
	$Sh = Sh_0 \left[1 + 0.21\, Mv^{-0.61} \left(U_G / U_L\right)^{0.70}\right]$					
	$Sh = Sh_0 \left[1 + 0.43\, Mv^{-0.87} \left(U_G^2 / gd\right)^{0.42}\right]$					
	$Sh_0 = B(GaMvSc)^{1/3}$					
	$Sh = 0.33(GaMvSc)^{1/3}\left[1 + 0.4 Mv^{-0.57} \times \left(U_G / U_L\right)^{0.77}\right]$					$0.11\times10^6 < Ga < 157\times10^6$
	$Sh = 0.33(GaMvSc)^{1/3}\left[1 + 0.46 Mv^{-0.77} \times \left(U_G^2 / gd\right)^{0.41}\right]$					$0.27 < Mv < 7.07$
	$3.10 < d < 10 \times 10^{-3}\ m$					$860 < Sc < 19900$
	$1340 < \rho_s < 8150\ \ kg / m^3$					$0 < U_G / U_L < 3.9$
	$5 \times 10^{-2} < U_L < 25 \times 10^{-2}\ m / s$					$0 < U_G^2 / gd < 6.28$
	$0 < U_G < 43 \times 10^{-2}\ m / s$					
	$0.80 \times 10^{-6} < \nu < 3.40 \times 10^{-6}\ m^2 / s$					
	$1.70 \times 10^{-6} < D < 9.31 \times 10^{-10}\ m^2 / s$					
	$0.050 < d_c < 0.094\ \ m$					
	$1020 = \rho < 1040\ \ kg / m^3$					

Table 2.8(cont.)

Reference	Equation	Packing		Media	Parameter	
		ρ(kg/m^3)	d_p(mm.)		Solid loading	Parameter ranges
Nikov and Delmas (1992)	$K_a = 0.807 \left(\frac{D^2 S}{L_e} \right)^{1/3}$ $L_e = 0.820\ d_e$ $C_{Df} = \frac{F_f}{\pi R^2 0.5 V_L^2 L \rho_L}$ $C_x = 0.133 \left(1 + \frac{150}{\mathrm{Re}} \right)^{1.565} + 4Tu$ $\mathrm{Re}_r = \left(\frac{4}{3} \frac{Ga\ Mv}{C_x} \right)^{1/2}$	10 and 1.8	1260 and 1340	5*10^{-3}M in potassium ferricyanide and potassium ferrocyanide in 0.5N sodium hydroxide solution and plastic spheres, glass spheres		$50 < \mathrm{Re} < 700$ $0.07 < Tu < 0.5$
	$Sh = 0.956\ \mathrm{Re}^{0.485}\ Sc^{0.312} \left(1 + 0.129\ \mathrm{Re}^{0.37}\ Tu^{1.32} \right)$					$170 < \mathrm{Re} < 700$ $Tu < 0.50$
	$Sh = 0.253\ \mathrm{Re}^{0.004}\ Ga^{0.319}\ Mv^{0.299}\ Sc^{0.400}$					
S.Jiasen(1999)		6.35	1160	Water, polycarbonate spheres		V_L = 1.68, 2.08cm/s

