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Inventor(s)

COTE; Pierre Lucien et al.

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### MEMBRANE ASSEMBLY FOR SUPPORTING A BIOFILM

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#### Abstract

A cord for supporting a biofilm has a plurality of yarns. At least one of the yarns comprises a plurality of hollow fiber gas transfer membranes. At least one of the yarns extends along the length of the cord generally in the shape of a spiral. Optionally, one or more of the yarns may comprise one or more reinforcing filaments. In some examples, a reinforcing yarn is wrapped around a core. A module may be made by potting a plurality of the cords in at least one header. A reactor may be made and operated by placing the module in a tank fed with water to be treated and supplying a gas to the module. In use, a biofilm covers the cords to form a membrane biofilm assembly.

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**Inventors:** COTE; Pierre Lucien (Ancaster, CA), PEDERSEN; Steven Kristian (Nottawa, CA)

**Applicant:** BL TECHNOLOGIES, INC. (Minnetonka, MN)

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] This application is a continuation of U.S. application Ser. No. 18/338,182, filed Jun. 20, 2023, which is a continuation of U.S. application Ser. No. 16/998,704, filed Aug. 20, 2020, issued on Aug. 15, 2023 as U.S. Pat. No. 11,724,947, which is a of continuation of U.S. application Ser. No. 14/769,461, filed Aug. 21, 2015, issued on Sep. 22, 2020 as U.S. Pat. No. 10,781,119, which is a National Stage Entry of International Application No. PCT/US2013/027435, filed Feb. 22, 2013. U.S. application Ser. No. 18/338,182, Ser. No. 16/998,704 and Ser. No. 14/769,461 and International Application No. PCT/US2013/027435 are incorporated herein by reference.

## FIELD

[0002] This specification relates to wastewater treatment, to membrane biofilm reactors, and to assemblies of gas permeable membranes for supporting a biofilm.

## BACKGROUND

[0003] In a membrane biofilm reactor (MBfR), a membrane is used to both support a biofilm and to transport a gas to the biofilm. Membrane biofilm reactors were recently reviewed by Martin and Nerenberg in “The membrane biofilm reactor (MBfR) for water and wastewater treatment: Principles, applications, and recent developments” (Bioresour. Technol. 2012). Membrane-aerated biofilm reactors (MABR) are a subset of MBfRs in which an oxygen containing gas is used. MABRs were reviewed by Syron and Casey in “Membrane-Aerated Biofilms for High Rate Biotreatment: Performance Appraisal, Engineering Principles, Scale-up, and Development Requirements” (Environmental Science and Technology, 42(6): 1833-1844, 2008).

[0004] U.S. Pat. No. 7,169,295 describes a membrane supported biofilm reactor with modules having fine hollow fiber membranes. The membranes are made from dense wall polymethyl pentene (PMP) used in tows or formed into a fabric. The membranes are potted in a header of a module to enable oxygen containing gas to be supplied to the lumens of the hollow fibers. The reactor may be used to treat wastewater. Mechanical, chemical and biological methods are used to control the thickness of the biofilm.

## SUMMARY OF THE INVENTION

[0005] This specification describes an assembly, alternatively called a cord, which may be used for supporting a biofilm. The cord comprises a plurality of hollow fiber gas transfer membranes. The cord may optionally also comprise one or more reinforcing filaments.

[0006] The cord may comprise a plurality of yarns. At least one of the yarns comprises a plurality of gas transfer membranes. At least one of the yarns extends along the length of the cord generally in the shape of a spiral. In some cases, the cord has a core and one or more wrap yarns. In some other cases, the cord comprises a set of braided yarns.

[0007] The cord preferably has an outside diameter in the range of about 0.3 mm to 2.0 mm. The gas transfer membranes preferably have an outside diameter that is less than 200 microns. The sum of the circumferences of the gas transfer membranes is preferably at least 1.5 times the circumference of the smallest circle that can surround the cord. In use, a biofilm covers the cord and the outer surface of the biofilm is substantially round.

[0008] A module may be made by potting a plurality of cords in at least one header. The cords are generally independent of each other except in the header. A reactor may be made by placing the module in a tank adapted to hold water to be treated and providing a gas delivery system. A process for treating wastewater comprises steps of feeding water to the tank and supplying a gas to the module. In use, a biofilm may cover a cord to form a membrane biofilm assembly.

[0009] The cord, module, reactor and process may be used to treat water, for example in, or in the manner of, an MBfR.

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## Description

### BRIEF DESCRIPTION OF THE FIGURES

[0010] FIG. 1 is a photograph of a cord.

[0011] FIGS. 2 to 4 are photographs of alternative cords.

[0012] FIG. 5 is a schematic drawing of a machine for making a cord.

[0013] FIGS. 6 to 8 are schematic drawings of steps in a process for making a module comprising a plurality of cords.

[0014] FIG. 9 is a schematic drawing of a module comprising a plurality of cords.

[0015] FIG. 10 is a schematic drawing of a reactor comprising the module of FIG. 9.

[0016] FIGS. 11 to 14 are drawings of the cords in FIGS. 1 to 4 respectively.

### DETAILED DESCRIPTION

[0017] FIGS. 1 to 4 and FIGS. 11 to 14 each show a cord 10 comprising a plurality of yarns 8. At least one of the yarns 8 comprises a plurality of hollow fiber gas transfer membranes 14.

Preferably, at least one of the yarns 11 comprises at least one reinforcing filament 34.

