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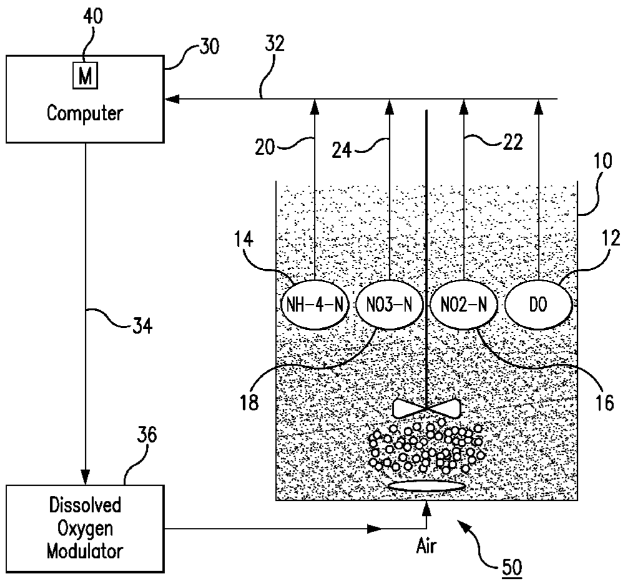

FIG. 11

(57) Abstract: A reactor and control method for maximizing nitrogen removal and minimizing aeration requirements through control of transient anoxia and aerobic SRT, repression of NOB, and control of dynamic DO concentrations or aeration interval by keeping the reactor NH4 and NOx concentrations approximately equal. Controls are provided for maximizing the potential for TIN removal through nitrification, limited nitritation, nitritation, denitrification, limited denitritation, denitritation making use of 1) real time measurement of ammonia, nitrite, nitrate, 2) operational DO and the proper use of DO setpoints, and 3) proper implementation of transient anoxia within a wide range of reactor configurations and operating conditions.

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METHOD AND APPARATUS FOR MAXIMIZING NITROGEN REMOVAL FROM WASTEWATER

[001] This nonprovisional application claims the benefit of U.S. Provisional Application No. 61/783,232, filed March 14, 2013. The entire disclosure of U.S. Provisional Application No. 61/783,232 is incorporated herein by reference.

Simultaneous nitrification and denitrification (SND) in a single tank is highly desirable compared to the conventional systems, since separate tanks and recycling of mixed liquor nitrate from the aerobic nitrifying zone to the anoxic denitrifying zone is not required. The benefits of SND are further extended by exploiting the nitrite shunt pathway as has been demonstrated by the use of aeration duration control with ORP (*see* Guo et al. 2009, the disclosure of which is expressly incorporated by reference herein in its entirety) and ammonia pH profile (*see* Peng et al. 2004, the disclosure of which is expressly incorporated by reference herein in its entirety). The reactor microenvironments (aerobic and anoxic zones developing within reactor due to combination of poor mixing and reactor design) and the floc microenvironments (aerobic and anoxic zones developing within the activated sludge flocs) have been postulated as possible mechanisms for SND (*see* Daigger et al. 2007, the disclosure of which is expressly incorporated by reference herein in its entirety). It is difficult to incorporate control strategies in the above-mentioned mechanisms to achieve stable SND performance. The occurrence of SND are reported in staged, closed loop reactors (such as oxidation ditch, orbal) (*see* Daigger and Littenton, 2000, the disclosure of which is expressly incorporated by reference herein in its entirety) that typically employ long hydraulic residence time (HRT), solids retention time (SRT), and continuous low dissolved oxygen (DO).

[002] The inhibition of nitrite oxidizing bacteria (NOB) is a precondition for the implementation of short-cut biological nitrogen removal (ScBNR) processes such as nitritation-denitritation (*see* Ciudad et al., 2005; Gee and Kim, 2004, Ju et al., 2007, Yoo et al., 1999, Yu et al., 2000, Zeng et al., 2008, the disclosures of which are expressly incorporated by reference herein in their entirety), nitrite-shunt and partial nitritation-anammox (*see* Fux et al., 2002,

Hippen et al., 1997, van Dongen et al., 2001,Wett, 2006, Wett, 2007, Wett et al., 2010, the disclosures of which are expressly incorporated by reference herein in their entirety), and deammonification. Successful suppression of nitrite oxidation by controlling NOB saves 25% oxygen and 40% organic carbon compared to conventional nitrification-denitrification (*see* Turk and Mavinic, 1986; Abeling and Seyfried, 1992, the disclosures of which are expressly incorporated by reference herein in their entirety). In deammonification processes, the control of NOB results in added benefits in further reductions in aeration energy required, and reduced costs of electron donor and solids handling. **FIG. 1**, **FIG. 2** and **FIG. 3** show flowcharts for nitrogen removal through conventional nitrification/denitrification, nitritation/denitritation and deammonification (partial nitritation + anaerobic ammonia oxidation), respectively.

[003] In view of high cost of biological nutrient removal (BNR) to meet increasingly stringent effluent standards, ScBNR through repression of NOB is a topic of interest. Efforts to understand NOB repression have been discussed in many publications, including those that are more specific to the use of high temperature (*see* Hellinga et al., 1998, the disclosure of which is expressly incorporated by reference herein in its entirety), high levels of free ammonia inhibition, or dissolved oxygen (DO) concentration (*see* Blackburne et al., 2008, the disclosure of which is expressly incorporated by reference herein in its entirety) and transient anoxia (*see* Kornaros and Dokianakis, 2010, the disclosure of which is expressly incorporated by reference herein in its entirety). Particularly, all of these conditions are used in part or as a whole, in various approaches, with success in controlling NOB in systems treating ‘high strength’ (high free ammonia) waste streams, such as anaerobic digester dewatering liquor (also usually at high temperature) and landfill leachate. Control of NOB repression in low strength waste streams such as domestic wastewater remains a challenge and is the subject of this disclosure. Controls that are currently used to repress NOB in ScBNR processes are described below.

[004] Temperature and Ammonia: Both temperature and free ammonia are features believed to provide an advantage to ammonia oxidizing bacteria (AOB) over NOB. Free ammonia (FA) inhibition of NOB has been well-documented in literature ever since it was considered by Anthonisen et al. (1976), the disclosure of which is expressly incorporated by reference herein in its entirety. However, knowledge of controlling FA inhibition to obtain stable nitritation is more limited since NOB adaptation has been reported (*see* Turk and Mavinic,

1989; *and* Wong-Chong and Loehr, 1978, the disclosures of which are expressly incorporated by reference herein in their entirety). Further, high temperature is known to favor growth of AOB over NOB (*see* Kim et al., 2008, the disclosure of which is expressly incorporated by reference herein in its entirety).

[005] The increased activity of AOB compared to NOB at higher temperature, greater disassociation of total ammonia to free ammonia and resulting NOB inhibition at higher temperatures, combined with low DO operation (often conducted using intermittent aeration and with managed aerobic solids retention time (SRT)), results in enrichment of AOB and selective wash out of NOB. These approaches are variously described (*see* EP 0826639 A1, EP 0872451 B1, US 2010/0233777 A1, US 7,846,334 B2, US 6,485,646 B1, *and* WO 2012/052443 A1, the disclosures of which are expressly incorporated by reference herein in their entirety) to control NOB in 'high strength' wastewater. These methods either use suspended growth (*see* WO 2006/129132 A1, the disclosure of which is expressly incorporated by reference herein in its entirety), attached growth on the support media (*see* US 2011/0253625 A1 *and* EP 0931768 B1, the disclosures of which are expressly incorporated by reference herein in their entirety) or granular sludge (*see* Wett, 2007; *and* US 7,846,334 B2, the disclosures of which are expressly incorporated by reference herein in their entirety) to accomplish ScBNR.

[006] In spite of being effective, the role of elevated temperature to increase activity of AOB and for the control of NOB growth is not feasible in low strength mainstream processes operating under a wide range of temperatures. Consequently, NOB control in low strength wastewater remains intractable and requires careful manipulation of factors other than temperature or free ammonia.

[007] Dissolved Oxygen: Dissolved oxygen (DO) can play a significant role in control of NOB in low strength wastewater. Sustained nitritation with the use of low DO concentration has been observed in a variety of reactor configurations (*see* Sliekers et al., 2005,Wyffels et al., 2004, *and* Blackburne et al., 2008, the disclosures of which are expressly incorporated by reference herein in their entirety). Although, all of these reports lack account of underlying mechanisms, they resort to a hypothesis of higher oxygen affinity of AOB compared to the NOB (*see* Hanaki et al., 1990; Laanbroek and Gerards, 1993; *and* Bernet et al., 2001, the disclosures of

which are expressly incorporated by reference herein in their entirety) as an explanation for the observed phenomenon (*see* Yoo et al., 1999, Peng et al., 2007, Lemaire et al., 2008, Gao et al., 2009, *and* Zeng et al., 2009, the disclosures of which are expressly incorporated by reference herein in their entirety). In a study Sin et al. (2008), the disclosure of which is expressly incorporated by reference herein in its entirety, has documented the prevalence of the belief that AOB oxygen affinity is greater than NOB oxygen affinity and that low DO operation favors AOB over NOB, however, there are studies that report the opposite (*see* Daebel et al., 2007, *and* Manser et al., 2005, the disclosures of which are expressly incorporated by reference herein in their entirety).

[008] Transient Anoxia: The use of transient anoxia has been a common approach to achieve NOB suppression (*see* Li et al., 2012; Ling, 2009, Pollice et al., 2002, Zekker et al., 2012, US 7,846,334 B2, EP 0872451 B1, *and* WO 2006/129132 A1, the disclosures of which are expressly incorporated by reference herein in their entirety). Transient anoxia allows for a measured approach to control the aerobic SRT as well as to introduce a lag-time for NOB to transition from the anoxic to aerobic environment. Kornaros and Dokianakis (2010), the disclosures of which are expressly incorporated by reference herein in their entirety, showed delay in NOB recovery and NOB lag adaptation in aerobic conditions following transient anoxia, thus confirming the observations of the usefulness of transient anoxia by many others (*see* Allenman and Irvine, 1980, Katsogiannis et al., 2003, Sedlak, 199, Silverstein and Schroeder, 1983, Yang and Yang, 2011, *and* Yoo et al., 1999, the disclosures of which are expressly incorporated by reference herein in their entirety). Although transient anoxia has been used successfully to control NOB in 'high strength' wastes (*see* Wett, 2007; *and* US 7,846,334 B2, the disclosures of which are expressly incorporated by reference herein in their entirety) and the ability to use it in low strength wastes has been suggested (*see* Peng et al., 2004, the disclosure of which is expressly incorporated by reference herein in its entirety), the ability to control the features associated with transient anoxia remains an enigma. To summarize, strategies for controlling NOB repression in low strength wastewater, which is the basis for emerging ScBNR technologies, vary widely and a need still exists for more effective control strategies.

