

Chapter 1

INTRODUCTION

Suspended solids are the most visible of all impurities in waste water and may be either organic or inorganic in nature. It is therefore not surprising that the first waste water treatment systems, introduced by the end of the 19th century, were designed as units for the separation of solids and liquid by means of gravity settling: a process known as the primary treatment of waste water. When the first efficient and reliable treatment units entered in operation, it soon became clear that these could treat waste waters only partially for a simple reason: a large fraction of the organic material in waste water is not settleable and therefore is not removed by primary treatment.

With the objective of improving the treatment efficiency of waste water treatment plants, secondary treatment was introduced in the first decades of the 20th century. Secondary treatment is characterised by the use of biological methods to remove the organic material present in the waste water. In search of an efficient waste water treatment system, the activated sludge process was developed in 1914 by Lockett and Arden at the University of Manchester. They noted that aeration of municipal sewage resulted in an increased removal rate of organic material, while at the same time the formation of macroscopic flocs was observed, which could be separated from the liquid phase by settling, forming a biological sludge. The important contribution made by Lockett and Arden was the observation that the addition of this sludge to a new batch of waste water tremendously accelerated the removal rate of the organic material. The capacity of the sludge to increase the removal rate of organic material led to the common denomination “activated sludge”.

In its original version, the activated sludge process was operated as a batch process: waste water was introduced into a biological reactor containing settled sludge, the reactor contents were then aerated, resulting in the removal of organic material from the liquid phase. Subsequently, the aeration was interrupted and the sludge was then separated from the treated influent by settling. After discharging the treated water as effluent, a new batch of waste water was introduced into the reactor and a new cycle was initiated. Although this “ancient” activated sludge process has been replaced gradually by other configurations, nevertheless it has survived in the form of the Sequential Batch Reactor (SBR), which has regained popularity over the last decades, especially for application to smaller waste water streams. Furthermore, a new variant of the SBR has been developed recently, in which a granular sludge is cultivated that settles very well, resulting in a significant reduction of required reactor volume.

The basic principle of the activated sludge process has not changed since the first application: organic material is still placed in contact with activated sludge in an aerobic environment. However, in the decades that followed the introduction of the activated sludge process, many researchers made important contributions, which improved the performance of the activated sludge process both in terms of organic material removal efficiency and of treatment capacity. In addition operational stability was increased as well.

1.1 ADVANCES IN SECONDARY WASTE WATER TREATMENT

The first important advance in the development of the activated sludge process was the transformation of the original sequential batch process into a continuous process, through the addition of a settling tank after the biological reactor. Figure 1.1 shows the basic configuration of a continuous activated sludge process designed for both primary and secondary waste water treatment.

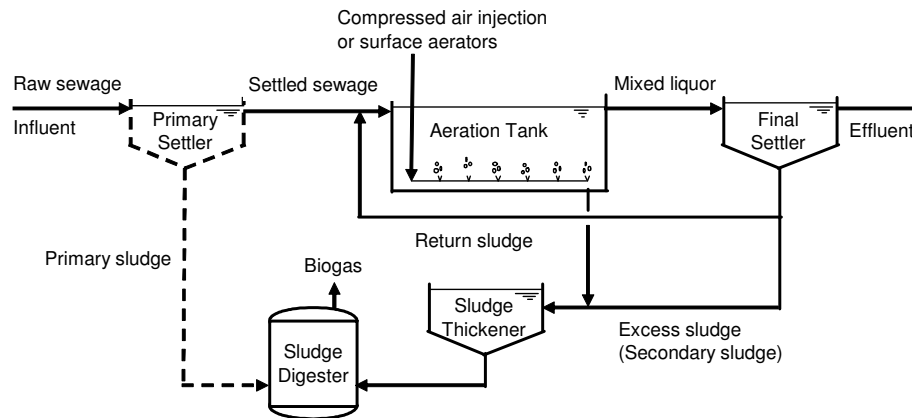


Figure 1.1 Representation of the basic configuration of the activated sludge process (primary and secondary waste water treatment)

The biological reactor or aeration tank is filled with a mixture of activated sludge and influent, known as “mixed liquor”. The aeration equipment (either surface aerators or compressors connected to submerged air diffusers) transfers the oxygen necessary for the oxidation of organic material into the reactor, while simultaneously introducing enough turbulence to keep the sludge flocs in suspension. The continuous introduction of new influent results in a continuous discharge of mixed liquor to the final settler (or secondary clarifier), where phase separation of solids and liquid takes place. The liquid leaves the system as treated effluent, whereas the sludge is recirculated to the aeration tank and for that reason is called “return sludge”. A primary settler (or primary clarifier) may be introduced to remove part of the suspended solids present in the influent. This reduces the organic load to the biological reactor. The settled suspended solids (“primary sludge”) are often sent to an anaerobic digester, together with the activated sludge that is discharged from the biological reactor: the excess sludge. In the anaerobic digester, the volatile suspended solids in the excess sludge are, in the absence of oxygen, partly degraded into methane and carbon dioxide.

