Wat. Res. Vol. 21, No. 12, pp. 1521–1524, 1987
Printed in Great Britain.

0043-1354/87 \$3.00 + 0.00

THEORIES FOR ESTIMATION OF THE FRACTION OF DENITRIFIERS IN COMBINED NITRIFYING–DENITRIFYING TREATMENT PLANTS

MOGENS HENZE[M]
Department of Environmental Engineering, Technical University of Denmark, Building 115, DK-2800 Lyngby, Denmark

(*Received November 1986*)

Abstract—Theories for the estimation of the fraction of denitrifiers in active biomass are proposed and discussed. Two concepts are used for decay. One is the decay–growth concept, where organic matter cycles between substrate and biomass, and the second is the traditional decay concept, where biomass decays without any recycling of substrate. It is shown that the fraction of denitrifiers is a function of three variables, the potential inlet fraction of denitrifiers (the fraction of the influent material which after primary growth upon the substrate is denitrifiers) the anoxic solids retention time ratio and the total solids retention time. The potential inlet fraction of denitrifiers is the dominating variable. In order to maximize the fraction of denitrifiers in the activated sludge, the influent wastewater should be anoxic treated as the first step of the process and the anoxic fraction of the total solids retention time should be as high as possible.

Key words—wastewater, activated sludge, nitrification, denitrification, fraction of denitrifiers, modelling, treatment of wastewater

NOMENCLATURE

b_H = Decay coefficient (d^{-1})
b'_H = Decay coefficient (d^{-1})
$f_{D,anox}$ = Anoxic fraction of primary production (—)
F_E = Fraction of inert (endogenous matter in biomass) (—)
Q = Wastewater flow ($m^3 d^{-1}$)
S_S = Soluble substrate (kg COD m^{-3})
V = Volume of reactor (m^3)
X_A = Concentration of aerobic biomass (kg COD m^{-3})
X_D = Concentration of anoxic biomass (kg COD m^{-3})
X_S = Concentration of suspended substrate (kg COD m^{-3})
Y_H = Heterotrophic yield coefficient (kg COD kg COD^{-1})
θ_X = Total solids retention time (d)
$\theta_{X,A}/\theta_X$ = Aerobic solids retention time ratio (—)
$\theta_{X,D}/\theta_X$ = Anoxic solids retention time ratio (—)
η = Fraction of denitrifiers (or denitrifying metabolic rate) in active biomass (—)
η_{P0} = Potential inlet fraction of denitrifiers (—)

Subscripts

0 = Influent
1 = Reactor
2 = Effluent
3 = Surplus sludge
A = Aerobic
D = Denitrifying/anoxic

INTRODUCTION

Modelling of combined nitrification–denitrification processes can be done by the activated sludge model (Grady *et al.*, 1986). In this model, the fraction of denitrifiers or denitrifying metabolic capacity, η, plays an important role. Not much is known about the magnitude of η and about which factors that govern its magnitude. Van Haandel and Marais (1981) have found a value of 0.38 during hydrolysis, Matsche (1982) has observed a value of 0.7 and Henze (1986) has reported a value of 0.57. Obviously, the value is not constant but varies as a function of different factors. This paper presents theories which allow for estimation of η based upon wastewater characteristics, treatment plant layout and treatment plant operation.

THEORY

Denitrifying biomass found in an activated sludge plant can have its origin from two sources

—influent wastewater
—in-plant production (primary or secondary).

Thus the fraction of denitrifiers, η_0, in the influent may differ significantly from the fraction of denitrifiers, η_1, in the activated sludge.

The in-plant production of denitrifiers can be based on the influent substrate ($S_{S0} + X_{S0}$) which can give a total primary production of $Y_H(S_{S0} + X_{S0})$. A secondary production might be the result if a decay–growth cycle occurs. This is the death–regeneration concept of Dold *et al.* (1980).

The alternative concept of a decay–growth cycle is used in order to model electron acceptor consumption. The traditional decay concept of active biomass does not include any secondary growth of biomass. From a biological point of view, the truth might be in between these two decay models. The effect of both will be explored in the models discussed below. The models will be based on mass balances around a treatment plant as shown in Fig. 1. A general assumption is that denitrifiers are facultative and can use either nitrate or oxygen as final electron acceptor.