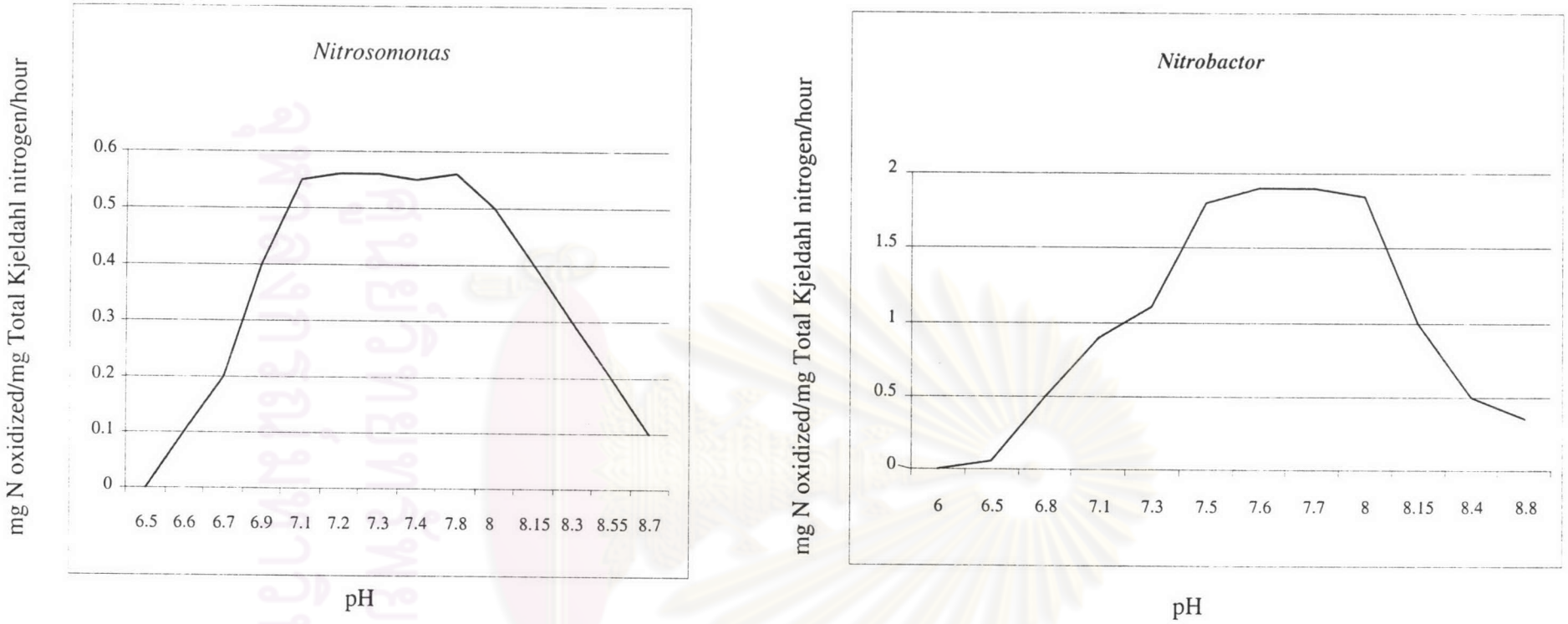

Figure 2.1 Effects of pH on nitrification rates by *Nitrosomonas* and *Nitrobactor* enrichment cultures [Grady and Lim,1980]

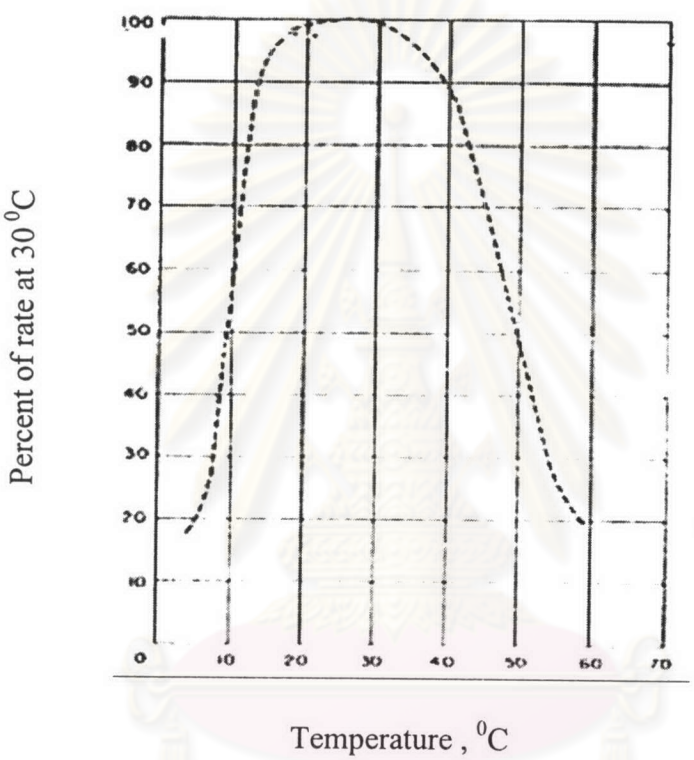

Figure 2.2 Effect of temperature on nitrification rate compared to the rate at 30°C [Wild *et al.*, 1971]