Without the discharge of excess sludge, there would be a continuous growth of sludge in the reactor and consequently, an increase of the sludge concentration in the process. In practice the activated sludge concentration must not be allowed exceed a certain maximum value in order to guarantee proper functioning of the final settler (secondary clarifier). For concentrations beyond the maximum, sludge will escape together with the effluent. A constant sludge mass is maintained when the rate of sludge production is equal to the rate of sludge wastage, where this wastage may be unintentional (in the effluent) or intentional (as excess sludge). In practice, excess sludge is discharged either directly from the aeration tank or from the return sludge line, although the first option has some advantages, which will be explained later in this book. The production of excess sludge adds an extra dimension to the activated sludge process: apart from the waste water treatment process, there is also a need to find a suitable method for the treatment and final disposal of the produced excess sludge. In practice the sludge is generally submitted to a biological stabilisation process with the objective to reduce the fraction of biodegradable material (biomass and organic material) and as such to avoid putrefaction. After removing a large part of the water fraction of the sludge, a solid end product is obtained that may be used in agriculture, disposed into a landfill or sent to an incinerator.

The importance of a controlled rate of sludge wastage was only recognized in the 1950s, when the first models to quantitatively describe the activated sludge process were developed. In these models the concept of sludge age was defined as the ratio between the sludge mass present in the process and the rate of sludge wastage. Physically the sludge age is equal to the mean retention time of the sludge in the process. In this text the sludge age will be identified as the most important operational- and design variable of the activated sludge process.

In the 1950s, additional to the organic material removal, nitrification was introduced in the activated sludge process. Nitrification is a two-step biological oxidation of ammonium, using oxygen as an oxidant: the first step is the oxidation of ammonium to nitrite, while the second step is the oxidation of nitrite to nitrate. Nitrification was initially applied only to reduce the effluent oxygen demand. In the case of municipal waste water, the oxygen demand for nitrification makes up about half of the demand for organic material removal. It was noted that nitrification in the activated sludge process was perfectly feasible if the applied sludge age was long enough. This requirement was due to the relatively slow growth rate of the nitrifying bacteria.

1.2 TERTIARY WASTE WATER TREATMENT

Once it was possible to produce an effluent with a very low oxygen demand, it became clear that this per se was not always sufficient for significant improvement of the quality of the receiving water bodies. It was established that the presence of mineral compounds in the effluent, especially the so-called macro-nutrients nitrogen and phosphorus, could cause a serious disruption of the ecological equilibrium in the receiving water. This phenomenon, called eutrophication, was due to an excessive growth of the aquatic life that was able to develop because of the availability of the nutrients. To protect the water quality in the receiving water bodies, it became necessary to develop tertiary treatment systems, in which, in addition to the removal of suspended solids (primary treatment) and organic material (secondary treatment), also the nutrients nitrogen and phosphorus were eliminated.

Biological nitrogen removal is possible when the processes of nitrification and denitrification are applied sequentially. Denitrification is the reduction of nitrate (or nitrite) to nitrogen gas, using organic material as a reductor. Denitrification only develops in an anoxic environment, which is characterized by the presence of nitrate or nitrite and the absence of dissolved oxygen. In the first units constructed for biological nitrogen removal, the nitrified effluent from an activated sludge process was discharged in a second reactor, operated without aeration. Organic material, usually in the form of methanol, was added to the second reactor. Thus, the treatment system was composed of two reactors with different sludges, the first one being for organic material removal and nitrification and the second one for denitrification. However, soon it was established that the organic material present in the waste water could very well be used for nitrate reduction, with the double advantage that neither external organic material was needed nor a separate unit with denitrifying sludge. These “single sludge” processes have unaerated zones for denitrification and aerated zones where nitrification takes place together with organic material removal.

