Activated Sludge Bulking : A Review of Causes and Control Strategies

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Bulking of activated sludge can lead to a loss of bio-oxidation, further deterioration of effluent quality and in persistent cases, a complete breakdown of the entire treatment process. Because bulking is a very common operational problem in most activated sludge treatment plants, detailed knowledge of its causes and remediation are important. A review of causes and control strategies as reported in literature is therefore presented in this study. To date, research has resulted in the publication of much conflicting information and advice on bulking control. This review has revealed that successful bulking control measures in everyday practice are still very much empirical in nature.

Keywords: Activated sludge bulking; Review; Causes; Remediation

INTRODUCTION

Since its development, the activated sludge process has undergone continual evolution in an effort to maximise process efficiency. This has lead to the nature of causes and control of activated sludge bulking becomes diverse. The term 'bulking' has been used for many years to describe problems associated with the separation of activated sludge. A precise definition of the term is difficult since in the past is has been used to describe a variety of problems (Tomlinson[1]). Broadly speaking, activated sludge bulking is defined as the phenomenon which occurs in activated sludge plants when the sludge occupies excess volume and does not readily settle so that in extreme cases the effluent contains excessive suspended solids (SS). According to Jenkins[2], *et al*, the phenomenon is very important as it undermines the function of the secondary sedimentation tanks, which is to provide 'clarified, low suspended solids (SS), low turbidity overflow'.

There is no indication in the literature to suggest that problems of poor settleability occurred when the first experiments with activated sludge were performed in the early part of the last century. However, by the 1920s a number of problems had been reported[3] and from that time onwards is become known that these problems could be serious and were widespread. Tomlinson[1] associated the appearance of bulking problems with 'the departure from the conditions provided by the early fill-and draw plants and by continuous flow plants'. The fill-and-draw plants of the early days were essential the sequencing batch reactors (SBRs) of today, which has been made popular with the development of modern technology. Tomlinson and Chambers[4] estimated that bulking was a problem prevalent in half of the activated sludge plants world-wide. In surveys conducted by Tomlinson[5] in 1976, 27 of the 65 activated sludge plants in UK had an average yearly sludge volume index (SVI) of greater than 200 ml/g. Wagner[6] reported that about half of the Germany's activated sludge plants suffered from sludge bulking problems. Similarly, surveys conducted by Blackbeard[7], *et al*, in South Africa and by Pujol and Boutinin[8] in France revealed about 32% and 25% of the activated sludge plants suffered from bulking problems, respectively.

Because of such widespread nature of the bulking problem, it is important for the activated sludge plant manager to be aware of the possible causes and control strategies. In this study, we therefore felt it important to review the causes and remedies of activated sludge bulking as reported in literature. The study is divided into two major sections — Section 2 describes the causes while Section 3 dwells on the control strategies reported in literature. The salient points have been summarized in a manner that is expected to be potentially useful for a manager searching for clues on bulking. Finally, Section 4 presents the overall conclusions of this review.

CAUSES OF ACTIVATED SLUDGE BULKING

There are at present two distinct schools of thought that attribute the causes of bulking to the type of microbial population in the activated sludge. These are:

(i) according to Eikelboom[9], bulking is caused by an over abundance of filamentous micro-organisms known as filamentous bulking, and;

(ii) according to Heukelekian and Weisberg[10], bulking is caused by certain non-filamentous microbes that produce an excess of bio-polymers on their surface to effect poor compaction of the sludge known as non-filamentous or Zoogleal bulking.

A closer examination of the literature however revealed bulking to be related to the following growth specific environments in the activated sludge plant:

(i) low dissolved oxygen (DO) concentration in activated sludge (Heukelekian and Ingols[11], Adamse[12], Sezgin[13], *et al*, Palm[14], *et al*);

(ii) high DO concentration in activated sludge (Bhatta[15], Benefield[16], *et al*);

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This paper was received on June 23, 2003. Written comments on this paper will be received till November 30, 2004.