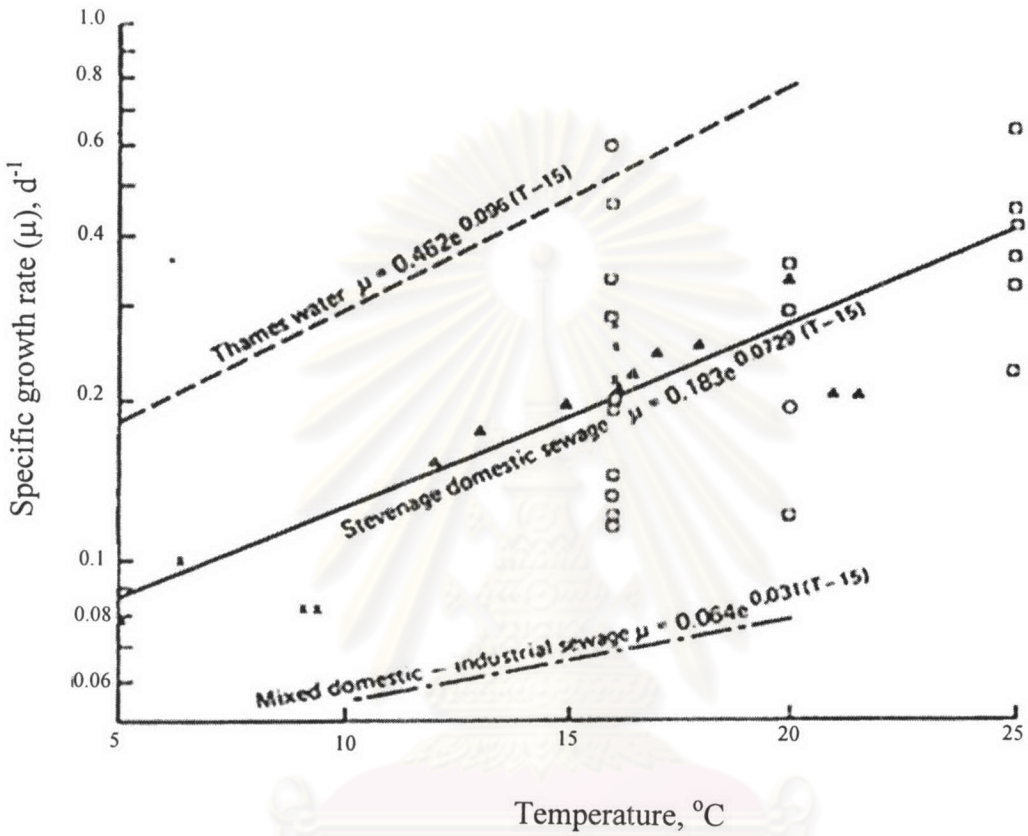

Figure 2.3 Specific growth rate of *Nitrosomonas* at various temperature in Thames water and in sludge grown on sewage [Painter and Loveless, 1983]

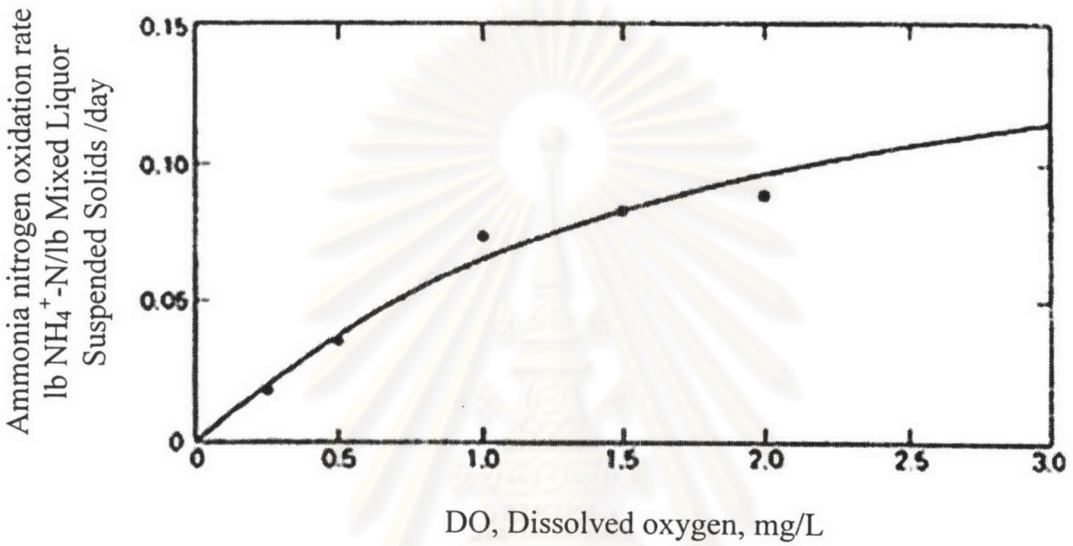

Figure 2.4 Effect of dissolved oxygen on nitrification rate at 30 ^{0}C [Nagel, and Hawort, 1969]