SUMMARY

[009] Accordingly, the instant disclosure provides a system and method of removing nitrogen from wastewater in a reactor for biological nitrogen removal, wherein an aerobic-anoxic duration and/or a concentration of dissolved oxygen in the reactor is controlled based on a ratio of an [ammonia concentration] to a [sum of nitrite and nitrate concentrations] measured in real time. Typically, the aerobic-anoxic duration and/or the concentration of dissolved oxygen in the reactor is controlled to achieve a ratio of [ammonia concentration] to a [sum of nitrite and nitrate concentrations] that is about 1. Alternatively, the aerobic-anoxic duration and/or the concentration of dissolved oxygen in the reactor may be controlled to achieve a predetermined ratio of [ammonia concentration] to a [sum of nitrite and nitrate concentrations] that is less than or greater than 1. By employing the system and method of the instant disclosure, overall nitrogen removal is maximized because denitrification (dependent on COD input) and subsequent ammonia oxidation balance each other while also favoring AOB over NOB.

[0010] The system and method of the disclosure can be used to achieve a proper and measured control of a mainstream SND process that maximizes TIN removal through one of several nitrogen removal mechanisms including, nitrification-denitrification, nitritation-denitritation (scBNR), partial nitritation-denitritation producing an effluent stream appropriate for polishing by anammox in a separate downstream reactor, and partial nitritation-anammox in a single tank with selective anammox retention. These systems and methods use various control strategies, including: 1) real time measurement of ammonia, nitrite and nitrate, 2) operational DO and the proper use of DO setpoints controlled based on a ratio of the ammonia concentration to the nitrite + nitrate concentration measured in the reactor, 3) control of a frequency of aeration based on a ratio of the ammonia concentration to the nitrite + nitrate concentration measured in the reactor, and 4) proper implementation of transient anoxia within a wide range of apparatus (reactor configurations) and operating conditions.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. 1 is a molar flowchart showing the reactions associated with conventional nitrification and denitrification.

[0012] FIG. 2 is a molar flowchart showing the reactions associated with nitritation and denitritation.

[0013] FIG. 3 is a molar flowchart showing reactions associated with deammonification.

[0014] FIG. 4 is a line graph comparing collected data of K_O-values of AOB and NOB in a nitritation reactor of the HRSD Pilot

[0015] FIG. 5 is a flowchart showing a DO control algorithm based on ammonia, nitrite, nitrate and DO concentrations.

[0016] FIG. 6 is a comparison graph showing an illustration of implementation of transient anoxia logic with representative setpoints and control parameters.

[0017] FIG. 7 is a flowchart showing an aerobic duration control algorithm based on ammonia, nitrite, nitrate and DO concentrations.

[0018] FIG. 8 is a comparison graph showing an illustration of implementation of aerobic-anoxic duration control logic with representative setpoints and control parameters.

[0019] FIG. 9 is a graph comparing ammonia oxidation rates and nitrite oxidation rates in a reactor operated under strategy described in completely mixed process.

[0020] FIG. 10 is an illustration of possible effects of AVN control logic on overall system performance.

[0021] FIG. 11 is a lateral cross-sectional view of a BNR reactor fitted with a mechanical mixer, an air diffuser, an ammonia sensor, a nitrite sensor, a nitrate sensor and a dissolved oxygen sensor.

[0022] FIG. 12 illustrates real time ammonia, nitrite and nitrate measurements in a nitritation reactor operated under AVN control.

[0023] FIG. 13 illustrates TIN removal performance of a nitritation reactor operated under AVN control.

DETAILED DESCRIPTION

[0024] This application describes a system and method for removing nitrogen from wastewater processed in a reactor. The system and method of the disclosure maximizes nitrogen removal while minimizing aeration and organic carbon requirements through control of transient anoxia and aerobic SRT, repression of NOB, and control of dynamic DO concentrations or aeration interval by maintaining a predetermined ratio of [an ammonia (NH_4) concentration] to [a sum of nitrite and nitrate concentrations]. The predetermined ratio of an ammonia concentration to a sum of nitrite and nitrate concentrations is typically 1 but can be less than or greater than 1. The controller that leverages these dynamic control strategies has been named AVN (NH_4 vs. NO_x). AVN control not only maximizes the potential for TIN removal through the normal pathway (**FIG. 1**), but it also provides an opportunity for NOB repression and the associated benefits in terms of TIN removal according to **FIG. 2** and **FIG. 3**.

[0025] <u>Reactor Ammonia and Nitrite+Nitrate</u>: The current disclosure makes use of direct measurement of ammonia, nitrite and nitrate and DO in the BNR reactor to control the aerobic and anoxic SRT and HRT as well as the reactor DO concentration to maximize ammonia oxidation and denitrification. The DO concentration or aeration interval or both are effectively controlled depending on the influent Carbon:Nitrogen (C/N) and reactor conditions such that reactions needed to eliminate nitrogen are favored at any given time. DO is directed more to ammonia oxidation over COD oxidation and available COD is used to drive denitrification at all times, thus, maximizing the overall nitrogen removal (**FIG.10**). The extent of ammonia oxidation allowed by this disclosure is controlled by the availability of incoming COD for denitrification, so it is by nature that ammonia oxidation and denitrification are balanced by each other for maximum nitrogen removal. DO concentration and/or aeration duration are typically controlled to maintain approximately equal NH_4-N and NO_x-N concentrations in the reactor at all times, the amount of NH_4 oxidation and thus the amount of oxygen delivered is controlled based on the amount of incoming COD available to denitrify the produced NO_x. This minimizes aerobic heterotrophic COD consumption and maximizes the opportunity for denitrification, which requires time at low DO and available COD. The controller allows the input of offsets that would allow the NH_4-N or the NO_x-N concentration to be removed to meet specific discharge limits for these parameters. For example, the controller could be tuned to ensure compliance with an NH_4 limit by setting the controller to provide an effluent that contains NH_4 at 20-90% of the effluent NOx-N concentration.

[0026] Dissolved Oxygen: As described above and shown in **FIG. 4**, ammonia oxidation occurs at a faster rate at high DO concentrations (*i.e.*, concentrations greater than 1 mg/L) compared to nitrite oxidation. Therefore, it is desired to operate the BNR reactor at transiently high DO concentration such that AOB growth is favored over NOB. This strategy is in opposition to the large body of literature that indicates high oxygen affinity of AOB compared to NOB at low DO concentrations.

[0027] Intermittent Aeration: Rapid transition from a high DO into anoxia is very important considering the fact that the lag in NOB growth compared to AOB at high DO can only be exploited by imposing anoxic conditions. It means that at the end of the aerated period there will be some nitrite accumulation, for which NOB will have to compete with COD driven heterotrophic denitrifiers in scBNR and anammox in single stage deammonification processes. Therefore, DO pressure maintained in the aerated period from AOB and nitrite pressure from denitrifiers and anammox during anoxic period is greatly aided by rapid transition to anoxia.

[0028] Maintaining higher oxygen uptake rate (OUR) is the key for implementation of rapid transient anoxia. It is feasible to operate a BNR reactor at high OUR conditions by increasing MLSS concentration and COD input such that DO is rapidly consumed following onset of anoxia. The use of direct DO, ammonia, nitrite and nitrate measurement to control aerobic and anoxic SRT and HRT in a BNR reactor has been demonstrated in **FIGS. 6 and 8** which show rapidly alternating aerobic and anoxic conditions in a reactor. Under this strategy, the NH_4-N concentration is measured and maintained close to the NO_x-N concentration, or at any offset needed. Aeration is provided for ammonia oxidation such that the reactor NH_4-N concentration approximately matches the reactor NO_x-N concentration. This maintains elevated NH_4 concentration in the reactor at all times or locations ensuring that AOB rates are kept high. Hence, known NOB repression strategies may be exploited with use of a robust control algorithm based on direct NH_4, NO_2, NO_3 and DO signals. **FIG. 9** demonstrates the performance of this strategy in controlling NOB to achieve ScBNR in a nitrite-shunt process.

[0029] Specific controls are now described.

[0030] Aerobic SRT and DO setpoint: The aerobic SRT is controlled through two approaches. An increase in solids wasted decreases the total and aerobic SRT. A second approach to decreasing the aerobic SRT is by increasing the anoxic time step during transient anoxia. In an intermittently aerated (in time or space) BNR reactor operated under AVN control strategy, the aerobic SRT is determined by aeration needs of AOB to oxidize ammonia to nitrite or nitrate such that NH_4-N and NO_x-N concentration remain equal. For example, if AOB's ammonia oxidation rate is lower, more aeration (time or higher DO concentration or both) will be required to maintain this condition compared to when AOB rates are higher. In such a scenario, intentional lowering of the total SRT gradually results in a reduction in AOB ammonia oxidation rate at a certain DO value. Consequently, AOB require more aeration to increase their growth rate and to meet the desired condition (NH_4-N = NO_x-N) causing the operational high DO set point (in time) and aerobic HRT (in space) to increase and be at a point where the growth of AOB are favored over NOB.

[0031] Aggressive SRT control is not commonly accepted as a means for achieving nitrite shunt, which also coincides with inability to sustain stable NOB repression. When the BNR reactor is operated at high DO set points, AOB grow faster than NOB, which allows the system to be operated at low SRT further disadvantaging NOB. In addition, the application of aggressive SRT pressure is easily controlled according to this disclosure. Since the ammonia, nitrite and nitrate concentrations determine the operational high DO set points or aeration duration (in time) and aerated fraction (in space), it is a simple matter to control the total SRT such that the DO remains at a high concentration, in excess of 1 mg/L.

[0032] Transition to Anoxia Control: To extend this disclosure of AVN control to NOB repression, a more rapid transition between aerobic setpoint and anoxia is desirable to minimize the time available for NOB to grow favorably over AOB. There are at least three approaches to increase the oxygen uptake rates to transition to anoxia. One approach is to operate the reactor at higher mixed liquor solids concentration, such that there are more organisms seeking air in the same volume. Another approach is to use influent COD to allow for the scavenging of oxygen during the transition periods. A third approach is to increase the temperature and thus the growth rates of all organisms. The key feature is to allow for high oxygen uptake rates to transition from oxic to anoxic conditions.

