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Preface

ACTIVATED sludge is the most vital wastewater treatment process today. For almost a century, it has been successfully utilized as a conventional system for carbon removal. For the last few decades, its potential to remove nutrients has been explored and tested. Despite substantial practice and accumulated experience, it is wide open to research and conceptual development.

Activated sludge design and practice have always depended upon a modelling approach. The traditional models developed for carbon removal had to be constantly reviewed and revised to reflect improvements achieved in the mechanistic understanding of the process.

This book attempts to provide up-to-date and comprehensive coverage of activated sludge modelling. It reviews appropriate kinetic models incorporating relevant microbiological mechanisms used to define meaningful operational parameters. It also emphasizes the bridge between the design and the mechanistic understanding of the process.

Kinetic evaluation of the activated sludge process involves three basic steps: microbiological basis, reactor kinetics and design approach. The book deals with these steps in sequence. The first chapter provides a review of process evolution both in terms of practice and basic understanding. The relevant microbiological basis is summarized in the second chapter. Chapter 3 reviews reactor engineering aspects. The traditional modelling approach and related design practice are summarized in Chapter 4. In the next chapter, the new modelling efforts are correlated with the traditional concepts associated with basic system configurations for carbon removal. Chapters 6 and 7 are devoted to biological conversion and removal of nitrogen, while Chapter 8 covers biological phosphorus removal. The last chapter reviews major experimental methods for the assessment of biological treatability.

The book is primarily written for students. Chapters are organized so that it may be used both for advanced undergraduate and graduate programs.

Currently, it serves as the reference material for three different graduate courses offered at the Technical University of Istanbul: Reactor Kinetics in Activated Sludge Systems, Nutrient Removal by Activated Sludge and Experimental Methods in Biological Treatment. Numerous examples are included in the text to illustrate significant issues discussed. A number of study problems are presented at the end of each chapter. A wider audience is also envisaged in the sense that design aspects are presented in a format that can be readily used by those in the wastewater treatment industry.

The contributions of all people to the preparation of this book are gratefully acknowledged. Special thanks are due to E. Görgün, E. Ubay, O. Aşikoğlu and S. Viç for their dedicated work in the final production of the manuscript.

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CHAPTER 1

The Evolution of Activated Sludge Modelling

1.1 INTRODUCTION

IMMEDIATELY after its discovery, the activated sludge process found wide application as an effective means of wastewater treatment. Nevertheless, the process has been continuously challenged by the ever-increasing magnitude and complexity of waste loads, and, more recently, by fundamental changes in traditional concepts of wastewater treatment.

The growing public concern about environmental protection spurred efforts to better understand the effects of wastewater discharges—after various degrees of treatment—on receiving waters and their ecological balance. These efforts, along with the increasing public exposure to pollution and its consequences, brought about an extensive reevaluation of existing wastewater management concepts, both in terms of reviewing and developing parameters to better describe various types of wastes, and in promoting more effective treatment methods. This conceptual change significantly affected biological treatment, and in particular the activated sludge process. From a modelling standpoint, it manifested itself as a challenge to the validity of the organic matter and suspended solid parameters in traditional treatment practices. This challenge led to the inclusion of new substrate and biomass components for a better understanding and interpretation of the traditional BOD, COD and VSS measurements, along with additional parameters describing nutrients, priority pollutants, inert organics, etc., and to the development of advanced processes for their removal. Therefore, while the activated process maintained its importance as the most practical and widely used means of removing soluble and colloidal organic waste constituents, it now requires a much better mechanistic understanding of complex biochemical processes, such as nitrification, denitrification and biological phosphorus removal, as they affect the performance of more thorough wastewater treatment systems.