(iii) low organic loading (Low Food to Microorganism (F/M) ratios) (Logan and Budd[17], Ford and Eckenfelder[18], Pipes[19]);

(iv) high organic loading (High F/M) ratios) (Logan and Budd[17], Genetelli and Heukelegian[20], Ford and Eckenfelder[18], Chudoba[21], *et al*);

(v) completely-mixed reactor configuration (Chudoba[22], *et al*; Rensink[23], Houtemeyers[24], White[25], *et al*, Tomlinsonl[1]);

(vi) conventional plug-flow reactor configuration (Imhoff and Fair[3], Committee of Water Pollution management[26]);

(vii) inadequate micro nutrient concentrations in the activated sludge (Carter and McKinney[27], Wood and Tchobanogolous[28]);

(viii) elevated metal concentrations (Ingols and Felner[29]);

(ix) low pH of the activated sludge leading to excessive growth of fungi (Jones[30]); and

(x) low relative influent macronutrient content (*N, P*) (Greenberg[31], *et al*).

Since, many of the causes listed above are primarily extreme cases of a growth environment, (*ie*, too low or too high), the literature appeared ill defined and possibly contradictory on bulking control. For example, according to Bhatta[15] and Benefield, *et al*[16], an activated sludge affected with low DO bulking could not always be cured by an increase in DO as that might possibly enhance bulking again through the flourishing growth of filamentous organisms. Similarly, from Ford and Eckenfelder[18], a plant operating at a high loading (high F/M ratio) is likely to experience bulking, which cannot always be controlled by lowering the loading (lowering F/M ratio).

Richards[32], *et al*, in 1985 reported that bulking caused by a certain Type 1701 filamentous organisms could be strongly controlled by the DO in the mixed liquor. However, the question of the critical value of DO concentration in the mixed liquor for Type 1701 bulking remained unanswered. Wanner[33] argued that the question could not be answered without an exact knowledge of the ratio between substrate and oxygen flux into the flocs of the activated sludge. In another investigation by Palm[14], *et al*, a striking paradox was observed — that low DO bulking may apparently occur under high DO concentration. As the actual DO uptake rate governed by the floc loading was the decisive parameter, Grau and Dohanyos[34] reported low DO bulking even in activated sludge systems aerated with pure oxygen at DO concentrations of about 10 mg/l. Therefore, from these reports[14,33,34] one can comment on the nature of activated sludge system being 'a complicated living system' where 'strange things happen for no apparent reason'.

In a comparative survey of lab-scale bulking-affected systems where Sphaerotilus natans was the dominant filamentous organism, Gabb[35], *et al*, reported the causative factors to be very diverse and often dependent on the wastewater and operating regime. In their literature survey, the DO concentration ranged from 0.1 mg/l to 16 mg/l, the F/M ratio (in terms of COD per VSS) ranged from 0.2 to 1.72 while the critical MCRT was as diverse as 1.9 days to 30 days. Table 1 shows some of the salient findings of their own literature review on activated sludge bulking related to Sphaerotilus natans.

Table 1 Some salient environmental conditions for sphaerotilus natans affected laboratory-scale activated sludge systems (Gabb[35], *et al*)

Author (s)	DO, mg/l	MCRT, Day	HRT, h	F/M Ratio, gBOD/gVSS
Chudoba[22], *et al*	—	—	8	1.1
Houtmeyers[24], *et al*	6	7	1	0.4
Palm[14], *et al*	0.1-5.5	1.9-11	—	0.38-1.72
Lee[36], *et al*	4.5-16	15	19	0.31-1.00
Van Niekerk[37]	3.5-4.5	20-30	—	0.20-0.30

Note : Sphaerotilus natans growth occurred at high DO only when a high F/M (low MCRT) prevailed