[0033] Transient Anoxia Frequency (TAF) Control: To extend this disclosure of AVN control to NOB repression, it is desirable to have a high TAF to allow for rapid changes between aerobic and anoxic conditions while maintaining the same overall aerobic SRT. For example a 5 minute aerobic/anoxic cycle is preferred over a 15 minute aerobic/anoxic cycle, which is preferred over a 30 minute aerobic/anoxic cycle. A highest practicable TAF allows for disruption of NOB while allowing for preferential growth of AOB in the aerobic phase and denitrifying organisms or anammox organisms in the anoxic phase. There are constraints to maximizing this frequency. The increase in frequency, maximum value, is eventually constrained in the aerobic step by the time required to allow oxygen to achieve its setpoint and then to sufficiently oxidize ammonia. Additionally, a minimum anoxic time is required to allow denitrifying or anammox organisms to convert nitrite to nitrogen gas.

[0034] Reactor Configurations: Several apparatus are available to execute this

AOB oxidation and NOB repression framework, including complete mixed reactors, sequencing batch reactors, oxidation ditches and plug flow reactors. It should be noted that the reactor apparatus can be adjusted to deliver the control features for achieving SRT, ammonia oxidation requirements, high DO concentrations and anoxia transitions, where possible, by providing mechanical and hydraulic flexibility. Swing zones or reactors to accommodate variable flows and loads that are typical to a wastewater treatment process can be provided. Apart from suspended growth reactors, biofilm, granular sludge or hybrids of these reactors are also feasible. Finally, the solid-liquid separation could occur using any separation device including clarifiers, membranes or dissolved air floatation tanks.

[0035] Plug flow reactors are characterized as continuously fed reactors with very high length to width ratio and can be simulated as a series of completely mixed reactors where the pollutant concentration decreases along the flow pathway across the reactor's length (i.e. concentration gradient). In plug flow continuously fed reactors, which are more commonly used in large treatment plants, the process controls to achieve AVN control can be addressed using two configurations: (1) controlling aeration in space by alternating between aerobic and anaerobic zones; and (2) controlling aeration in time by cycling air throughout the reactor in "air on" and "air off" sequence similar to a SBR configuration.

[0036] AVN control can be integrated in various reactor configurations to achieve maximum nitrogen removal through nitrification-denitrification, nitritation-denitritation, and partial nitritation-anammox.

[0037] AVN control can be implemented in a single reactor or reactors in series with goal to achieve nitrogen removal through nitrification and denitrification when influent C/N is high. If the goal is to further improve nitrogen removal, provided the influent C/N is sufficient, the AVN control could also be used to repress NOB enabling ScBNR/nitritation-denitritation in any single reactor configuration or reactors in series. When influent C/N is low, AVN control can be used to realize autotrophic nitrogen removal through partial nitritation and anammox in any single reactor configuration or reactors in series, assuming selective anammox retention such as cyclone separation (US 2011/0198284 Al). Controls allow for appropriate reactor concentrations of NH_4 and NO_2 at all times and locations to allow for anammox growth. Above-mentioned reactor configurations could be used to feed a separate fully anoxic anammox reactor following the solids separation device, since with NOB repression effluent itself contains the right blend of NH_4 and NO_2 to serve as a substrate for anammox. This fully anoxic anammox reactor can be of any configuration, including but not limited to moving bed biofilm reactor, granular sludge reactor, suspended growth reactor, biologically active granular media filter, and membrane bioreactor.

[0038] Control Strategies

[0039] Several control strategies are available that can be applied in the above-mentioned reactor configurations that make use of features of this disclosure to achieve maximum TIN removal and can be extended to NOB repression. A few exemplary strategies are described below, optimized for various configurations.

[0040] Control Strategy A: The first control strategy under which the operational DO is variable and controlled by the NH_4-N and NO_x-N concentrations in the BNR reactor will optimize the DO for high ammonia oxidation rate and under anoxia, heterotrophic denitrification or anammox-driven ammonia oxidation. This approach is valid in a wide range of reactor configurations including plug flow, complete mix, complete mix reactors in series, and sequencing batch reactor. Under this approach the DO cycles between the low DO setpoint (which is fixed) and a variable high DO setpoint, usually greater than 1 mg/L and controlled by reactor NH4-N compared to NO_x-N concentrations. An aggressive aerobic SRT is maintained to increase the demand for oxygen, thus allowing for the controller to automatically increase the DO levels to greater than 1 mg/L. In this control strategy, the aerobic and anoxic periods are dictated by the AOB's aeration requirement to meet the objective for NH_4-N to be approximately equal to NO_x-N, as opposed to being fixed.

[0041] In this exemplary embodiment, a BNR reactor 10 **(FIG. 11)** may be fitted with DO, ammonia, nitrite and nitrate probes (or sensors) 12, 14, 16, 18. It will be possible to have any reactor configuration as described in the next subsection where the control can occur either in time or in space. In case of multiple or plug flow reactors, multiple DO probes are installed along each major section along a train, while an ammonia, nitrite and nitrate probe will be installed strategically in a latter reactor or section, to manage reaction rates such that small amounts of ammonia concentration remain at the end of the reactor and such that the reactor effluent contains NH_4-N concentrations approximately equal to NO_x-N.

[0042] The disclosure provides a system for removing nitrogen in a reactor for biological nitrogen removal from wastewaters. The system comprises: a reactor 10; an ammonia sensor (or probe) 14 that senses a concentration of ammonia in the reactor 10 in real time and generates an ammonia concentration signal 20; a nitrite sensor (or probe) 16 that senses a concentration of nitrite in the reactor 10 in real time and generates a nitrite concentration signal 22; a nitrate sensor (or probe) 18 that senses a concentration of nitrate in the reactor 10 in real time and generates a nitrate concentration signal 24; a controller 30 that receives the ammonia concentration signal, nitrite concentration signal and nitrate concentration signal via one or more communication links 32 and generates one or more instructions, which the controller 30 supplies to dissolved oxygen supply and control system (not illustrated) via communication link(s) 34, for increasing, decreasing or maintaining a concentration of dissolved oxygen in the reactor 10 by controlling concentrations of ammonia, nitrite, and nitrate based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate]; and a dissolved oxygen modulator 36 that supplies dissolved oxygen to the reactor 10 under control of the controller 30 based on the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate]. The dissolved oxygen modulator 36 may be coupled to the controller 30 via the one or more communication links 34. The system may further comprise one or more electronically (or mechanically) controlled valves that may be linked to the controller via communication links. The controller may generate instructions for increasing the concentration of dissolved oxygen if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is greater than 1. The controller 30 may generate instructions for decreasing the concentration of dissolved oxygen in the reactor 10 if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is less than 1. The controller 30 may generate instructions for maintaining the concentration of dissolved oxygen in the reactor 10 if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is 1.

[0043] The controller may be one or more computers. A “computer”, as used in this disclosure, means any machine, device, circuit, component, or module, or any system of machines, devices, circuits, components, modules, or the like, which are capable of manipulating data according to one or more instructions, such as, for example, without limitation, a processor, a microprocessor, a central processing unit, a general purpose computer, a super computer, a personal computer, a laptop computer, a palmtop computer, a notebook computer, a desktop computer, a workstation computer, a server, or the like, or an array of processors, microprocessors, central processing units, general purpose computers, super computers, personal computers, laptop computers, palmtop computers, notebook computers, desktop computers, workstation computers, servers, or the like.

[0044] A “communication link”, as used in this disclosure, means a wired and/or wireless medium that conveys data or information between at least two points. The wired or wireless medium may include, for example, a metallic conductor link, a radio frequency (RF) communication link, an Infrared (IR) communication link, an optical communication link, or the like, without limitation. The RF communication link may include, for example, WiFi, WiMAX, IEEE 802.11, DECT, 0G, 1G, 2G, 3G or 4G cellular standards, Bluetooth, and the like.

[0045] The controller 30 may include a computer-readable medium 40 that includes a computer program having code sections or segments, which when executed by the computer(s) 30, cause each of the processes described herein to be carried out. A "computer-readable medium", as used in this disclosure, means any medium that participates in providing data (for example, instructions) which may be read by a computer. Such a medium may take many forms, including non-volatile media, volatile media, and transmission media. Non-volatile media may include, for example, optical or magnetic disks and other persistent memory. Volatile media may include dynamic random access memory (DRAM). Transmission media may include coaxial cables, copper wire and fiber optics, including the wires that comprise a system bus coupled to the processor. Transmission media may include or convey acoustic waves, light waves and electromagnetic emissions, such as those generated during radio frequency (RF) and infrared (IR) data communications. Common forms of computer-readable media include, for example, a floppy disk, a flexible disk, hard disk, magnetic tape, any other magnetic medium, a CD-ROM, DVD, any other optical medium, punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a PROM, an EPROM, a FLASH-EEPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read. The computer-readable medium may include a "Cloud," which includes a distribution of files across multiple (e.g., thousands of) memory caches on multiple (e.g., thousands of) computers.

[0046] According to another aspect of the disclosure, the system for removing nitrogen in a reactor for biological nitrogen removal from wastewaters may comprise: a reactor; an ammonia sensor (or probe) that senses a concentration of ammonia in the reactor in real time and generates an ammonia concentration signal; a nitrite sensor (or probe) that senses a concentration of nitrite in the reactor in real time and generates a nitrite concentration signal; a nitrate sensor (or probe) that senses a concentration of nitrate in the reactor in real time and generates a nitrate concentration signal; a controller that receives the ammonia concentration signal, nitrite concentration signal and nitrate concentration signal via one or more communication links and generates instructions, which may be supplied to one or more valves and/or an aerator, for increasing, decreasing or maintaining DO concentration and aerobic-anoxic duration within the reactor based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate]; and the aerator that aerates the reactor at a frequency controlled by the controller, wherein the frequency is based on the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate]. The controller may generate instructions for increasing DO concentration or the aerobic duration (or decreasing the anoxic duration) if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is greater than 1. The controller may generate instructions for decreasing DO concentration or the aerobic duration (or increasing the anoxic duration) treatment if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is less than 1. The controller may generate instructions for maintaining DO concentration and aerobic-anoxic duration if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is 1.