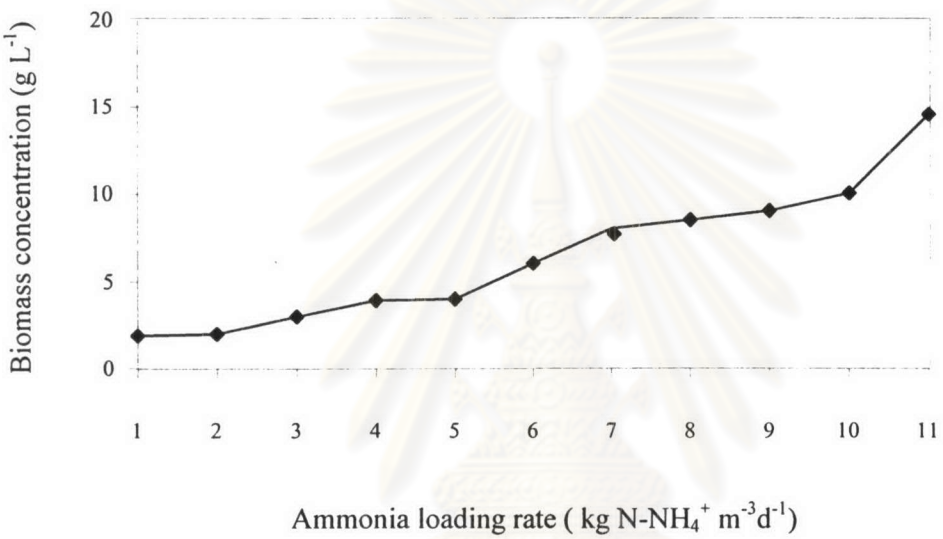

Figure 2.5 Effect of ammonia loading rate on biomass concentration [Campoas *et al.*, 1999]

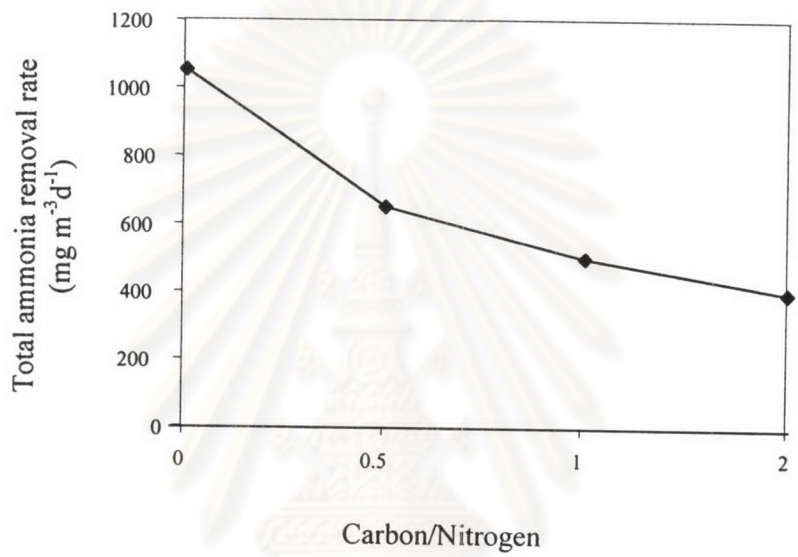

Figure 2.6 Effect of C/N ratio on nitrification rate [Zhu *et al.*, 2001]

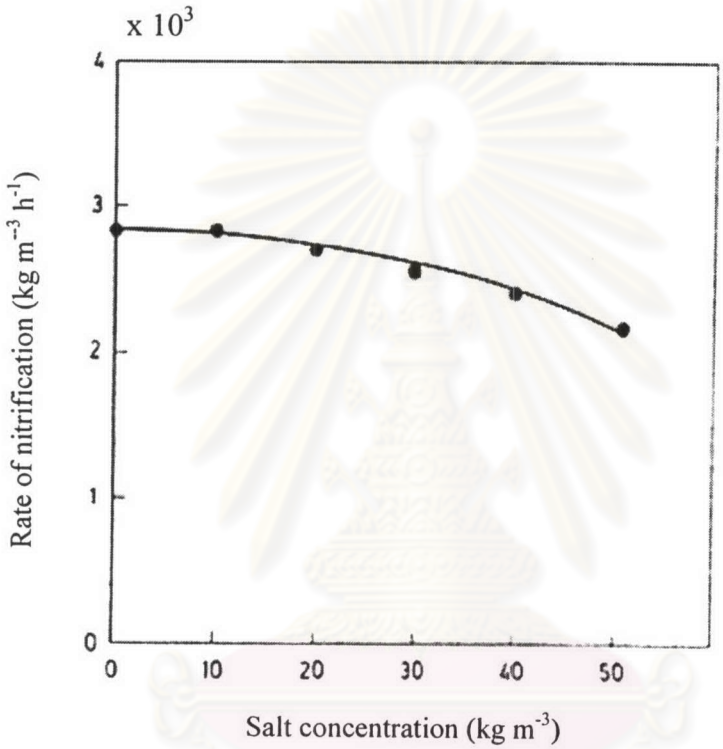

Figure 2.7 Variation of nitrification efficiency with salt content [Dincer *et al.*, 2001]