Recently several new processes have been developed that optimise the nitrogen removal process further. However, application is currently restricted to waste waters with high ammonium nitrogen content, such as reject water that is produced during the dewatering of digested sludge. An example of such a new process is nitrogen removal over nitrite instead of over nitrate, as for instance applied in the Sharon (Single reactor for High rate Ammonium Removal over Nitrite). The reactor is operated under conditions where the second nitrification step, oxidation of nitrite to nitrate, is not allowed to occur. This has two advantages: (1) reduction in oxygen demand and (2) reduction in the consumption of organic material.

The latter is an advantage as many waste waters contain insufficient organic material to completely remove the nitrate produced by nitrification. A second innovation is the Anammox process (ANAerobic AMmonium OXidation), where a recently discovered bacterial species is used to remove ammonium, using nitrite as the oxidant instead of oxygen. Furthermore, in contrast to the conventional removal of nitrite or nitrate by the process of denitrification, no organic material is required. A logical next step, which has recently been applied in full-scale, is the combination of the Sharon and Anammox processes, where Sharon is used to produce a suitable feed for the Anammox reactor, i.e. an effluent containing ammonium and nitrite in approximately a fifty-fifty percent ratio.

The second macro-nutrient, phosphorus, can be removed using either biological- or chemical methods. Chemical precipitation with metal salts or lime results in the formation of an insoluble metal-phosphate complex, which is removed together with the excess sludge. A disadvantage is the large increase in excess sludge production. Biological phosphorus removal (often referred to as bio-P removal) depends on the artificial increase of the phosphorus content of the activated sludge. Once again, the actual phosphorus removal mechanism is disposal with the excess sludge. Bio-P removal is enhanced when an anaerobic zone is introduced in the biological reactor. The term anaerobic indicates that both dissolved oxygen and nitrate/nitrite are absent. The mixed liquor is exposed first to the anaerobic environment and subsequently to either an anoxic- or an aerobic phase. Phosphate is removed from the liquid phase and stored in the form of poly-phosphates inside the bacterial cell, resulting in an increased phosphorus content of the sludge. The need for an anaerobic zone implies that in general biological nitrogen removal is a prerequisite for biological phosphorus removal, as the removal of nitrate will be required.

1.3 TEMPERATURE INFLUENCE ON ACTIVATED SLUDGE DESIGN

Currently numerous full-scale activated sludge systems for tertiary treatment are in operation and the majority of these discharge an effluent substantially free of organic material and nutrients. Most of these waste water treatment plants have been constructed in regions with a temperate climate, notably in Europe and North America. South Africa is the only nation with a large number of tertiary waste water treatment plants located in regions with a hot climate. Other countries in the tropics and subtropics have usually built activated sludge processes for secondary treatment only.

In many cases the performance of activated sludge processes in regions with a warm climate has been less than satisfactory, especially when these are designed for secondary treatment only. This can be attributed partially to the lack of financial means for proper operation, but in many cases the problem is mainly due to the fact that inadequate design criteria are used. Often these criteria are adaptations from those developed in regions with a colder climate, where the vast majority of the activated sludge processes have been constructed. However, the difference in temperature has such an important influence on the activated sludge behaviour, that some of the design criteria developed in regions with a temperate climate have only a limited applicability in the tropics and subtropics. A clear example concerns the process of nitrification.

In regions with a cold climate, nitrification will develop only when the activated sludge system is specifically designed for it, through application of a long sludge age. In contrast, in the tropics the growth rate of the nitrifiers is so fast that nitrification is practically unavoidable, even when the applied sludge age is very short. Thus in the tropics, nitrification is not an optional process and will develop at least partially. If the aeration capacity of the process is insufficient for organic material removal and nitrification together, there will be competition for the available oxygen by the different bacteria, with the result that both processes develop only partially.

The resulting effluent quality will be poor, containing both organic material and ammonium. Frequently, the low dissolved oxygen concentration in the reactor will lead to the development of a sludge that exhibits extremely poor settling behaviour (filamentous sludge), resulting in the discharge of suspended solids together with the effluent. In that case, even primary treatment quality cannot always be guaranteed.

If the activated sludge process is designed for nitrification but not for denitrification, the latter process is likely to occur spontaneously in the final settler, in the absence of dissolved oxygen. Nitrogen gas bubbles will form and rise to the liquid surface. These bubbles tend to attach to the sludge flocs they encounter on their way up to the interface. Together, the combined flocs and nitrogen bubbles will form a layer of floating sludge on the surface of the final settler, which will eventually be discharged with the effluent. This loss of sludge may lead to serious disruption of the treatment process: not only will the effluent quality be poor due to the presence of suspended solids, but also the remaining sludge mass may be too small to metabolise the applied organic material load present in the influent. Thus, the absence of provisions for tertiary treatment in regions with a warm climate will tend to cause a decrease in the efficiency of both primary- and secondary treatment. It is concluded that in the tropics and subtropics, tertiary treatment in activated sludge processes is not really optional: if biological nitrogen removal is not applied, the performance of the process will be far below the usual level obtained in regions with a temperate climate.