Model with decay–growth concept

The general mass balance for denitrifying biomass in the plant can be written as:

influent + primary production + secondary production − decay = surplus sludge + effluent

where

$$\text{influent} = Q_0 \cdot X_{D0}$$

$$\text{primary production} = Q_0 \cdot f_{D,\text{anox}}(S_{S0} + X_{S0}) \cdot Y_H$$

$$\text{secondary production} = \left\{\frac{\theta_{X,D}}{\theta_X} + \eta_1 \cdot \frac{\theta_{X,A}}{\theta_X}\right\} \times b_H \cdot Y_H \cdot (1 - f_E) \cdot V_1(X_{D1} + X_{A1})$$

$$\text{decay} = b_H \cdot V_1 \cdot X_{D1}$$

$$\text{surplus sludge} = Q_3 \cdot X_{D3}$$

$$\text{effluent} = Q_2 \cdot X_{D2}.$$

The primary production is the amount of denitrifiers produced from the substrate in the influent $(S_{S0} + X_{S0})$. A fraction of this substrate $f_{D,\text{anox}}$ is metabolized by denitrifying bacteria either under aerobic or anoxic conditions. The fraction is primarily a function of plant layout and operation. If the influent enters an anoxic tank and stays there for a reasonable time (say 1 h) a major fraction of the substrate will result in growth of denitrifiers.

The secondary production, which is growth from decay products will give rise to growth of denitrifiers during anoxic periods. The anoxic fraction of the total solids retention time is $\theta_{X,D}/\theta_X$. During the aerobic solids retention time fraction $\theta_{X,A}/\theta_X$, aerobic (non-denitrifying) organisms as well as denitrifying organisms are produced. The denitrifying organisms will account for $\eta \cdot \theta_{X,A}/\theta_X$ of that production. The total fraction of substrate from decay which is used for growth of denitrifiers is

$$\left\{\frac{\theta_{X,D}}{\theta_X} + \eta \frac{\theta_{X,A}}{\theta_X}\right\}.$$

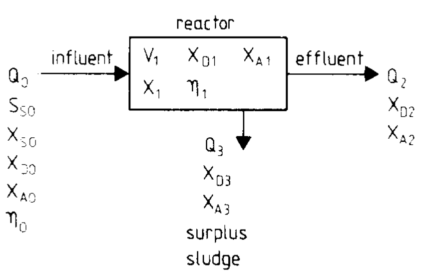

Fig. 1. Notation.

The substrate left-over from decay is in total $b_H \cdot Y_H(1 - f_E)\ V_1(X_{D1} + X_{DA})$.

It is seen that the effect of the decay–growth is that biomass decay gives rise to production of new biomass, which can have a different composition to the one which was decayed.

The mass balance is solved with respect to η_1 by using

$$Q_3 \cdot X_{D3} + Q_2 \cdot X_{D2} = V_1 \cdot X_{D1}/\theta_X \tag{1}$$

$$X_{D1} = \eta_1 X_1 \tag{2}$$

$$\theta_{X,D} + \theta_{X,A} = \theta_X \tag{3}$$

and by introducing the potential inlet fraction of denitrifiers η_{P0} as

$$\eta_{P0} = \frac{X_{D0} + f_{D,\text{anox}}(S_{S0} + X_{S0}) \cdot Y_H}{X_{D0} + X_{A0} + (S_{S0} + X_{S0}) \cdot Y_H} \tag{4}$$

$$\eta_1 = \frac{\frac{1}{\theta_X}\{1 + b_H \cdot \theta_X[1 - Y_H(1 - f_E)]\}\eta_{P0} + \frac{\theta_{X,D}}{\theta_X} \cdot b_H \cdot Y_H(1 - f_E)}{\frac{1}{\theta_X}\{1 + b_H \cdot \theta_X[1 - Y_H(1 - f_E)]\} + \frac{\theta_{X,D}}{\theta_X} \cdot b_H \cdot Y_H(1 - f_E)}. \tag{5}$$

The potential inlet fraction of denitrifiers, η_{P0}, records the denitrifying fraction of the influent biomass plus the primary produced anoxic biomass.

