Future perspectives in bioreactor development

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Abstract The paper discusses conversion capacities of both anaerobic and aerobic wastewater treatment systems in relation to growth kinetics, hydrodynamics and biomass concentration. In the current modern anaerobic high-rate reactors the conversion potentials are optimally exploited. This is not yet true for aerobic systems since operation of aerobic systems under conditions of low biomass growth reduces the maximum applicable loading rates significantly. Both the concept of granulation and the introduction of fluidised bed systems have increased conversion capacities for both anaerobic and aerobic systems significantly. One of the latest development concerns the SBR with granular biomass. The grazing concept, in which ciliates convert aerobically grown dispersed cells, offers a possibility for significant improvement of aerobic systems. In the fields of psychrophilic and thermophilic anaerobic treatment, specific reactor development may contribute to further enhance volumetric conversion capacities. Due to reduced water usage, both COD and salt concentrations tend to increase for industrial effluents. As a consequence, there is a need for the development of anaerobic reactors retaining flocculant biomass. The membrane bioreactors offer a solution for certain niches in wastewater treatment. However the oxygen transfer economy is poor. There is a need for fundamental knowledge development to obtain a realistic image of this technology.

Keywords Aerobic; anaerobic; conversion rate; fluidised bed; granules; growth kinetics; psychrophilic; thermophilic; UASB

Introduction
In the development of wastewater treatment systems most effort has been put into the uncoupling of Hydraulic Retention Time (HRT) from the Sludge Retention Time (SRT). Formation of aggregated biomass and development of appropriate settlers have been the key items for successful wastewater treatment in the past decades. In this paper the parameters determining volumetric conversion capacities in wastewater treatment systems are dealt with and possible future developments are discussed in relation to specific industrial effluent characteristics.

The following parameters determining volumetric conversion capacities are addressed.
1. Biological conversion capacity; determined by the bacterial kinetic parameters like, growth rate, maintenance and yield as well as by process conditions like pH, temperature and water activity.
2. Mass transport; in which hydrodynamics, reactor geometry and physical structure of the biomass are the determining factors.
3. Biomass concentration; governed by retention of biomass, for which aggregation of bacteria, type of settler system and viscosity of the fluid are the crucial parameters.

Discussion
Theoretical considerations
The substrate conversion rate dS/dt \( r_S \) is directly proportional to the growth rate (µ) via the yield factor \( Y \):

\[
    r_S = \mu * X_p / Y
\]  

(1)
in which \( X_b \) represents the biomass concentration.

Biological wastewater treatment aims for high conversion rates at low biomass production rates. Biomass production \( \frac{dX_b}{dt} \) is determined by the difference between actual growth rates (\( \mu \)) and biomass losses. To account for biomass losses a decay coefficient \( b_H \) is used in models describing the kinetics in wastewater treatment. This coefficient incorporates a large number of mechanisms including endogenous metabolism (maintenance) death, predation and lysis (Wiesman, 1986; Henze et al., 1987). The loss of biomass is considered to be independent of growth rates. Although microbiologically this is still under debate, it seems to describe kinetics in wastewater treatment systems adequately.

\[
\frac{dX_b}{dt} = (\mu - b_H)X_b \quad (2)
\]

\[
\mu = \mu_{\text{max}} \frac{S}{(K_S + S)} \quad (3)
\]

in which \( S \) represents the substrate concentration, \( K_S \) the half saturation value and \( \mu_{\text{max}} \) the maximum growth rate.

As the Yield factor is low for anaerobic conversions \( (Y = 0.02–0.15) \), systems may be designed at growth rates close to the maximum growth rate \( (\mu_{\text{max}} = 0.008–0.015 \text{ h}^{-1}) \) still allowing only limited biomass production.

For aerobic processes however, the Yield factor is approximately six times higher as compared to anaerobic processes \( (Y = 0.5–0.7) \). Because of the huge net sludge yield it is not recommended to use the full conversion potential in aerobic processes. Generally, designs are made in which growth rates are close to maintenance and/or decay losses otherwise specific biological sludge productions \( \frac{dX_b}{dS} \) (in kg VSS produced/kg COD converted) would be enormous. This is accomplished through biomass retention. Despite the fact that maintenance requirements and maximum growth rates are much higher \( (\mu_{\text{max}} = 0.3–0.6 \text{ h}^{-1}) \) aerobically, actual growth rates need to be reduced close to anaerobic values (see Figure 1) to obtain low biomass production.

In general, biomass retention is achieved by settling of aggregated biomass (flocs or granules), in this manner the volumetric conversion capacities may be increased significantly. However, the biological conversion capacities will be reduced in aggregated biomass due to diffusion limitations. In a well mixed aerobic reactor system like the CIRCOX® that is operated with granular biomass at 35°C, and where approximately 5% of the COD is converted into biomass (Frijters et al., 2000), conversion rates amount to approximately 0.2 kg COD converted/(kg VSS*day). In practice the optimal conversion rates for anaerobic granular well mixed systems like the IC® reactor, converting carbohydrates, with a sludge production of approximately 5%, lie around 0.8 kg COD converted/(kg VSS*day) respectively.