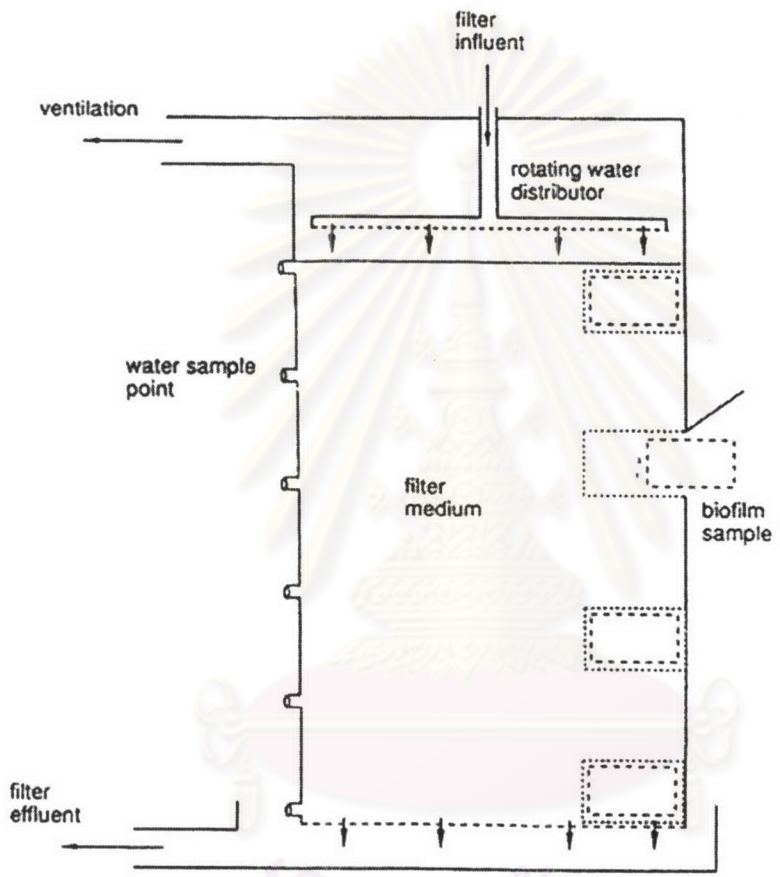

Figure 2.8 Trickling filter for nitrification [Nijhof, 1995]

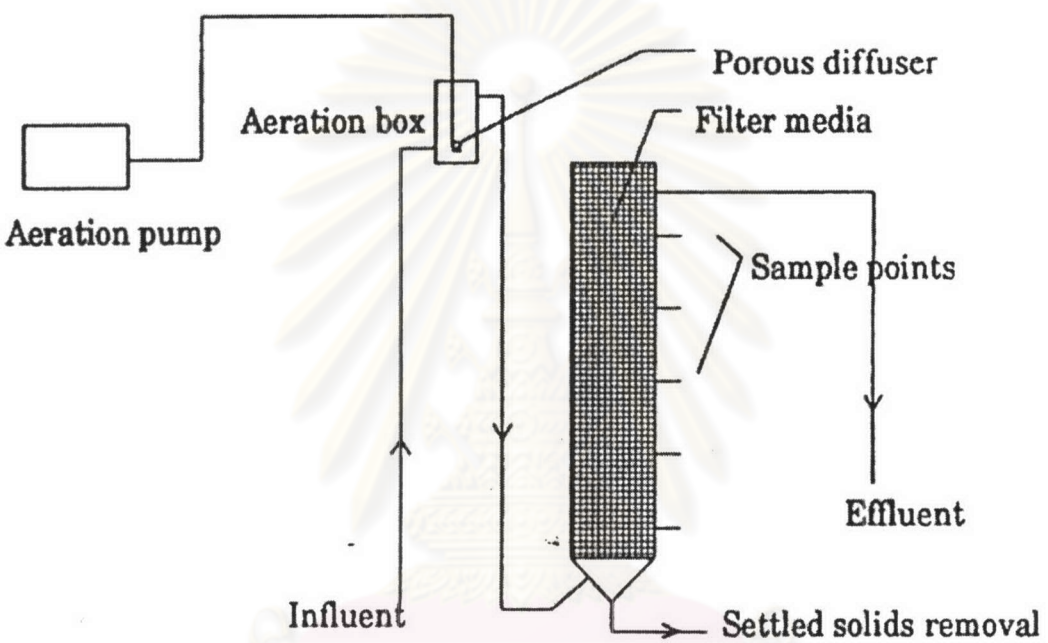

Figure 2.9 Submerged filter for nitrification [Abeysinghe, 1996]