[0047] In an example, the dissolved oxygen concentration and/or the duration of the aerobic and anoxic periods is regulated by switching an air control valve 50 either ON or OFF, based on a high DO (HDO) and low DO (LDO) setpoint. For instance, to increase the duration of an aerobic period and decrease the duration of an anoxic period, the air control valve 50 can be switched ON. In contrast, to decrease the duration of an aerobic period and increase the duration of an anoxic period, the air control valve 50 can be switched OFF. The LDO setpoint is fixed at near zero (0.001 to 0.1 mg/L) whereas HDO is variable (based on NH_4-N, NO_3-N and NO_2-N measured real-time in the tank) from 0.3 mg/L (MinHDO) to 3.0 mg/L (MaxHDO). The MaxHDO is set at 2.0-3.0 mg/L, since adding more aeration beyond this point is believed to provide no added benefit in terms of ammonia oxidation rate. When the NH_4-N in the reactor 10 is greater than the NO_x-N (YES from S10, **FIG. 5**), the HDO is increased (S12) until the NH_4-N gets below NO_x-N. When the NH_4-N concentration is lower than the NO_x-N (NO from S10), the HDO is decreased (S14) until the NH_4-N concentration becomes equal to or greater than the NO_x-N. Offsets can be applied as discussed above to allow for a higher effluent NH_4 versus NO_x or vice versa as required. Aggressive SRT control is accomplished by wasting solids such that the HDO setpoint is consistently greater than 1mg/L.

The total SRT can also be controlled automatically by maintaining the waste flow rate based on reactor DO concentration over certain averaging time.

[0048] Control Strategy B – In this strategy, DO set point is fixed while aerobic and anoxic duration is variable. The total aerobic-anoxic cycle time can be maintained at certain set point while allowing aerobic and anoxic durations to vary. In another instance, anoxic duration can be fixed, allowing the controller to modify only the aerobic duration, such that overall anoxic + aerobic duration remains dynamic depending on the nitrogen removal potential. Mechanical mixing (60, Fig. 11) should be provided when aeration (50) is not provided. In the example illustrated in **FIG. 7**, aerobic duration is variable between 5 minutes to 15 minutes while anoxic duration is 10 minutes. When the NH_4-N in the reactor is greater than the NO_x-N (YES from S20), the aerobic duration is increased (S22) until the NH_4-N gets below NO_x-N. When the NH_4-N concentration is lower than the NO_x-N (NO from S20), the aerobic duration is decreased (S24) until the NH_4-N concentration becomes equal to or greater than the NO_x-N. Offsets can be applied as discussed above to allow for a higher effluent NH_4 versus NO_x or vice versa as required.

[0049] Control Strategy C: AVN control can also be used in plug flow tank with multiple aerobic and anoxic swing zones in series. AVN control affects which zones in series are maintained anoxic or aerobically to achieve to the control objective.

[0050] EXAMPLES

[0051] The system for removing nitrogen in a reactor for biological nitrogen removal from wastewaters of the present disclosure was operated with 2-3 hr hydraulic residence time (HRT), ~5 day SRT, 3500±500 mg/L mixed liquor suspended solids (MLSS) at 25 °C. The reactor was operated under the AVN control strategies set forth at paragraph [0047] (above) and shown in **FIGS. 5 and 7**. **FIG. 9** represents the NOB repression that was observed. The AVN controller performance is demonstrated in **FIG.12**. As seen in **FIG. 13**, high TIN removal, wherein the removal was dependent on COD input, was also achieved using the same operating conditions.

Relevant Acronyms:

AOB: ammonia oxidizing bacteria
BNR: biological nutrient removal
COD: chemical oxygen demand
C/N: Carbon to nitrogen ratio
DO: dissolved oxygen
FA: free ammonia
HDO: high DO
HRT: hydraulic residence time
LDO: low DO
NOB: nitrite oxidizing bacteria
NO_x: Nitrate
NO_x-N: Nitrate-nitrogen plus Nitrite-nitrogen
NO_3-N: Nitrate-nitrogen
NO_2-N: Nitrite-nitrogen
NO_3: Nitrate
NO_2: Nitrite
NH_4-N: Ammonia-nitrogen
OUR: oxygen uptake rate
ScBNR: short-cut biological nitrogen removal
SRT: solids retention time
TAF: Transient Anoxia Frequency
TIN: Total Inorganic Nitrogen
TN: Total Nitrogen

AMENDED CLAIMS

received by the International Bureau on 22 September 2014 (22.09.14)

1) A system for removing nitrogen from a reactor for biological nitrogen removal from wastewaters comprising:

   a) a reactor;

   b) an ammonia sensor that senses a concentration of ammonia in the reactor in real time and generates an ammonia concentration signal;

   c) a nitrite sensor that senses a concentration of nitrite in the reactor in real time and generates a nitrite concentration signal;

   d) a nitrate sensor that senses a concentration of nitrate in the reactor in real time and generates a nitrate concentration signal;

   e) a controller that receives the ammonia concentration signal, nitrite concentration signal and nitrate concentration signal and generates instructions for increasing, decreasing or maintaining a concentration of dissolved oxygen in the reactor based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate]; and

   f) a dissolved oxygen modulator that supplies dissolved oxygen to the reactor under control of the controller based on the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate].

2) The system of claim 1, wherein the controller generates instructions for increasing the concentration of dissolved oxygen if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is greater than 1.

3) The system of claim 1, wherein the controller generates instructions for decreasing the concentration of dissolved oxygen if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is less than 1.

4) The system of claim 1, wherein the controller generates instructions for maintaining the concentration of dissolved oxygen if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is 1.

5) The system of claim 1, wherein the controller generates instructions for increasing or decreasing or maintaining the concentration of dissolved oxygen to maintain a ratio of [a sum of the concentrations of nitrite and nitrate] to a [concentration of ammonia] that is from about 1.18 to about 1.45.

6) The system of claim 5, wherein the controller generates instructions for increasing or decreasing or maintaining the concentration of dissolved oxygen to maintain the ratio of [the sum of the concentrations of nitrite and nitrate] to the [concentration of ammonia] that is equal to about 1.32.

7) A system for removing nitrogen from a reactor for biological nitrogen removal from wastewaters comprising:

a) a reactor;

b) an ammonia sensor that senses a concentration of ammonia in the reactor in real time and generates an ammonia concentration signal;

c) a nitrite sensor that senses a concentration of nitrite in the reactor in real time and generates a nitrite concentration signal;

d) a nitrate sensor that senses a concentration of nitrate in the reactor in real time and generates a nitrate concentration signal;

e) a controller that receives the ammonia concentration signal, nitrite concentration signal and nitrate concentration signal and generates instructions for increasing, decreasing or maintaining a duration of aerobic and anoxic period within the reactor based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate]; and

f) a dissolved oxygen modulator that supplies the dissolved oxygen to the reactor to control the duration of aerobic and anoxic periods, wherein the dissolved oxygen modulator is under the control of the controller and controls the duration of the aerobic and anoxic periods based on the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate].

8) The system of claim 7, wherein the controller generates instructions for increasing the duration of the aerobic period and/or decreasing the duration of the anoxic period if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is greater than 1.

9) The system of claim 7, wherein the controller generates instructions for decreasing the duration of the aerobic period and/or increasing the duration of the anoxic period if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is less than 1.

10) The system of claim 7, wherein the controller generates instructions for maintaining the duration of the aerobic period and/or the duration of the anoxic period if the ratio of the [concentration of ammonia] to [the sum of the concentrations of nitrite and nitrate] is 1.

11) A method of removing nitrogen from wastewaters in a reactor comprising:

a) oxidizing a fraction of an influent ammonia load to produce nitrite and nitrate, wherein the oxidation is conducted by providing an amount of aeration that is sufficient to oxidize only a fraction of the influent ammonia for which there is a sufficient amount of chemical oxygen demand (COD) in the reactor that will subsequently reduce the oxidized nitrogen species;

b) measuring a concentration of ammonia, a concentration of nitrite and a concentration of nitrate in the reactor in real time; and

c) controlling a concentration of dissolved oxygen (DO) supplied to the reactor, and/or a frequency at which aeration occurs in the reactor, based on a ratio of the [concentration of ammonia] to a [sum of the concentrations of nitrite and nitrate].

12) The method of claim 11, wherein the concentration of dissolved oxygen supplied to the reactor and/or the frequency at which aeration occurs in the reactor is increased if the ratio of the [concentration of ammonia] to the [sum of the concentrations of nitrite and nitrate] is greater than 1.

13) The method of claim 11, wherein the concentration of dissolved oxygen supplied to the reactor and/or the frequency at which aeration occurs in the reactor is decreased if the ratio of the [concentration of ammonia] to the [sum of the concentrations of nitrite and nitrate] is less than 1.

14) The method of claim 11, wherein the concentration of dissolved oxygen supplied to the reactor and/or the frequency at which aeration occurs in the reactor is maintained if the ratio of the [concentration of ammonia] to the [sum of the concentrations of nitrite and nitrate] is 1.

15) The method of claim 11, further comprising controlling a limited aerobic sludge retention time in the reactor, wherein the limited aerobic sludge retention time is controlled based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate].

16) The method of claim 11, further comprising controlling an extension and/or volume of anoxic periods, wherein the extension and/or volume of anoxic periods is controlled based on a ratio of the [concentration of ammonia] to [a sum of the concentrations of nitrite and nitrate].

17) The method of claim 11, further comprising enhancing an oxygen uptake rate (OUR) to facilitate a plurality of rapid transitions from an aerobic condition to an anoxic condition by maintaining a concentration of a mixed liquor solid (MLSS) that is higher than 2 g/L or by maintaining equivalent biomass quantities in a biofilm system.

18) The method of claim 17, wherein an aeration control system is used to control a frequency of the transitions between the aerobic and anoxic conditions.

19) The method of claim 11, wherein the reactor is a sequencing batch reactor or a completely mixed reactor.

20) The method of claim 11, wherein the method is an oxidation ditch process or a plug flow process.

21) The method of claim 11, further comprising at least one of a suspended growth process, a granular process, a biofilm process or a combination thereof.

22) The method of claim 11, further comprising a separation process using a settler, a dissolved air flotation device, a filter or a membrane.

23) The method of claim 11, further comprising feeding a minimum mass-flow of organic carbon to the reactor to facilitate a rapid transition to an anoxic state from an aerated state and to provide additional competition for nitrite to improve repression of NOB.

24) The method of claim 11, further comprising supplying the reactor with an anammox organism to provide competition for nitrite to improve repression of NOB.