It may be postulated that under these practical conditions a much bigger proportion of the theoretical conversion potential (maximum growth rate) is exploited in full-scale anaerobic systems as compared to aerobic systems in which the biomass production rate is controlled at a low value.

An interesting concept has been presented, however, to actually elevate this capacity for aerobic processes still allowing low sludge production (Welander et al., 2000). This concept concerns the integration of a grazing compartment with higher organisms like ciliates in a two stage system. In the first reactor dispersed biomass is produced at a high yield without biomass retention and in the second stage biomass is consumed. In this manner higher growth rates, thus conversion rates can be applied still allowing low biomass production rates of 0.02 kg TSS/kg COD removed. In this case the much higher maintenance requirements of the ciliates are the key to low biomass production rates. The concept has been applied for upgrading of an existing activated sludge system with a very high sludge
production. The process might be interesting for high strength waste waters which cannot be treated anaerobically. It may be appreciated that nitrogen removal will be difficult to integrate in the process as growth rates of the nitrifiers will not be able to meet the heterotrophic values.

One field in which biomass conversion capacity could be expected to be the limiting factor concerns anaerobic treatment of industrial effluents at low temperatures, i.e., psychrophilic treatment. However, it has already been demonstrated (Rebac, 1998) that, surprisingly, high methanogenic conversion rates can be accomplished of approximately 10 kg COD/(m³.day) at 10–12°C with completely acidified wastewater in well mixed granular systems. The problem in this process lies with the population responsible for hydrolysis and acidification. As maintenance requirements diminish more in comparison to growth rates with decreasing temperature, there is a tendency for high solids production in the acidification process. This will interfere with conversion efficiencies feasible, as these solids will wash through the anaerobic system and are not converted.

The key to success lies with the development of acidifying systems with retention of granular biomass. In this manner specific biomass production can be reduced. Already in the past these types of systems have been investigated at lab scale (Zoutberg, 1990; Mulder, 1990). The challenge for the near future will lie in the design of a full-scale system.

Mass transport
In order to use the available biomass optimally, mass transport limitations should be reduced as much as possible. Especially in systems containing granular biomass, diffusion limitations for both electron donor as well as electron acceptor may limit conversion capacities. The hydrodynamics in a reactor system is therefore a determinative factor for the conversion capacity. When hydrodynamics are addressed, reactor geometry is an important issue.

Ideally either the gas that is being produced, or the gas which is required for aeration, is used for mixing by means of gas lift action, as this will reduce additional energy requirements. As the driving force for mixing with gas is the density difference between the fluids in several reactor compartments, height is an important issue. Apart from higher fluid velocities driven by gas lifts, increase in reactor height itself will also contribute to higher fluid velocities if the same HRTs are applied.

Examples of these high reactor systems are the IC® reactor and Biobed® reactor for anaerobic treatment and the CIRCOX® reactor for aerobic treatment (Vellinga et al., 1986; Franklin et al., 1992, Heijnen et al., 1993).
With an increase in mixing intensity the mechanical shear exerted on the biomass will increase as well. This may become a limiting factor for processes in which biomass production is extremely low. Considerable progress has been made in the anaerobic treatment of wastewaters with high temperatures (van Lier, 1995). At higher temperatures growth rates will increase, but maintenance requirements will increase even more, as a result, sludge production rates are very low and formation of granular sludge seems to be affected.

This may have consequences for the type of reactor that can be applied. Although in practice Upflow Anaerobic Sludge Blanket Reactors (UASB) have already been applied successfully, the full conversion potential is probably not expressed in these systems. Efforts are needed for the development of high rate reactor systems in which sufficient biomass growth and retention can be accomplished. It is not clear yet whether the present fluidised bed concepts are the optimal choice for thermophilic treatment.

**Biomass concentration**

*Granular biomass.* Aggregation of biomass has been the key item in improving conversion capacities. With the acknowledgement of the potential of granular biomass for reactor design by Gatze Lettinga *et al.* (1980), a major step forward could be made in industrial wastewater treatment. The UASB system was developed in which the good settling characteristics of these granules were exploited and high biomass concentrations were accomplished reaching 60–100 kg VSS/m³. With these concentrations, conversion capacities of approximately 10 kg COD_{converted}/(m³.day) could be attained in practice. Compared to the conversion capacities of approximately 1 kg COD_{converted}/(m³.day) for low loaded activated sludge systems this has been a major step forward for industrial wastewater treatment. With the introduction of the fluidised bed systems, as described above, converting up to 30 kg COD_{converted}/(m³.day) another significant improvement has been made.

Granulation in anaerobic systems subsequently stimulated the development of aerobic systems with granular biomass like the CIRCOX® system (Heijnen *et al.*, 1993). Moreover nitrogen removal has been integrated in these latter systems, providing the possibility of discharge to surface waters (Frijters *et al.*, 2000). In these systems conversion rates of approximately 5 kg COD_{converted}/(m³.day) can be accomplished.