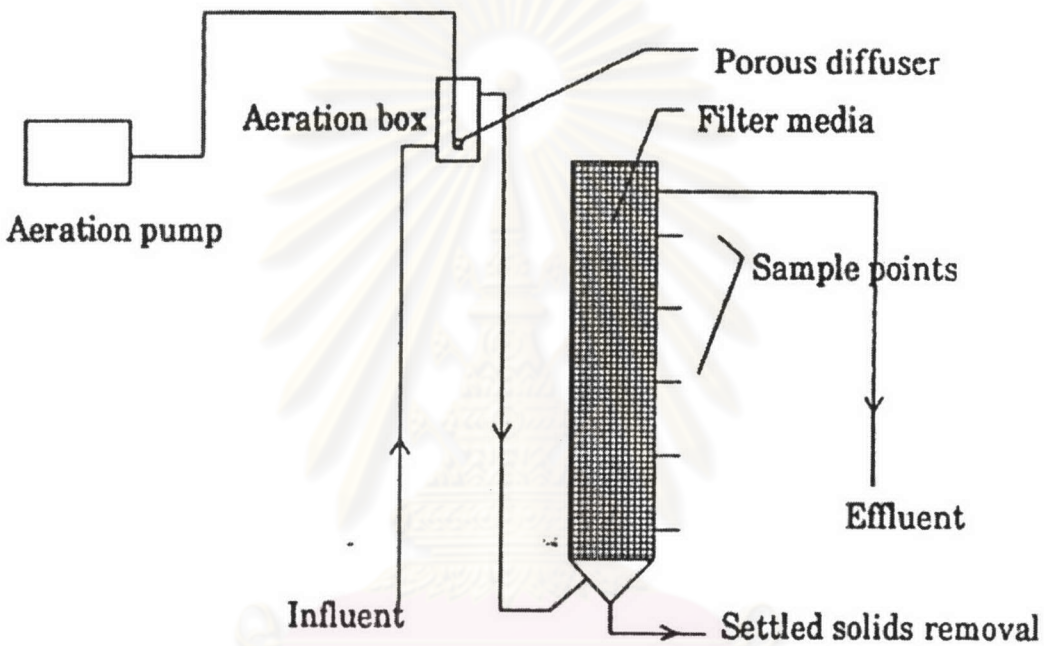

Figure 2.9 Submerged filter for nitrification [Abeysinghe *et al.*, 1996]

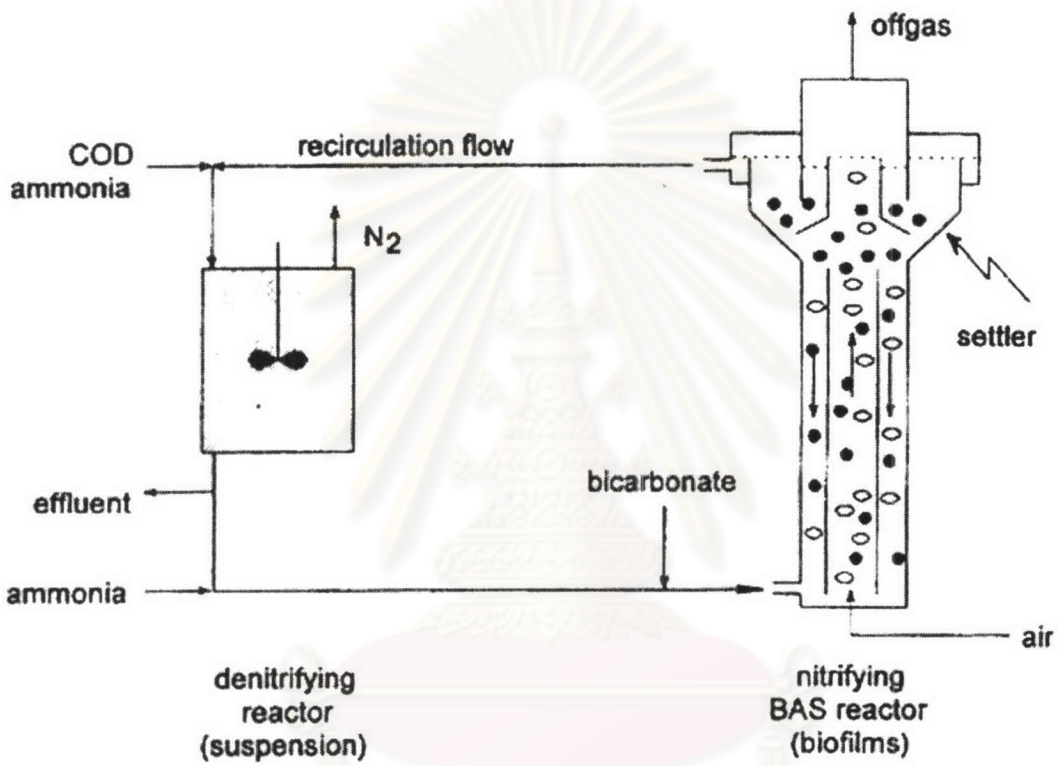

Figure 2.10 Airlift bioreactor for nitrification [Benthum *et al.*, 1997]