25) The apparatus of claim 1, wherein the apparatus is configured to provide conditions, with nitrite oxidizing bacteria repression and the production of an effluent stream containing approximately equal proportions of ammonia and nitrite on an as nitrogen basis, such that further nitrogen removal can be accomplished using anammox in a fully anoxic suspended or biofilm process, or to selectively retain anammox.

26) The apparatus of claim 25, wherein the apparatus is configured to provide conditions, with effluent stream containing a blend of ammonia, nitrite, and nitrate, such that further nitrogen removal can be accomplished using anammox in a fully anoxic suspended or biofilm process whereby acetate or acetic acid or other organic substrate are added to accomplish denitratation (nitrate reduction to nitrite) and subsequent anammox growth on the provided ammonia and denitratation-produced nitrite.

27) The method of claim 11, further comprising the step of providing conditions, with nitrite oxidizing bacteria repression and the production of an effluent stream containing approximately equal proportions of ammonia and nitrite on an as nitrogen basis, such that further nitrogen removal can be accomplished using anammox in a fully anoxic suspended or biofilm process.

28) The method of claim 27, further comprising the step of providing conditions, with an effluent stream containing a blend of ammonia, nitrite, and nitrate, such that further

nitrogen removal can be accomplished using anammox in a fully anoxic suspended or biofilm process whereby acetate or acetic acid or other organic substrate are added to accomplish denitratation (nitrate reduction to nitrite) and subsequent anammox growth on the provided ammonia and denitratation-produced nitrite.

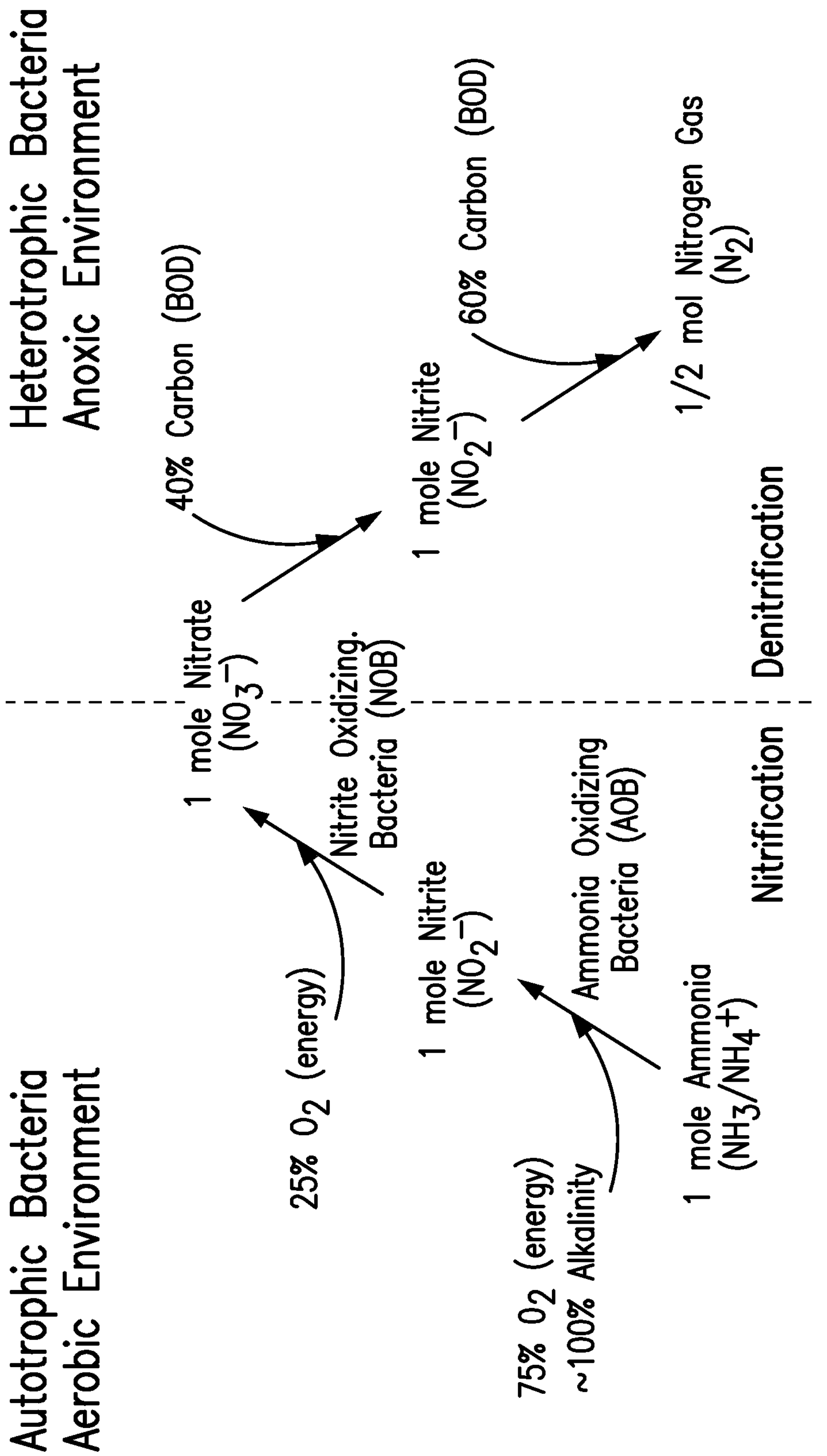

Autotrophic Bacteria
Aerobic Environment
Heterotrophic Bacteria
Anoxic Environment
1 mole Ammonia (NH_3/NH_4^+)
75% O_2 (energy)
~100% Alkalinity
Ammonia Oxidizing Bacteria (AOB)
1 mole Nitrite (NO_2^-)
25% O_2 (energy)
Nitrite Oxidizing. Bacteria (NOB)
1 mole Nitrate (NO_3^-)
40% Carbon (BOD)
1 mole Nitrite (NO_2^-)
60% Carbon (BOD)
1/2 mol Nitrogen Gas (N_2)
Nitrification
Denitrification

FIG. 1

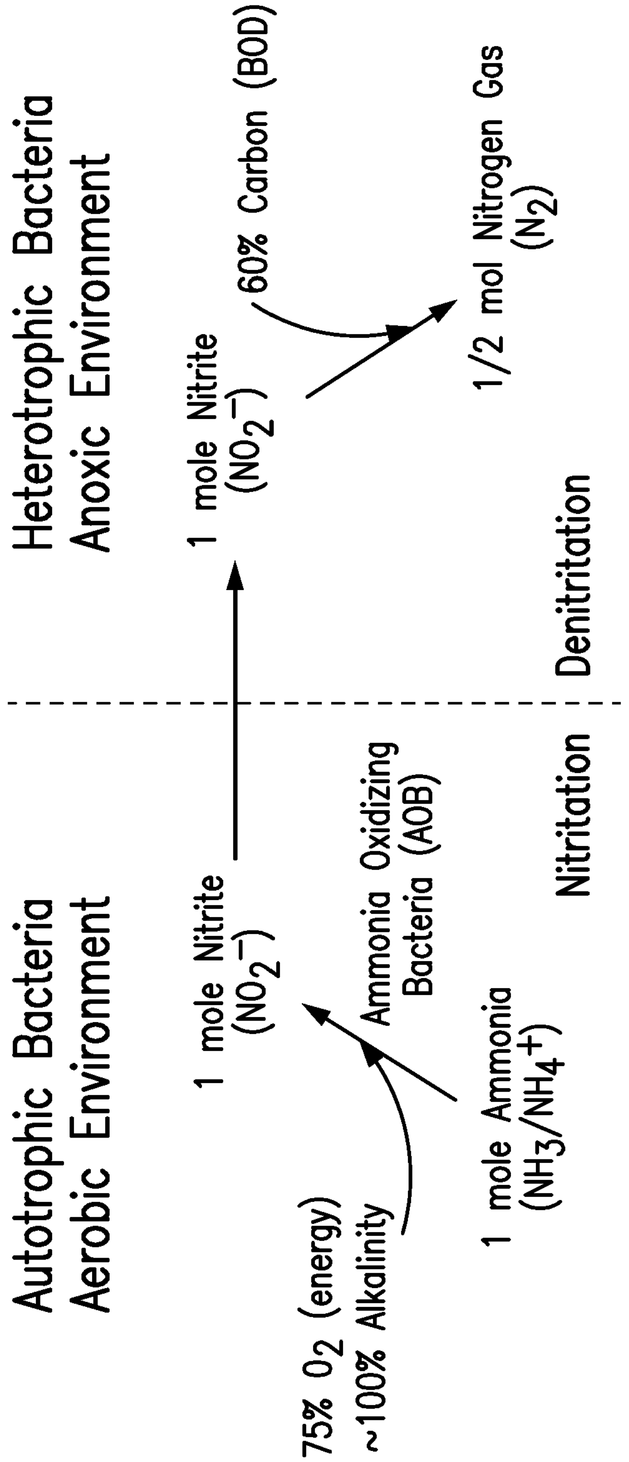

Autotrophic Bacteria
Aerobic Environment
Heterotrophic Bacteria
Anoxic Environment
75% O2 (energy)
~100% Alkalinity
1 mole Ammonia
(NH3/NH4+)
Ammonia Oxidizing
Bacteria (AOB)
1 mole Nitrite
(NO2−)
1 mole Nitrite
(NO2−)
60% Carbon (BOD)
1/2 mol Nitrogen Gas
(N2)
Nitritation
Denitritation