By combining these anaerobic and aerobic high rate reactors, compact wastewater treatment systems are available requiring surface areas, which represent only a fraction (15–20%) of the conventional aerobic flocculant systems, see Figure 2. In addition energy requirements are significantly diminished.

One of the latest developments in the field of granular technology concerns the Sequencing Batch Reactor (SBR) with granular biomass (Beun *et al.*, 1999). In this system relatively dense granules develop without the use of a carrier material and conversion capacities of approximately 4 kg COD/(m³.day) seem to be feasible, allowing low sludge production rates. The system has been tested on lab scale on a model substrate successfully and the challenge for the near future lies in the development of a full-scale system treating wastewater.

*Flocculant biomass.* By imposing an adequate selection pressure in a reactor system granulation can be induced. One of the major driving forces concerns the dilution rate \((D = 1/HRT)\) in h⁻¹ in the reactor system. By creating wash out rates for suspended bacteria, which are higher as compared to the rates at which the bacteria can grow, aggregated biomass can be selectively retained by specific settler systems. If HRTs are increased, the selection pressure for granular growth will decrease and a transition in biomass composition will take place from granular towards flocculant and finally suspended bacteria. As a
result, the selection pressure for aggregated biomass will decrease with increasing COD concentrations of the wastewater (Hulshoff Pol, 1989; Heijnen et al., 1992). Moreover, salt concentrations tend to be elevated in these concentrated wastewaters as well. High salt concentrations may hamper selection for granular growth in two manners. Firstly bacterial aggregation itself is negatively influenced at the level of polymer cell bonding (Mulder, 1990). Secondly the viscosity of the culture fluid will increase, which will effectively result in decreased settling velocities of aggregated biomass.

With the awareness that water is a scarce commodity, costs for process water have increased and will increase even more in the near future. Good housekeeping concerning water usage in industry will increase both COD, salt and solids concentrations of the industrial effluents. As a consequence there is a need for anaerobic reactor systems containing flocculant sludge. At COD concentrations above 15–20 g/l a transition towards flocculant sludge is evident. The challenge for the near future concerns development of well mixed anaerobic systems retaining flocculant biomass.

Membranes. A possible approach concerns the use of membranes for retention of dispersed bacteria. In that manner retention of biomass does not have to rely on aggregation of bacteria. For certain niches in wastewater treatment this is a promising alternative. High quality effluents are attained as optimal retention of dispersed bacteria and other colloidal material is accomplished and recycling of effluents as process water becomes an option. Up to the present, the applicability of the technology seems to be over estimated and often does not comply with sustainability as aeration requirements are much higher as compared to conventional aerobic processes.

In aerobic membrane reactors a dispersed biomass will develop. Not only bacteria and colloidal material are retained but also high molecular weight components either present in the wastewater or released through bacterial lysis; the viscosity of the reactor content is high. As a consequence, a high aeration capacity is required to counteract fouling of the membranes and to account for heavily decreased oxygen transfer coefficients. At the same time bacterial activity is limited due to low water activity.

In practice conversion capacities of 2–4 kg COD/(m$^3$.day) are reported at VSS concentration of 15–25 kg/m$^3$ under non-growing conditions; surplus sludge production is low or negligible. One drawback concerns the intolerance towards (partly) inert solids in the influent. For solids containing wastewaters, a pre-treatment is often required, as accumulation in the reactor would otherwise reduce the biological activity considerably. Harvesting sludge via a bleed could solve the problem, though the dispersed sludge is hard to dewater.

The high operational costs for membrane bioreactors often justify investment in anaero-
bic-aerobic treatment followed by solids removal by either sand or membrane filtration for the production of process water. Especially for effluents in the lower COD range (2,000–15,000 mg/l), as the solids load on the membranes is relatively low in such a configuration, costly membrane surface area and energy requirements may be reduced significantly.

The membrane bioreactors seem to offer a high potential for effluents extremely high in salt concentrations, for which natural retention by means of aggregation is not possible, and for high concentrated effluents containing components difficult to convert anaerobically.

However, to develop a realistic image of this technology, efforts should be focused on the understanding of the oxygen transfer economy and microbial kinetics in these systems with low water activity. In addition knowledge should be developed concerning the retention of colloidal material, macromolecular components and precipitates in relation to type and structure of membranes.

**Conclusions**

With the introduction of the granular sludge bed technology in the seventies and with the development of fluidised bed systems much progress has been made in industrial wastewater treatment coming from conversion rates of 1 kg COD/(m$^3$.day), towards rates of 30 kg COD/(m$^3$.day). The conversion potential for anaerobic processes seems to be optimally exploited, for aerobic processes sludge production is the limiting factor. The grazing concept offers an interesting opening however.

In the following industrial wastewater niches reactor development may contribute significantly to enhanced conversion capacities:

- acidifying reactor for psychrophilic treatment
- aerobic SBR technology with granular biomass
- reactor development for anaerobic treatment of high concentrated effluents with flocculant biomass
- development of high rate reactor for thermophilic anaerobic wastewater treatment
- fundamental knowledge development for membrane bioreactors

**References**