Equation (5) has three system variables, total solids retention time, θ_X, the potential inlet fraction of denitrifiers, η_{P0} and the anoxic solids retention time ratio $\theta_{X,D}/\theta_X$. The rest are constants which might vary with environmental factors but which are constant for a given plant. Figure 2 shows the variation of η_1 with $\theta_{X,D}/\theta_X$ and η_{P0}.

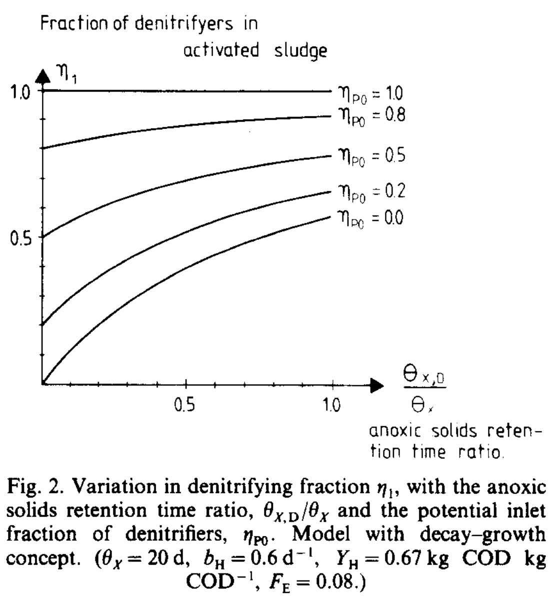

Fig. 2. Variation in denitrifying fraction η_1, with the anoxic solids retention time ratio, $\theta_{X,D}/\theta_X$ and the potential inlet fraction of denitrifiers, η_{P0}. Model with decay–growth concept. ($\theta_X = 20$ d, $b_H = 0.6\ d^{-1}$, $Y_H = 0.67$ kg COD kg COD^{-1}, $F_E = 0.08$.)

Model with decay concept

The general mass balance for denitrifying biomass can be written as:

influent + primary production − decay
= surplus sludge + effluent.

There is no secondary production in this mass balance. All elements are identical to those of the previous model except for the decay term which is now $b'_H \cdot V_1 \cdot V_{DI}$. The decay constant b'_H is smaller than b_H. It can be calculated from

$$b'_H = b_H[1 - Y_H(1 - f_E)] \quad (6)$$

(Henze *et al.*, 1987). The result of the mass balance is

$$\eta_1 = \eta_{P0}. \quad (7)$$

When there is no secondary production, the potential inlet fraction of denitrifiers is equal to the fraction of denitrifiers in the activated sludge. This is shown in Fig. 3.

DISCUSSION

The variation in the denitrifying fraction shown in Fig. 2 will be limited by practical constraints. Figure 4 shows some of the limitations. $\theta_{X,D}/\theta_X$ can never be 1.0, because a certain aerobic sludge age, $\theta_{X,A}$, is needed for nitrification. For $\theta_X = 20$ d and $(\theta_{X,A})_{min} = 5$ d one finds $(\theta_{X,D}/\theta_X)_{max} = 0.75$.

For a denitrifying plant, the anoxic sludge age, $\theta_{X,D}$, must be above some minimum value in order to have reaction time sufficient for denitrification. A minimum value of $\theta_{X,D}/\theta_X$ is approx. 0.25, as indicated in Fig. 4.

Finally the potential inlet fraction of denitrifiers η_{P0}, is restricted to a range which might be 0.4–0.8. This is also shown in Fig. 4.

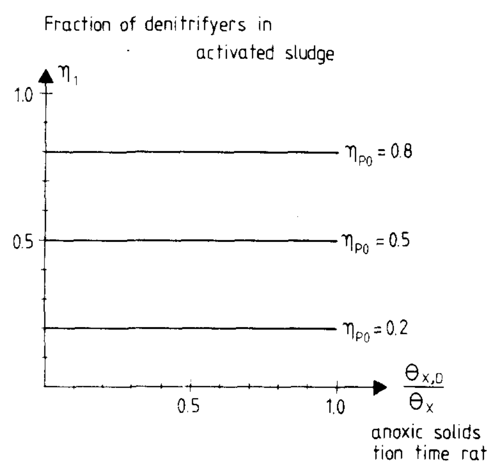

Fig. 3. Variation in denitrifying fraction, η_1, with anoxic solids retention time ratio $\theta_{X,D}/\theta_X$ and potential inlet fraction of denitrifiers, η_{P0}. Model with decay concept.