Jenkins[36], *et al*, attributed that the 'early' references on causes of filamentous bulking were 'confusing' as most of the early researchers assumed that only one type of filamentous organisms was responsible, mainly the Sphaerotilus natans. They carried out the filament identification work in US in the recent decade revealed that 90%-95% of the bulking episodes could be attributed to approximately 10 filament types. Though this work has made the control of bulking focused, the complex nature of its control has not been overcome yet as the causes for growth of filamentous bulking organisms still appear 'complex, variable' and 'specific' for a given set of growth conditions[38]. As an example, Sphaerotilus natans and Type 1701, two bacteria found in low DO bulking sludge, have very different half-saturation coefficient for DO (0.033 mg/l and 0.014 mg/l, respectively). This suggests that the former's growth would be caused by a modest DO limitation in the activated sludge while the latter would flourish under severe DO limitations. Similarly, when it is diagnosed that nutrient deficiency is one of the causes for sludge bulking, filament identification alone cannot offer satisfactory solutions for control, as nutrient deficient bulking is not caused by any specific type of filamentous micro-organism.

Correct identification of filamentous organisms is still extremely difficult and expensive. Wanner[33] argued that a compromise was necessary between the practical needs and the microbiological identification. The conventional methods of identification require laborious preparation of pure inocolum from mixed cultures. Some filamentous microorganisms exhibit low growth rates which cause identification to take weeks or even months. Thus results do not correspond with actual state of biocenosis in the sludge. Wanner[33] further highlighted that the method described by Eikelboom[39] could be used temporarily in place of conventional methods for reasons of simplicity and the lack of need for a trained microbiologist.

(iii) low organic loading (Low Food to Microorganism (F/M) ratios) (Logan and Budd[17], Ford and Eckenfelder[18], Pipes[19]);

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CONTROL STRATEGIES FOR ACTIVATED SLUDGE BULKING

System-Specific Methods

Specific methods for bulking control are those that are devised based on the specifications of the activated sludge plant, the type of wastewater being treated and other treatment characteristics. Specific methods aim to create environmental conditions in the aeration basin that could 'avoid' the growth of micro-organisms responsible for sludge bulking. Based on the premise that 90%-95% of bulking episodes in activated sludge plants can be explained by approximately 10 filamentous organisms, Jenkins[38], *et al*, recommended the following step-by-step approach for specific control of bulking:

(i) Examine the activated sludge microbiologically — identify the causative filamentous organisms.

(ii) From (i), plant design and operational data deduce the probable causes of bulking. For example, operational data indicating as pH of less than 6.5 in the mixed liquor could signify fungal growth in the biomass. Similarly, low DO coupled with a high F/M ratio could indicate the presence of Sphaerotilus natans as the bulking micro-organism in the sludge

(iii) If the probable causes suggest a nutrient deficiency (*N, P*), make provisions for nutrient supplement in the influent.

(iv) For other probable cause of bulking like low DO, low F/M etc, implement major changes, (*eg*, additional aeration capacity, compartmentalising the aeration basin configuration etc). Allows at least 3 tines the average MCRT for the activated sludge to return to non-filamentous conditions (for continuous flow systems).

Unfortunately, this specific method of Jenkins[38], *et al*, does not offer a clear-cut solution for bulking caused by fungal growth (low pH), or non-filamentous organisms. The modification of this process often requires a high capital investment and is often very slow to implement. Even after implementation, the beneficial effects are slow to occur. It has been observed by Wheeler[40], *et al*, that in one instance, a period of 6 months-7 months was required following the installation of a selector for achieving good settling characteristics. Novak[41], *et al*, reported that *Zoogleal* bulking might surprisingly occur when system is modified to improve setting by incorporating plug-flow characteristics. In such cases, Jenkins[2], *et al*, reported that non-filamentous bulking could not be controlled well with the addition of polymers or hydrogen peroxide. Proper economic evaluation of this specific method by Jenkins[38], *et al*, appears to be absents in literature. It seems the trade-off between the high costs for this specific method and the prospects of timely benefits has not been fully addressed.

To promote a specific technique for bulking control based on a more cost-effective and practical approach; Tomlinson and Chambers[42] suggested the following step-by-step procedures:

(i) Determine the SVI (at a given concentration of the MLSS (Mixed Liquor SS)).