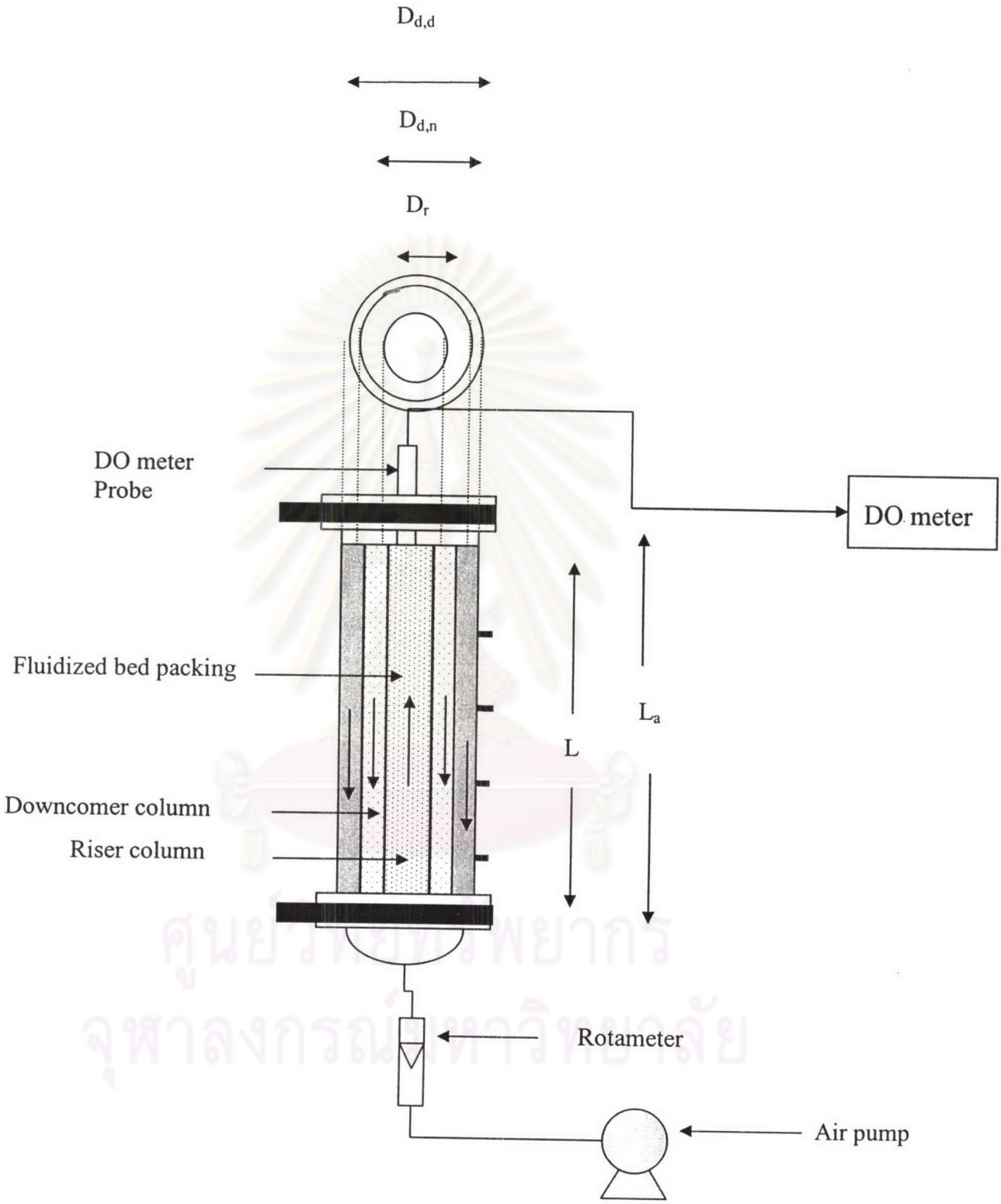

Figure 2.11 Airlift bioreactor for nitrification [Benthum *et al.*, 1999]