FIG. 2

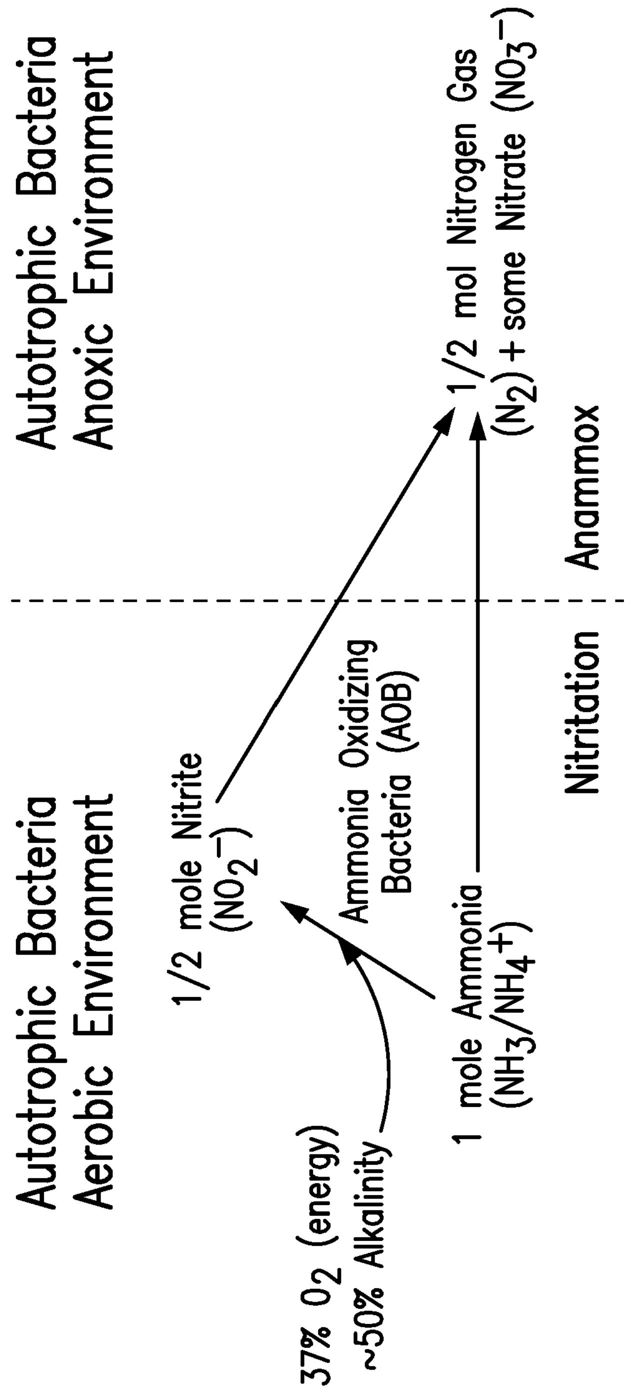

Autotrophic Bacteria
Aerobic Environment
Autotrophic Bacteria
Anoxic Environment
37% O_2 (energy)
~50% Alkalinity
1 mole Ammonia
(NH_3/NH_4^+)
1/2 mole Nitrite
(NO_2^-)
Ammonia Oxidizing
Bacteria (AOB)
1/2 mol Nitrogen Gas
(N_2) + some Nitrate (NO_3^-)
Nitritation
Anammox

FIG. 3

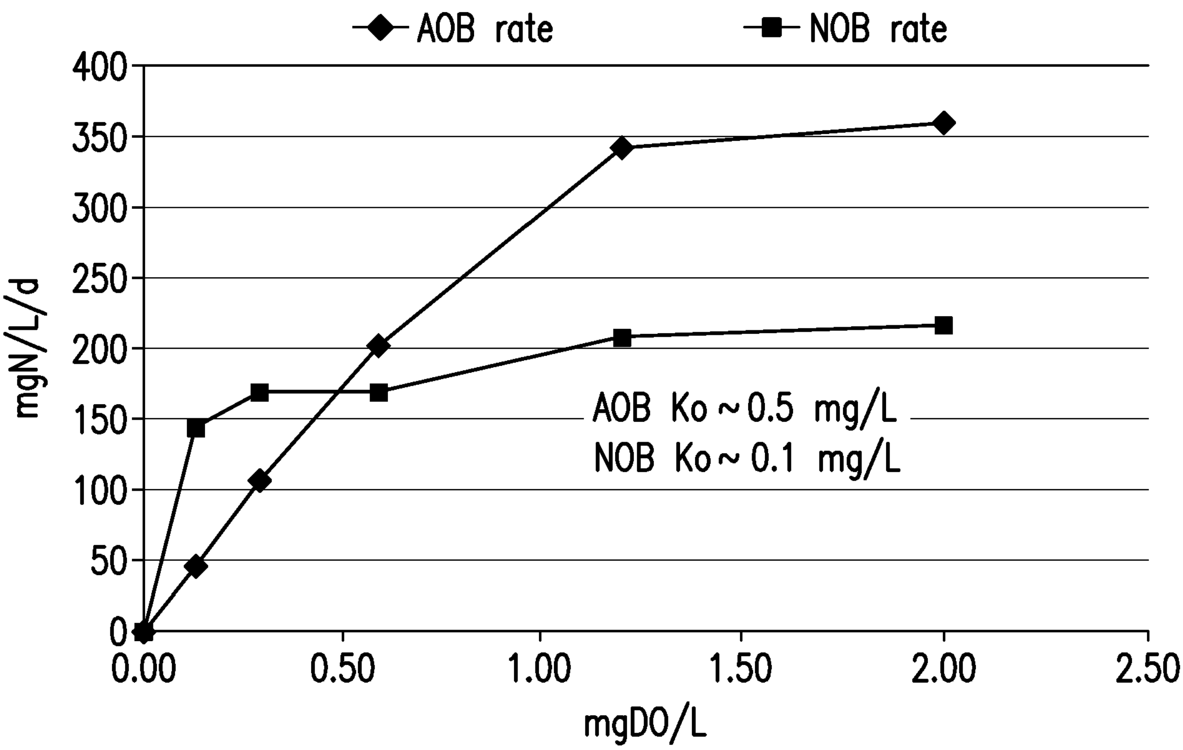

AOB rate
NOB rate
400
350
300
250
200
150
100
50
0
mgN/L/d
AOB Ko ~ 0.5 mg/L
NOB Ko ~ 0.1 mg/L
0.00
0.50
1.00
1.50
2.00
2.50
mgDO/L

FIG. 4

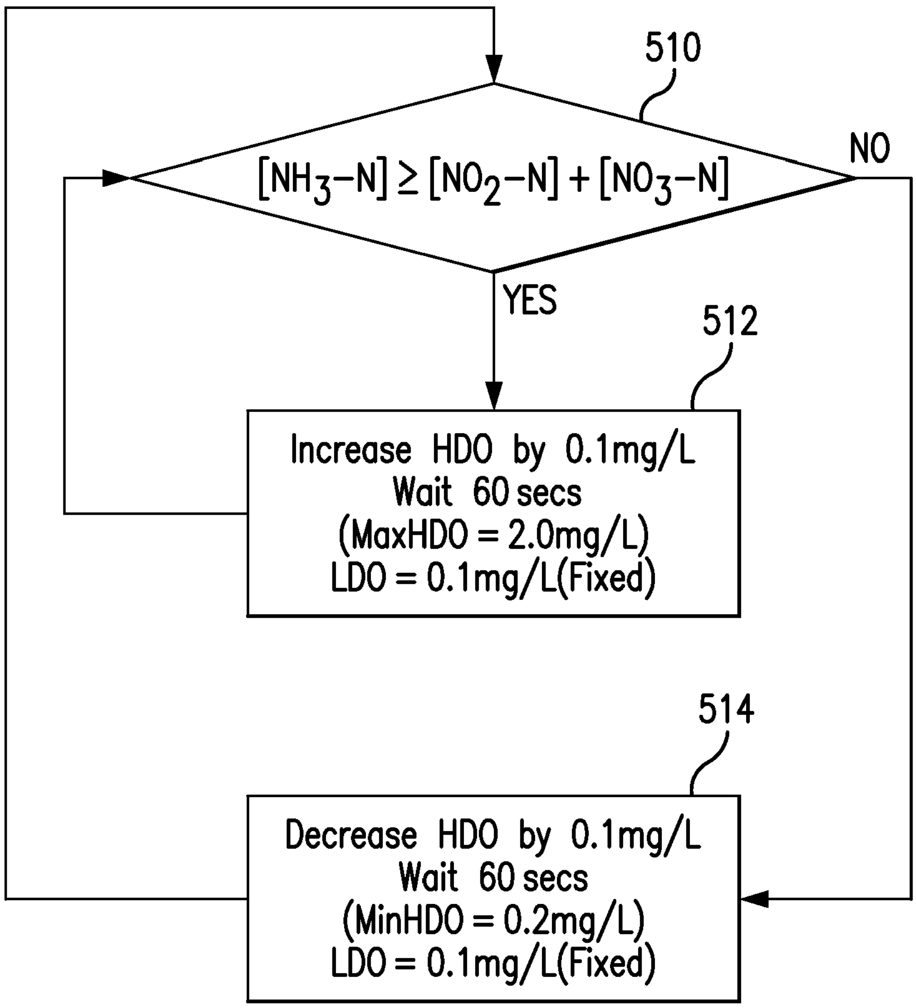
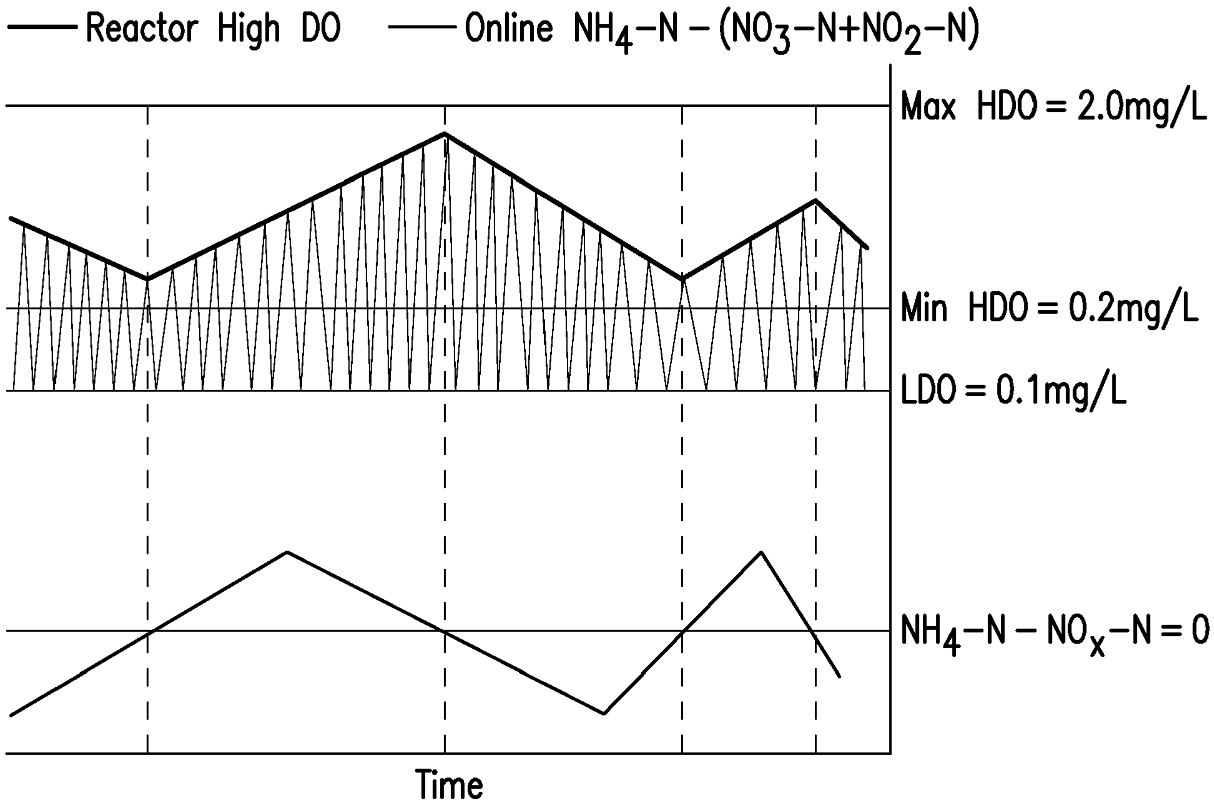