(ii) If SVI is greater than the permissible value (design SVI) beyond which the plant cannot operate satisfactorily, then compare the applied solids loading and the maximum permissible solids loading.

(iii) If the applied solids loading is greater than the maximum permissible loading then the system is unstable and requires immediate increase in the recycle ratio of the sludge, if possible.

(iv) If the recycle ratio cannot be manipulated than the MLSS should be reduced.

(v) If MLSS cannot be manipulated or the solids loading is stable then the DO of the mixed liquor should be checked.

(vi) Alter DO if it is insufficient.

(vii) Check if sewage is septic and reduce septicity.

(viii) Otherwise check for nutrient deficiency in the sludge and make provisions for nutrient supplement (Biochemical Oxygen Demand, BOD: N: P ratio as 100: 5:1).

(ix) If steps (v) to (vii) are found to be irrelevant or ineffective then find out if the system configuration is flexible or not.

(x) If the system has provisions for modifying the existing structure, then engage in pilot plant experiments for determinating the optimum system modification, (*ie*, the type of selector best suited for the given wastewater).

(xi) Otherwise investigate the use of toxicants (chemicals).

(xii) As a last resort, refer to available literature and expert help for remediation if (i) to (x) do not offer a feasible solution.

The above specific approach offers a more viable control strategy in a step by step manner of increasing cost and difficulty in implementation. Although the use of toxicants can be cheaper than modifying a plant's configuration, its use has been recommended with caution because of the potential danger of an overdose that can disrupt the entire system[42]. This specific method is also at odds with the earlier method of Jenkins[38], *et al*, as it disregards filament identification of the activated sludge. Research by Tomlinson and Chambers[42] in UK had revealed little consistent relationship between the presence of specific filamentous organisms and identifiable causes of bulking, country to the experiences of Jenkins[38], *et al*, in US. However, the method proposes[42] appears more practicable as it employs a holistic approach to bulking control. It emphasises cost-effective control srategies rather than costly extensive microbiological identification. Filament identification could result in considerable wastage of critical time during severe cases of bulking where a plant is likely to fail soon. This specific method is, however, restricted to continuous flow activated sludge plants and was devised with specific references to sewage treatment plants in mind.

As part of suggesting the use of selectors for bulking control, Salameh and Malina[43] reported that for a given selector, selection pressure on the microbes was more effective and occurred rapidly at lower sludge ages (below 4 days). They recommended that the substrate condition should be high in the selector to achieve effective bulking control. For an effective curve of activated sludge bulking, it was necessary to modify or change the wastewater characteristics and plant operation. They argued that a change in plant operation by modifying the aeration basin to a compartmentalised basin was the more realistic control strategy. However, their specific method for bulking control have led them the conclude that the use of selectors to alter the bulking sludge to a completely non-bulking one through selection in the microbial construction was a 'time-dependent process'. The exact nature of 'time-dependent process' had not been quantified by them[43].

Wagner[6] reported that a raising of the *P* content in sludge compounds through precipitation or direct addition resulted in a more favourable floc structure of the sludge. This could be achieved by:

(i) Addition of Ferrous or Aluminium salts;

(ii) Addition of lime to the influent of the sedimentation tanks; and

(iii) Addition of low solubility phosphate fertiliser in to the aeration tanks.

The use of long (Length: width > 20) plug-flow reactors or folded basins to minimise backmixing as described by Tomlinson and Chambers[4] and Albertson[44] are now recognised as a specific control method (system modification) for bulking control. The necessity of compartmentalisation of oxic zones in aeration tanks was reported by Wanner and Grau[45] for BNR (Biological Nutrient Removal) plants. Growth of most filamentous microbes was suppressed under anaerobic and anoxic conditions. Upon investigating the effect of aeration basin configuration on activated sludge bulking at low F/M ratios, Lee[36], *et al*, concluded that the initial mixing zones should be aerated. They further noted that increasing the F/M ratio, especially for plants that are practicing nitrification could not always control low F/M bulking. Their study was conducted on a bench-scale system spanning 160 days.