The lack of understanding of the true mechanisms of the biochemical processes involved has always been the major limitation on effluent quality control in activated sludge systems. As the process evolved, efforts to overcome operational difficulties have mostly been on a trial and error basis, with very little input from fundamental principles. Modifications introduced as corrective measures to specific problems have occasionally met with success in their particular situations, but the absence until recently of rational design parameters has significantly limited their practical evaluation in terms of applicability and process optimization. Operational difficulties encountered, together with additional parameters such as nutrient removal, greatly increased the use of process modelling. This led to an ever-increasing need for mathematical models incorporating the fundamental microbial mechanisms into a rational engineering description of the process. Consequently, a significant evolution in modelling practice was experienced in the last three or four decades, from the single-component model advocated by McKinney [1], to the elaborate model including 17 components and 28 different processes recently proposed for combined carbon, nitrogen and phosphorus removal [2]. The accumulated scientific information and the ingenuity of the recent modelling efforts are noteworthy. However, the reliability of the proposed models depends on an ever-increasing number of kinetic and stoichiometric constants in the experimental assessment of different kinds of wastewater. In this context, it may be concluded that the modelling of activated sludge still has room for development, despite major achievements in the last decade, as most of the collected kinetic information is still limited to domestic sewage. Application of the current modelling practice to industrial wastewater treatment still requires substantial additional information.

1.2 HISTORICAL DEVELOPMENT

The concept of using supplemental aeration as a means of sewage purification dates back to the 19th century. Early experiments on this subject showed the possibility of removing "the more readily putrescible matters" from sewage [3], with appreciable nitrification [4], and within an aeration period of 24 hours. In these experiments, no importance was attached to the formation of a "humus deposit" caused by the gradual decomposition of the organic matter in sewage, except that the deposit had to be disposed of before a new experiment could be started. In 1912, experiments at Lawrence Experiment Station in Massachusetts [5] demonstrated that aeration of sewage for a short time in a tank containing slabs of slate about one inch apart produced a "compact brown growth" on the slate, and the process produced a clear, nonnitrified effluent which was further treated on filter beds. Two years later, Arden and Lockett [6], in England, pioneered one of the most popular processes in sewage treatment. Disregarding the then-current practice, they saved the flocculent solids and studied the effect of their repeated use in sewage treatment by aeration. These flocculent solids, which they called *activated sludge* greatly increased the purification potential of simple aeration. The accelerating effect depended upon the proportion of activated sludge to the sewage treated. They also concluded that an average strength Manchester, England, sewage could yield a clear, well-oxidized effluent upon aeration in contact with activated sludge, for a period of six to nine hours – a period adopted as a design parameter in future treatment plants. News of these findings spread rapidly to the U.S. In 1914, similar studies were undertaken at the University of Illinois [7] where activated sludge was confirmed to be the indispensable factor for sewage stabilization within a six-hour aeration period. Fill-and-draw experiments also indicated that the air volume supplied for the process should be between 7 and 11 m^3 of air/m^3 of sewage (1.0 – 1.5 cu.ft. of air/gal. of sewage) – a second key design parameter which has survived the years.

The discovery found immediate response in practice, both in England and in the U.S. In 1914, shortly after the publication of the observations of Arden and Lockett, a fill-and-draw system was brought into operation in Daryhulme, Manchester [8]. Taking advantage of the flocculent properties of the activated sludge along with its "clarifying power," efforts were then directed towards the adaptation of the process to operate under continuous flow conditions. By 1917, two small-scale continuous flow plants in Worcester and in Wittington, England and a large (10 mgd) continuous flow plant at Houston, Texas, were put into operation [9]. Successful experience with these plants and the establishment of the diffused air process as a feasible means of air provision, encouraged the construction of other major plants which were soon placed in operation. All were based on the continuous flow principle which had proven itself as the major practical method for activated sludge operation.

The performance of the pioneer activated sludge plants in their early years of operation was quite satisfactory. They provided basic criteria for the principle design features of new plants, and firmly established the activated sludge process. The wide acceptance of the process in the U.S. is clearly reflected by the rapid increase of the total nominal capacity of activated sludge plants to around 400 mgd during the mid-twenties [10]. This situation did not persist for long. Rapid population expansion and industrial development greatly altered the magnitude and nature of sewage loads to existing treatment plants, and the effect of flow and organic load variations – which were not appreciable in large cities – became more pronounced as activated sludge plants were built for smaller communities and for cities with significant industrial activities. Under these conditions, serious problems developed, both with operating plants to maintain a high-quality effluent, and with the general attitude towards the process.