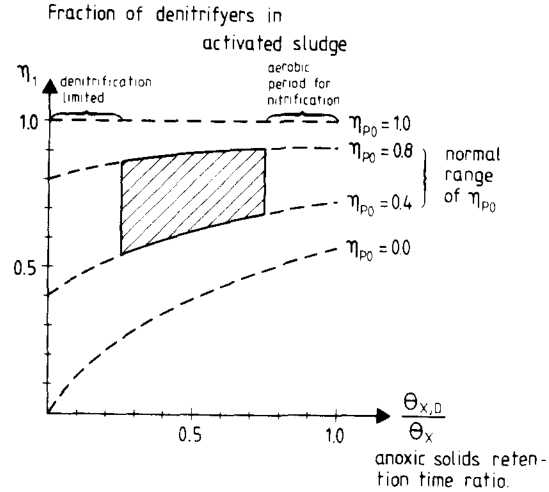

Fig. 4. Shaded area shows maximum variation of η_1, in practice. Model with decay-growth concept. ($\theta_X = 20$ d, $b_H = 0.6\ d^{-1}$, $Y_H = 0.67$ kg COD kg COD^{-1}, $F_E = 0.08$.)

In total, these practical restrictions limit the variation of η_1, to the shaded area shown in Fig. 4. This means that η_1, will be in the range 0.5–0.9. Figure 5 is similar to Fig. 4 and shows the maximum variation in η_1 with the decay concept used in the model.

From Figs 4 and 5 it is seen that the fraction of denitrifiers in the activated sludge, in practice is in the range 0.4–0.9. For fully denitrifying treatment plants the minimum $\theta_{X,D}/\theta_X$ value and the minimum η_{P0} value is probably increased to levels where the variation of η_1, is limited to 0.6–0.9.

From Figs 4 and 5 it is seen that η_{P0} is the dominating parameter with respect to η_1. $\theta_{X,D}/\theta_X$ has a smaller impact. The third variable which has not yet been investigated is the solids retention time θ_X. Figure 6 shows that the effect of this variable upon η_1 is very small, irrespective of the model concept used.

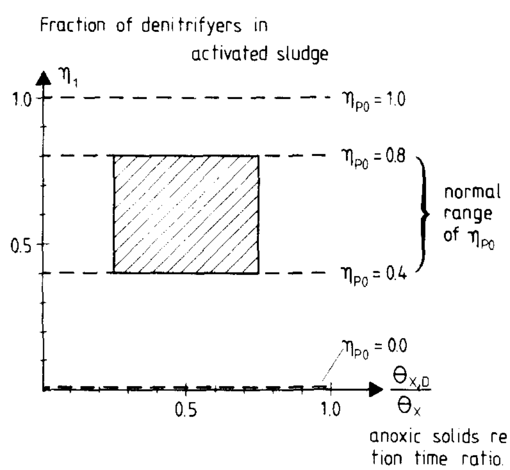

Fig. 5. Shaded area shows maximum variation of η_1 in practice. Model with decay concept.

It is thus seen that the potential inlet fraction of denitrifiers, η_{P0} is the most important variable with respect to the fraction of denitrifying biomass in the activated sludge, η_1. From equation (4) it is seen that a high concentration of denitrifying biomass in the influent, X_{D0}, will increase η_{P0}, as will a high fraction of denitrifiers in the influent, $\eta_0[\eta_0 = X_{D0}(X_{D0} + X_{A0})]$. For a nitrifying–denitrifying treatment plant a high value of η, is important in order to obtain high reaction rates under aerobic as well as under anoxic conditions. The plant layout and operation can influence η_{P0} considerably by ensuring that as much as possible of the total primary production $(S_{S0} + X_{S0})Y_H$ will be denitrifying biomass. This can be obtained by a plant layout and a plant operation where the influent raw sewage enters an anoxic tank. In this tank solely growth of denitrifiers occur and this increases the potential inlet fraction of denitrifiers, η_{P0}, and thus the fraction of denitrifiers in the activated sludge, η_1.