510
$[NH_3-N] \geq [NO_2-N] + [NO_3-N]$
NO
YES
512
Increase HDO by 0.1mg/L
Wait 60 secs
(MaxHDO = 2.0mg/L)
LDO = 0.1mg/L(Fixed)
514
Decrease HDO by 0.1mg/L
Wait 60 secs
(MinHDO = 0.2mg/L)
LDO = 0.1mg/L(Fixed)

FIG. 5



Reactor High DO
Online NH4–N – (NO3–N+NO2–N)
Max HDO = 2.0mg/L
Min HDO = 0.2mg/L
LDO = 0.1mg/L
NH4–N – NOx–N = 0
Time

FIG. 6

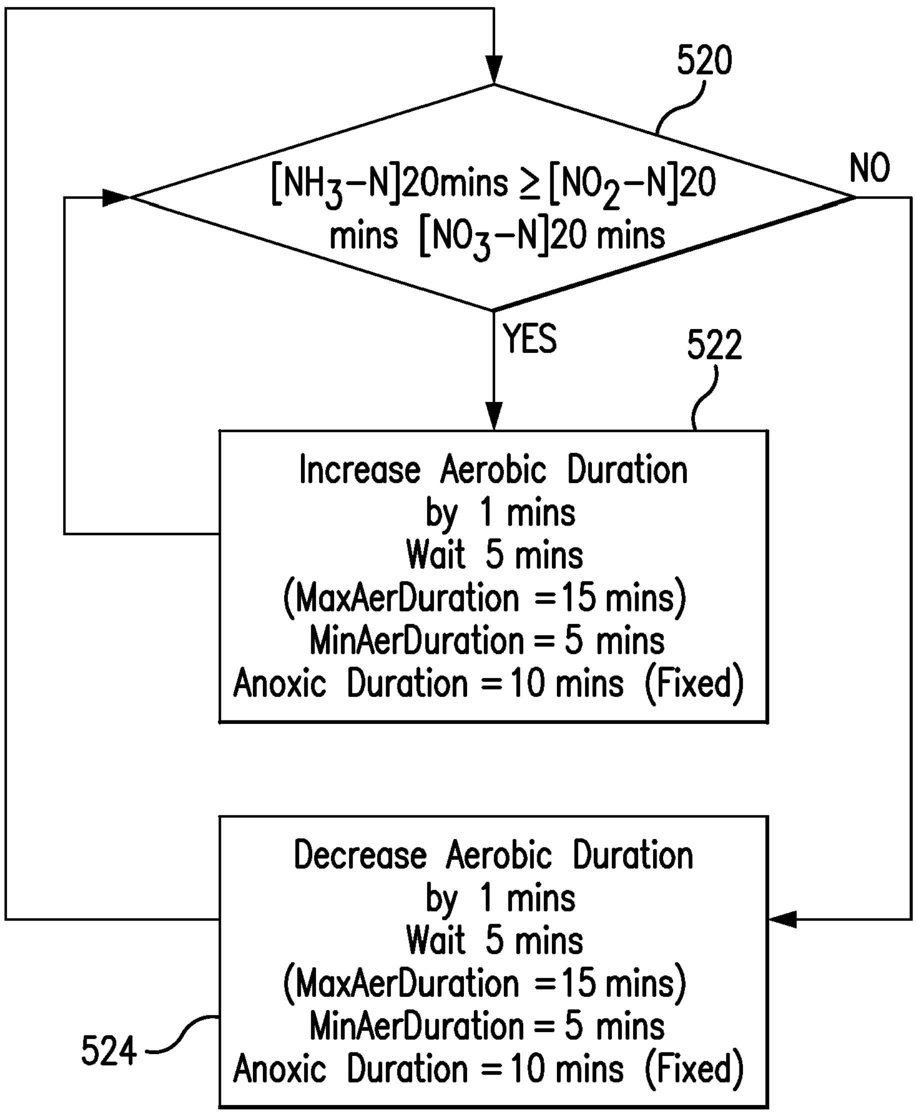

520
[NH3–N]20mins ≥ [NO2–N]20 mins [NO3–N]20 mins
NO
YES
522
Increase Aerobic Duration by 1 mins
Wait 5 mins
(MaxAerDuration = 15 mins)
MinAerDuration = 5 mins
Anoxic Duration = 10 mins (Fixed)
Decrease Aerobic Duration by 1 mins
Wait 5 mins
(MaxAerDuration = 15 mins)
MinAerDuration = 5 mins
Anoxic Duration = 10 mins (Fixed)
524

FIG. 7

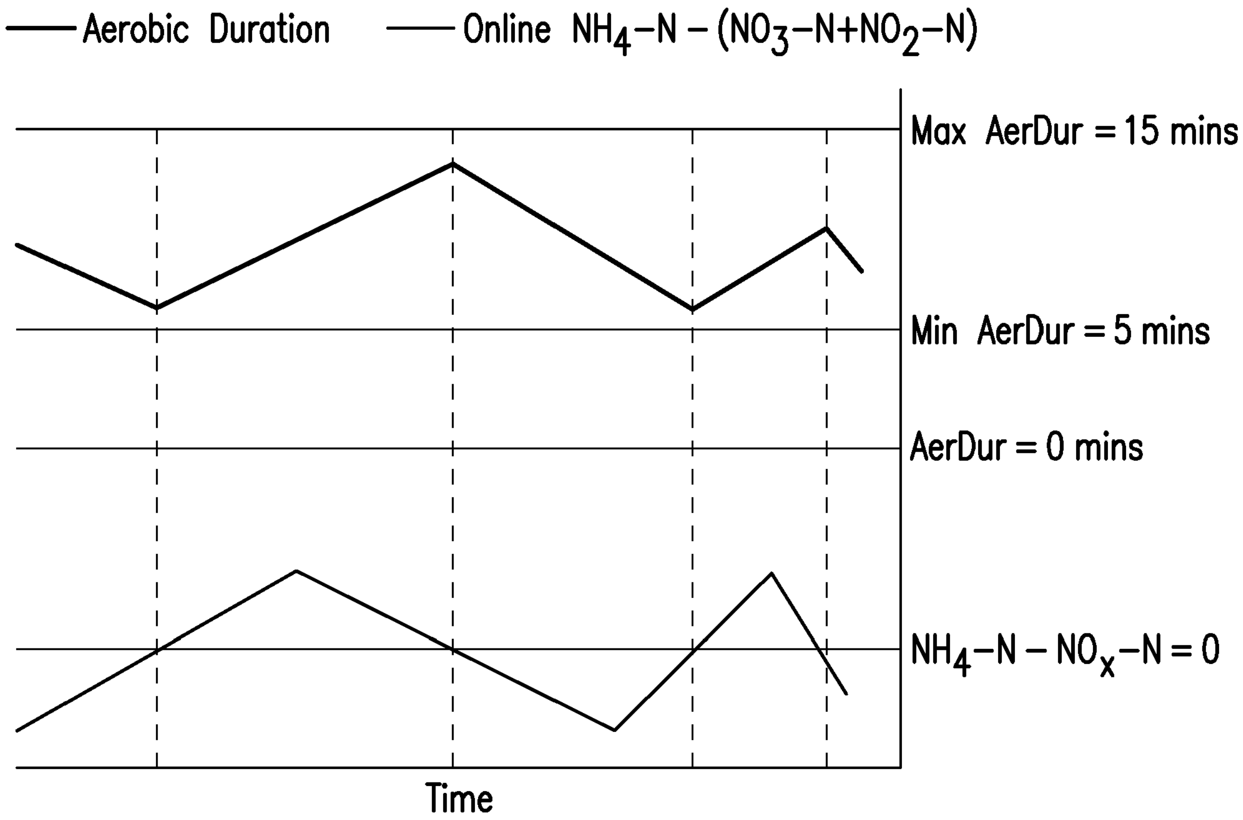

Aerobic Duration
Online NH4-N - (NO3-N+NO2-N)
Max AerDur = 15 mins
Min AerDur = 5 mins
AerDur = 0 mins
NH4-N - NOx-N = 0
Time