Foot[45], *et al*, proposed a 'systematic rather than symptomatic' approach to bulking using firm data and decision pathways. Their approach was similar to that of Tomlinson and Chambers[42]. In their approach[46] the sequence of measures has taken into account that engineered solutions involving process modifications and additional reactors such as selectors are often the most expensive alternatives. The need for dynamic modelling to reflect the properties of the bulking sludge was emphasised. They also suggested a reversion to more empirical method of data analysis rather than focusing on conceptual (deterministic) methods for bulking control.

Chisea and Irvine[47] reported that intermittently-fed systems were capable of operating over a wider range of operation conditions by accentuating differences in organisms physiology to control bulking. In their opinion, it had a greater flexibility in SBRs than in continuous flow activated sludge processes. Brenner[48], *et al*, observed that a short period of mixed fill involving anoxic stage was necessary for control of filamentous bulking in SBR treating high strength industrial waste water. Hsieh[49] investigated a modified activated sludge system for control of bulking. This modified system incorporated a compartmentalised aerated basin and the bulking was primarily due to the outgrowth of filamentous organisms, which was substrate-gradient dependent. In this study, it is noted that savings in initial cost, operation and maintenance were substantial due to the reduced size of the secondary clarifiers.

Non-specific Methods

This class of methods mainly refers to the application of toxicants like chlorine and peroxides to selectively destroy the filamentous microbes and various polymers to improve floc-forming characteristics of the activated sludge. Jenkins[2], *et al*, concluded that such non-specific methods offer themselves as only a short-term control measure for activated sludge bulking.

Frenze[50] reported that different chlorine dosages were required to control bulking due to different filamentous microbes. Eisenhaur[51], *et al*, described the successful use of chlorine to control activated sludge bulking in a nitrification-denitrification process. Jenkins[37], *et al*, also demonstrated the successful application of chlorine at various plants using the following step-by-step approach:

(i) Establish a target SVI — below that the plant can operate successfully.

(ii) Start chlorination when the target SVI is consistently exceeded.

(iii) Add chlorine in known and controlled doses to all the activated sludge at points of excellent mixing where the chlorine demand is minimum.

(iv) Conduct reliable SVI tests to determine when chlorination should be discontinued.

This approach recognised an important control parameter for activated sludge chlorination the 'frequency' of chlorination. Neethling[52] reported that the minimum threshold frequency of chlorination for a given system must be exceeded if chlorination is to be effective, In another report, Neethling[53], *et al*, concluded that chlorination of bulking activated sludge will 'cure' bulking only if survival of the flock-forming micro-organisms exceeded that of the filamentous ones. In a study Daigger[54], *et al*, it was observed that chlorination could be used only springly as an operational tool for control of sludge bulking biological phosphorus removal plants.

To maximise the beneficial effect, chlorination should be added at the location where the chlorine demand from the waste is at a minimum[38]. However, pertinent literature revealed the following drawbacks for chlorination:

(i) It is only a short-term remedial strategy. Continued use of chlorination escalates the cost for operation of the activated sludge system[42].

(ii) It has not been reported to be successful for nutrient deficient bulking[38].

(iii) It requires frequent and careful microscopic analysis of the sludge to avoid an overdose — which can destabilise the system[2].

CONCLUSION

A review of the causes and control strategies of activated sludge bulking as reported in literature has been presented. Because bulking is a very widespread operational problem in treatment plants, detailed knowledge of possible causes and remedies is necessary for uninterrupted functioning of the waste treatment process. To date, research has resulted in the publication of much conflicting information and advice on bulking control. This review has revealed that successful bulking control measures in everyday practice are still very much empirical and system-specific in nature. It is hoped that this review will be useful in the investigation of causes and control methods of bulking with a system-specific approach and cost-effective in mind.

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