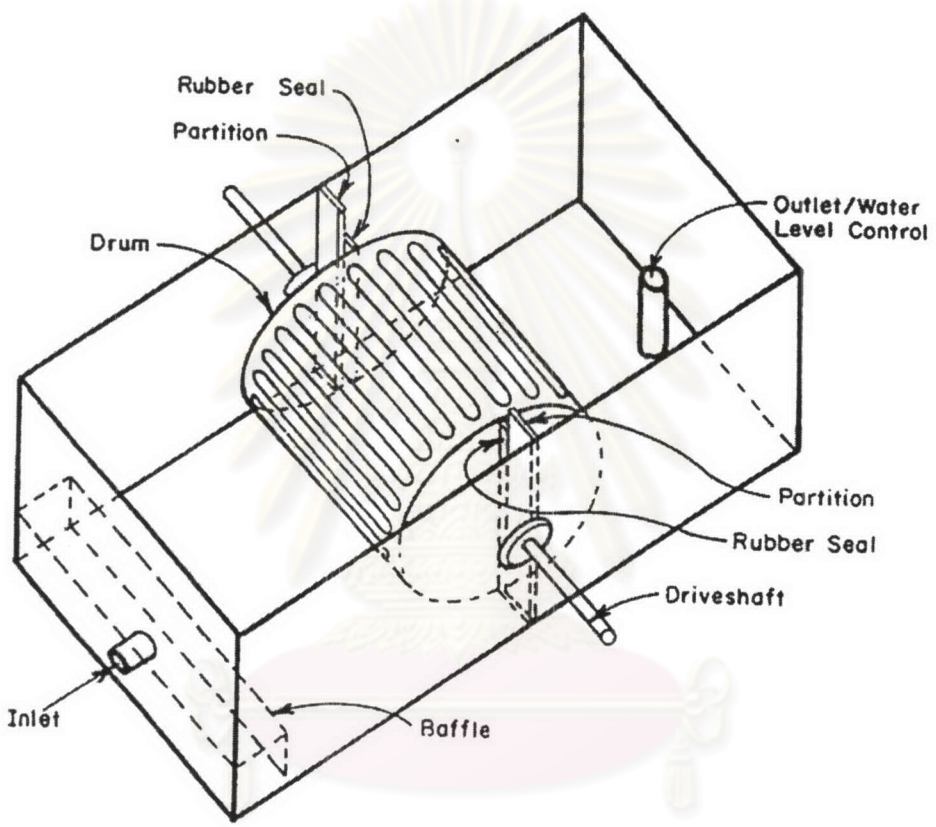

Figure 2.12 Rotating filter for nitrification [Wortman *et al.*, 1991]

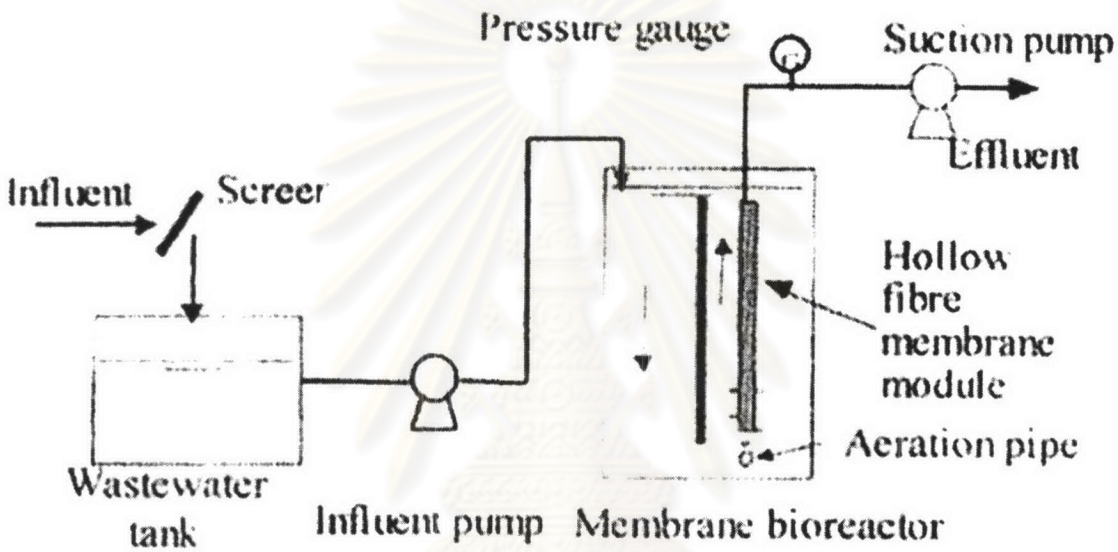

Figure 2.13 Membrane bioreactor for nitrification [Huang *et al.*, 2001]