One of the most serious problems was caused by what was generally described [11] as *sludge bulking,* a phenomenon which manifested itself as an appreciable reduction in settleability of activated sludge, often resulting in excessive suspended solids concentrations in the plant effluent. Although several corrective measures were suggested [12–14] to prevent bulking, the nature of the phenomenon has never been clearly elucidated. Heukelekian [15] chose to describe it as a disease of the sludge, developed under unfavorable environmental conditions. Extensive studies identified some of these conditions as:

- improper balance of food caused by high carbohydrate levels
- high carbon-to-nitrogen ratio [16,17], attributable to some industrial discharges
- low dissolved oxygen levels in the aeration tanks [18,19]
- increasing organic loads on the treatment plants

Another serious problem that haunted the activated sludge process was the shortage of oxygen, primarily at the head end of the aeration tanks. Although there was a tendency to relate incomplete oxidation of sewage and improper conditioning of the sludge to partially septic conditions that prevailed from time to time in the aeration tanks [20], it was only after the recognition of the importance of oxygen as a quantitative factor in the process that the nature of the problem was fully appreciated. After the studies on the quantitative measurements of oxygen utilization during sewage treatment [21–23], the frequent absence of dissolved oxygen at aeration tank inlets was related to high initial rates of biochemical oxygen demand. It was suggested that appreciable changes might take place in the character of sludge as a function of the length of the oxygen deficiency period, and that subsequent recoveries under aerobic conditions maintained in the latter part of the tank might not be complete. It was concluded that dissolved oxygen must be present at all points in the aeration tank [15].

1.2.1 PROCESS MODIFICATIONS

The ever-increasing difficulties encountered in the operation of activated sludge plants, in the face of the complex and variable nature of the wastes involved, triggered extensive efforts to review existing design criteria and operating practices, as well as to develop process modifications that would permit existing plants to treat larger flows and greater loads while maintaining a high effluent quality. While the problems were recognized, they were not always thoroughly and scientifically defined, so that rational corrective measures could not always be taken. Therefore, experience and good judgement had to form the basis for plant improvements and modifications. Plant engineers and operators developed new ideas by trial and error for their particular situations. Several original concepts and process modifications emerged from this individual work to gain universal acceptance in sewage treatment practice.

1.2.1.1 Tapered Aeration

The frequent shortage of oxygen in aeration tanks raised criticisms on the reliability of the existing air supply criterion for the maintenance of aerobic conditions. To find a more suitable aeration criterion, the conventional activated sludge process was characterized by rapidly decreasing oxygen requirements as the treatment progressed [24], and it was concluded that for the proper operation of a treatment plant, the air supply should be adjusted as a function of the oxygen requirements of the sludge [25]. Laboratory experiments on nonnitrifying sludge [23], indicated that 40–50% of the air was required in the first two hours, 28–31% in the second two hours, and 20–29% in the last two hours of a six-hour oxidation period. In light of these findings, a major modification of the activated sludge process, known as *tapered aeration,* was promoted. It involved sizing the aeration equipment as a function of anticipated oxygen requirements. For example, in a diffused-air system, the number of diffusers at the head end of the aeration tank would be increased, while those near the outlet would be decreased [Figure 1.1(a)].

This modification was soon incorporated into major treatment facilities. Haseltine [26] reported the use of tapered aeration at the Salinas, California plant, starting in 1930, in which 55–70% of the total air was applied in the first half of the aeration tanks. Almost all activated sludge plants now include provisions for tapered aeration.

1.2.1.2 Step Aeration

Concurrent with aeration studies, attention was focused on the daily and occasional load transients to which activated sludge is exposed and which it must accommodate. It was noticed that the oxygen demand of a mixture of activated sludge and sewage could often exceed the ability to dissolve oxygen by means of conventional and modified aeration systems, if the entire load of sewage were applied with the return sludge to the head end of an aeration basin [27]. This observation led Gould to develop the idea of adding sewage in regulated amounts, at multiple points along the tank, instead of tapering aeration [Figure 1.1(b)]. Despite many criticisms, the