The inclusion of biological nitrogen removal in the treatment process has important consequences for the design of activated sludge processes. Often it will be necessary to operate the process at a relatively long sludge age, which is achieved by reducing sludge wastage. As a consequence, the sludge mass in the system will increase and hence the reactor volume will be larger. On the other hand, the unit for excess sludge treatment will then be relatively small.

Sludge stabilisation is another aspect of the activated sludge process that is profoundly affected by temperature. The objective of sludge stabilisation is to reduce the fraction of biodegradable material in the sludge and thus to improve its hygienic quality and rheological properties. This stabilisation process is carried out in a separate biological reactor, the sludge digester. If the digester is aerated, the active sludge mass will decrease due to natural decay. If the digester is not aerated, an anaerobic sludge will develop, that uses the wasted sludge as a substrate.

Anaerobic sludge digestion has the advantage that oxygen is not required, but on the other hand, it develops very slowly at temperatures below 15 to 18°C. For this reason, anaerobic digesters operating in a cold climate usually are heated artificially, which reduces the attractiveness of this process. Under these circumstances aerobic sludge digestion, which is feasible at very low temperatures, may be an interesting option, especially for a small waste water treatment plant. However, in regions with a warm climate anaerobic digestion can be carried out at high rate without the need for artificial heating. Thus, in the tropics it is always advantageous to apply anaerobic digestion, unless the process cannot be applied, for instance due to the presence of toxic material in the wasted sludge, as may be the case for industrial waste water. In regions with a hot climate, the applicability of the anaerobic digestion process is not limited to the stabilisation of the excess sludge. In many cases the waste water itself can be submitted to high rate anaerobic digestion, followed by complementary treatment in an activated sludge process. Under favourable conditions, the combined anaerobic-aerobic process offers great advantages compared to the conventional activated sludge process: a high quality effluent can be obtained at substantially lower investment and operational costs, due to large reductions in both required reactor volume and oxygen demand. This text is mainly a reflection of experimental work in countries with a hot climate, and for that reason, much attention is paid to the particular problems and opportunities that a high average waste water temperature offers.

1.4 OBJECTIVE OF THE TEXT

The main objective of this text is to offer the reader the necessary tools for the design and optimisation of activated sludge processes for both municipal- and industrial waste waters. Nowadays, these processes will in general include tertiary treatment and anaerobic sludge digestion.

A simplified quantitative steady state model is presented that will prove extremely useful in the design and optimisation of activated sludge systems and auxiliary units such as final settlers, thickeners and sludge digesters. The model describes the removal of organic material in the activated sludge system and its consequences for the principal parameters of the process: effluent quality, excess sludge production and oxygen consumption. It has been extended to include both nitrogen- and phosphorus removal. A unique feature is the integrated design of the biological reactor and final settler, allowing true optimisation in terms of lowest total cost design.

The validity of the steady state model has been thoroughly tested during experimental research at bench-, pilot- and full-scale processes, treating different waste waters under very diverse operational conditions. Most of the concepts presented in this book have been developed at the University of Cape Town (UCT) in South Africa and form the backbone of the Activated Sludge Models I to III as developed by the specialist group of the International Water Association (IWA, 1987, 1994 and 2000).

However, as any reader with experience with these types of models may confirm, they are not exactly readily applicable to the design of activated sludge systems. In fact, they are much more appropriate for research purposes. The main problem is that these dynamic models (i.e. written in the form of differential equations so as to allow for the variation in concentration in time) are so complex that an analytical solution to the design problem cannot be derived. Instead a large series of time-consuming simulations is required, until in the opinion of the engineer an optimal solution is found. But even then one cannot be sure whether the design was truly optimal or not. In fact, all engineering companies use steady state models for the design of activated sludge systems, although dynamic models might be used to simulate the effect of transient events on the steady state design (e.g. rainwater conditions) or to evaluate the effect of certain process control strategies.

The text will also deal with operational problems of activated sludge systems: e.g. sludge settling and -thickening, oxygen transfer, maintenance of an adequate pH, sludge digestion and methane production. Finally, new developments in activated sludge configurations (such as the membrane bioreactor (MBR) and aerobic granulated sludge) and nitrogen removal (Sharon, Babe, Anammox) will be extensively discussed.