FIG. 8

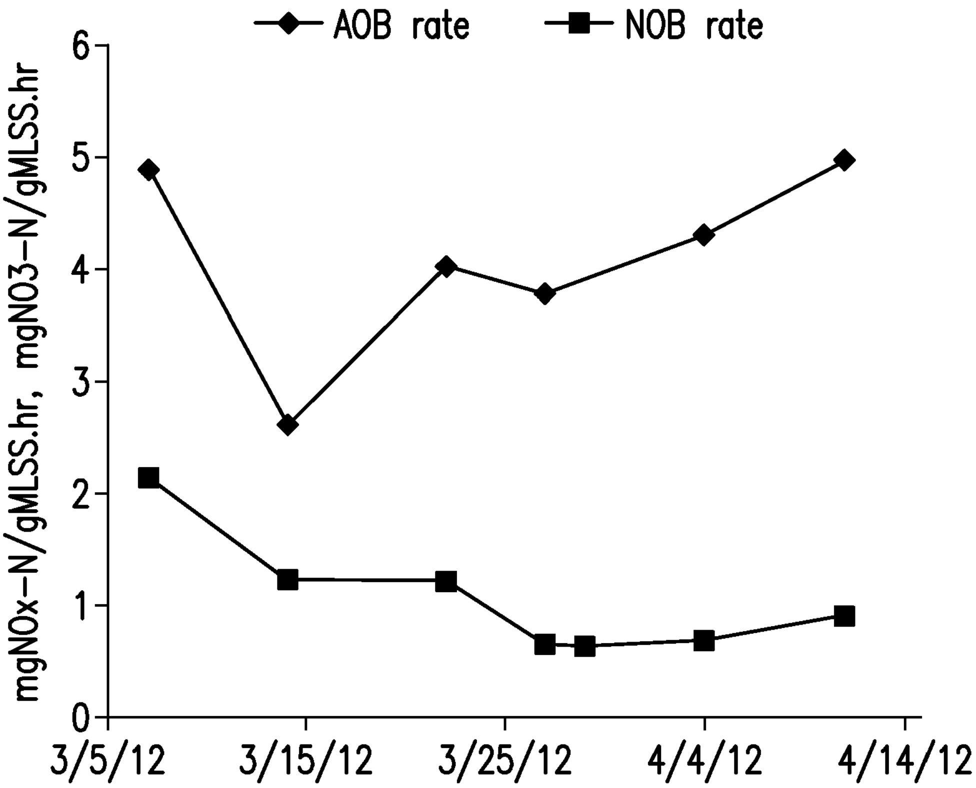

AOB rate
NOB rate
6
5
4
3
2
1
0
mgNOx-N/gMLSS.hr, mgNO3-N/gMLSS.hr
3/5/12
3/15/12
3/25/12
4/4/12
4/14/12

FIG. 9

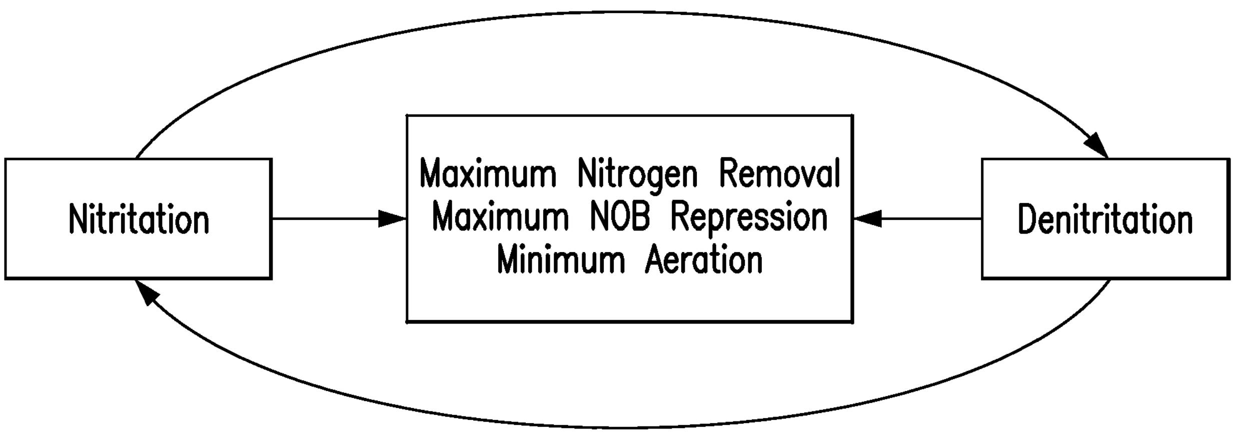

Nitritation
Maximum Nitrogen Removal
Maximum NOB Repression
Minimum Aeration
Denitritation

FIG. 10

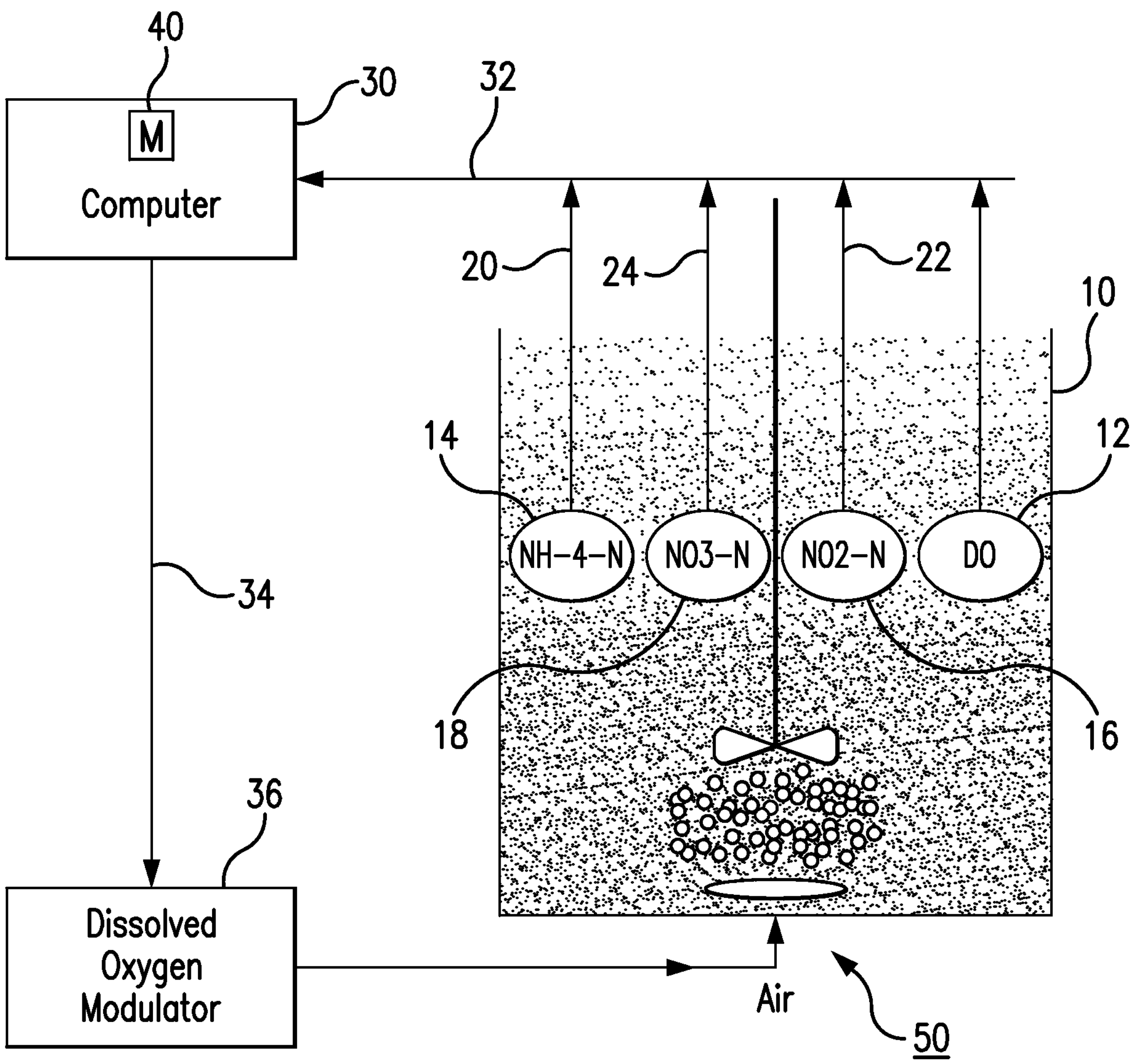

40
M
Computer
30
32
20
24
22
10
14
12
NH-4-N
NO3-N
NO2-N
DO
34
18
16
36
Dissolved
Oxygen
Modulator
Air
50

FIG. 11

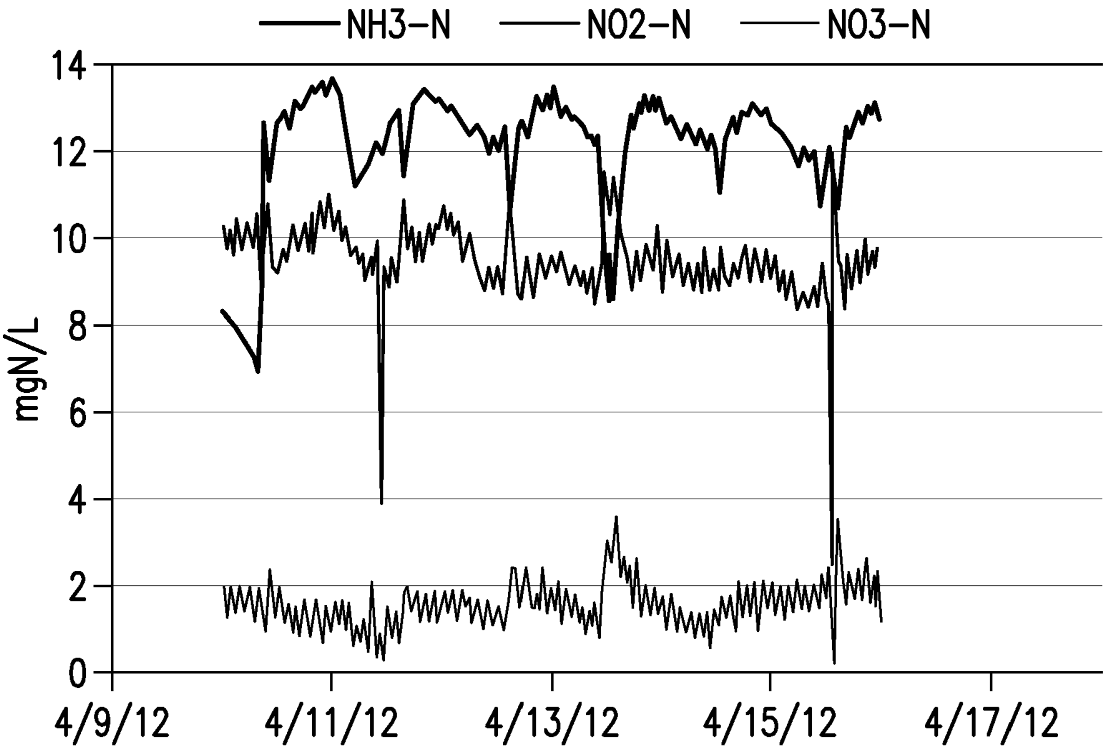


FIG. 12

Average (8/26/2012-9/4/2012)			
Influent	Influent	Nitritation Eff	Nitritation
NH3-N, mg/L	sCOD, mg/L	TIN, mg/L	% TIN Removal
32.1	145	5.3	84

FIG. 13