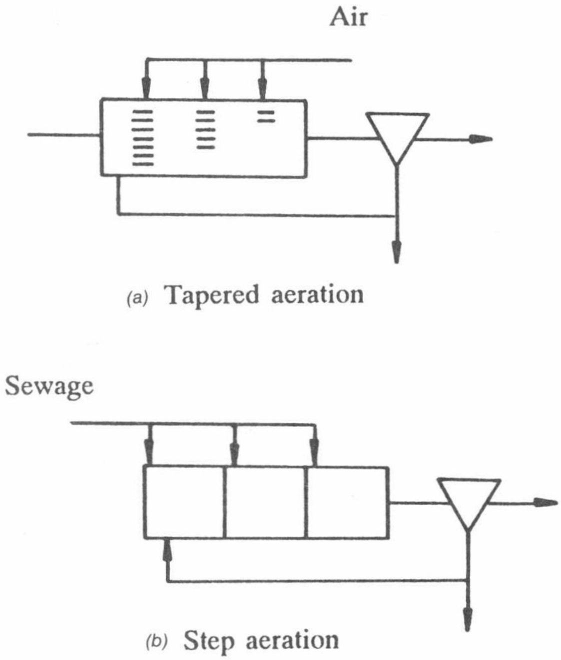


Figure 1.1 Process modifications—tapered aeration and step aeration.

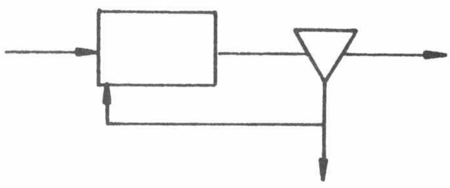
name *step aeration* that Gould proposed for the process persisted over the years. In 1940, this concept was applied for the first time to the Tallmans Islands (New York) treatment plant where serious problems were being experienced due to frequent heavy discharges of oil and dye wastes. After a short period of adjustment, consistent BOD and suspended solids removals of around 90% could be obtained with a 3.6-hour aeration period.

About the same time, the same modification was being studied at Harvard under different names—*distributed loading, multiple-point dosing* and *incremental dosing* [28]. The process was found flexible enough to adequately control bulking and blanket rising of the sludge, and to reduce the shock of sudden discharges. It was concluded that the process was capable of producing an activated sludge with good purifying capacity (82—95% BOD reductions) by maintaining the oxygen requirement at a more uniform level than in conventional operations. Savings in tank volume on the order of 23—55% resulted because of the ability of the system to concentrate the sludge, with the magnitude of the volume savings depending on the return sludge rate. Similar to tapered aeration, step aeration has also found wide application, mainly because of the saving in tankage and its satisfactory performance.

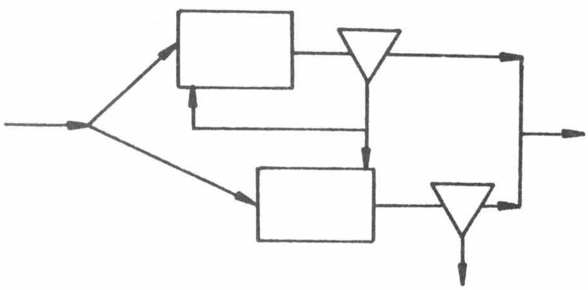
1.2.1.3 Partial Treatment Systems

1.2.1.3.1 *Modified Aeration*

Until 1940, all the modifications of the activated sludge process were directed towards improving its efficiency. In that year, however, an incidental observation of the substantial BOD reduction that took place during the start-up of the New York City Wards Island Treatment Plant instigated the idea that a treatment plant could be designed to produce any effluent quality between plain sedimentation and conventional activated sludge, together with potential economy in operational costs and capital investments [29]. Action was taken to investigate the results of aerating sewage for shorter periods and with a smaller quantity of biological solids in the aerators [Figure 1.2(a)]. Experimental results indicated that the process was free from bulking problems, and that a substantial reduction in the air volume was obtained while achieving BOD removals on the order of 65–68%. It was also noted that although the process might be upset by industrial discharges, it recovered within a few hours. The sludge settled rapidly, and compacted to a concentration twice that of conventional activated sludge, but it had a tendency to turn septic if left unaerated for more than two hours.



(a) Modified aeration



(b) Activated aeration

Figure 1.2 Process modifications–partial treatment systems.