The secondary production of denitrifiers which takes place in the decay–growth model can not influence the η_{P0} value, but can still increase η_1. This can be accomplished by operating the plant with as high an anoxic sludge age as possible. This will maximize the anoxic solids retention time ratio $\theta_{X,D}/\theta_X$ and maximize the fraction of denitrifying biomass.

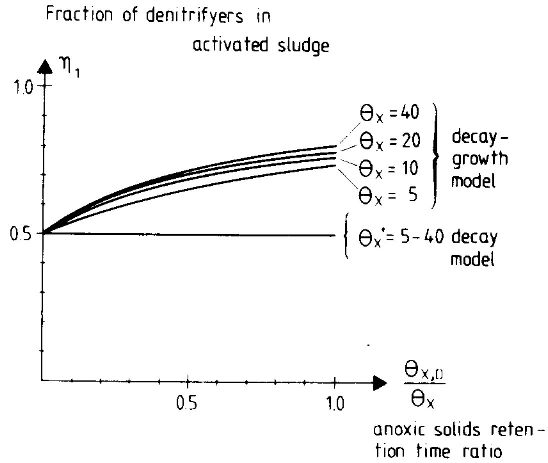

Fig. 6. Effect of solids retention time θ_X, on fraction of denitrifiers, η_1.

CONCLUSIONS

(1) Two concepts of decay can be used to model the fraction of denitrifiers in combined nitrification–denitrification plants. These are the decay–growth concept and the "traditional" decay concept. In practice the fraction of denitrifiers might be somewhat in between the predictions made from the two models.

(2) The fraction of denitrifiers in the activated sludge is a function of three variables

—the potential inlet fraction of denitrifiers, η_{P0}
—the anoxic solids retention time ratio, $\theta_{X,D}/\theta_X$
—the total solids retention time, θ_X.

(3) The potential inlet fraction of denitrifiers, η_{P0} exerts the most pronounced influence upon the fraction of denitrifiers in the activated sludge, η_1. η_{P0} is a function of wastewater characteristics, plant layout and plant operation. A high η_{P0} value can be obtained when the influent wastewater enters an anoxic tank as the first step of the process.

(4) The anoxic solids retention time ratio $\theta_{X,D}/\theta_X$ should be as high as possible in order to maximize the fraction of denitrifiers in the activated sludge.

(5) The total solids retention time, θ_X, has very little impact on the fraction of denitrifiers. The selection of θ_X will be governed by other factors, such as necessary aerobic sludge age and necessary retention time for denitrification to be complete.

(6) The above findings of the fraction of denitrifiers in activated sludge is in accordance with experimental determinations, but need further studies to be verified.

REFERENCES

Dold P. L., Ekama G. A. and Marais G. v. R. (1980) A general model for the activated sludge process. *Prog. Wat. Technol.* **12,** 47–77.

Grady C. P. L., Henze M., Gujer W., Matsuo T. and Marais G. v. R. (1986) A model for single-sludge wastewater treatment systems. *Wat. Sci. Technol.* **18,** 47–61.

Henze M. (1986) Nitrate vs oxygen utilization rates in wastewater and activated sludge systems. *Wat. Sci. Technol.* **18,** 115–122.

Henze M., Grady C. P. L., Gujer W., Marais G. v. R. and Matsuo T. (1987) Activated sludge model No. 1. IAWPRC Scientific and Technical reports. No. 1. IAWPRC, London.

Matsche N. (1982) Verfahrenstechnik Denitrifikation. 7. VSA-Fortbildungskurs., Verb. Schweiz. Abwasserfachleute, Grütlistr. 44, Zürich.

van Haandel A. C. and Marais G. v. R. (1981) Nitrification and denitrification kinetics in the activated sludge process. University of Cape Town, Dept. Civ. Engng, Research Report No. W39.