[0018] At least one of the yarns 8 extends along the length of the cord 10 generally in the shape of a spiral and may be referred to as a spiral yarn. Preferably, at least one spiral yarn 8 is wrapped at least partially around the outside of the other yarn or yarns 8 of the cord 10.

[0019] In the cords 10 of FIGS. 1 to 4 and FIGS. 11 to 14, the yarns 8 are arranged to provide a core 12 and one or more wraps 18. A wrap 18 travels in a spiral that is always outside of another yarn 8. For example, a wrap 18 may spiral around a core 12, or around one or more other wraps 18 that spiral around the core 12. An only or outer wrap 18 is located entirely outside of the other yarn or yarns 8 of a cord 10. Alternatively, a spiral yarn 8 may be wrapped only partially outside of the other yarns or yarns 8 or a cord. For example, two or more spiral yarns 8 may be twisted around each other or four or more spiral yarns 8 may be braided together to form a cord 10 with no wrap 18. In another alternative, four or more spiral yarns 8 may be braided together around a core 12.

[0020] Each cord 10 has a plurality of hollow fiber gas transfer membranes 14. The gas transfer membranes 14 may be located in a core 12, in one or more wraps 18, or in another yarn 8. The gas transfer membranes 14 are preferably provided in the form of a multi-filament yarn having a plurality of gas transfer membranes which may be called a gas transfer membrane yarn 15. Optionally, a cord may also have a reinforcing yarn 16. The reinforcing yarn has one or more reinforcing filaments 34. A yarn 8 having both a plurality of gas transfer membranes 14 and at least one reinforcing filament 34 may be called both a gas transfer membrane yarn 15 and a reinforcing yarn 16.

[0021] The outside diameter of a cord 10 is preferably in a range of about 0.3 to 2.0 mm. The outside diameter of the cord 10 may be measured as the largest width of a cord measured through its longitudinal axis or as the diameter of the smallest hole that the cord 10 will pass through. Anomalies, defects or non-repeating bumps are ignored in these measurements.

[0022] Generally speaking, a core 12 provides mechanical strength, defines a longitudinal axis of the cord 10, supports any wraps 18, and may also comprise gas transfer membranes 14. A wrap 18, or other yarn outside of the core 12, may do one or more of: protect the core 12 or another

underlying yarn **8**, comprise gas transfer membranes **14**, or contribute to the mechanical strength of the cord **10**.

[0023] A core **12** can be made of one or more monofilament yarns or multi-filament yarns. A Multi-filament yarn may comprise filaments that are braided, twisted or otherwise united, or filaments that are merely collected together in a bundle or tow. Multiple yarns may be arranged as parallel warp yarns or twisted, braided or otherwise united. For example a core **12** may consist essentially of a single monofilament yarn; a single multi-filament yarn; or, an assembly of about 2 to 6 monofilament or multi-filament yarns arranged in parallel or twisted or braided together. An assembly of twisted or braided yarns may be preferred since the assembly will be more flexible than a single monofilament of the same outer diameter. A core **12** typically, but not necessarily, comprises at least one reinforcing yarn **16**. A core **12** may optionally comprise one or more gas transfer membrane yarns **15**.

[0024] A wrap **18** is typically a multi-filament yarn. A multi-filament yarn may comprise filaments that are twisted or otherwise united or filaments that are merely collected together in a bundle or tow. A wrap **18** can be wrapped around a core **12** in a clockwise spiral or a counterclockwise spiral. Alternatively, a cord **10** may have at least one wrap **18** in each direction or no wrap **18**. A wrap **18** can be a gas transfer membrane yarn **15**, a reinforcing yarn **16**, or both.

[0025] A reinforcing filament **34** can be made of any water-resistant and non-biodegradable polymer such as polyethylene, nylon or polyester, preferably nylon or polyester. A reinforcing filament **34** is typically solid. Gas transfer membranes **14** tend to be expensive and weak relative to reinforcing filaments **34** made of common textile polymers such as nylon or polyester. A reinforcing yarn **16** can be a monofilament or multi-filament yarn. In the case of a multi-filament yarn, the reinforcing filaments **34** may be braided, twisted or otherwise united, or filaments that are merely collected together in a bundle or tow. Optionally, a yarn **8** may comprise one or more reinforcing filaments **34** mixed with the gas transfer membranes **14**.

[0026] The gas transfer membranes **14** preferably have an outside diameter of 500 microns or less, more preferably 200 microns or less, optionally 100 microns or less. The hollow area of a hollow fiber (meaning the cross sectional area of the lumen of a fiber as a percentage of its total cross sectional area) is preferably at least 20%, for example in the range of 20-50%. For example, a gas transfer membrane **14** may have an outside diameter in the range of about 30-70 microns and an inside diameter of about 15-50 microns. The wall thickness of a gas transfer membrane **14** may be 20 microns or less.

[0027] The gas transfer membranes **14** are preferably handled in a multi-filament gas transfer membrane yarn **15**. A gas transfer membrane yarn **15** may have between 2 and 200, between 12 and 96, or between 10 and 60 individual filaments of gas transfer membrane **14**. A gas transfer membrane yarn **15** used as a wrap **18** is preferably not tightly twisted, braided or crimped to allow the individual gas transfer membranes **14** to spread out over an underlying yarn **8**. A gas transfer membrane yarn **15** may be made by re-winding gas transfer membranes **14** from multiple take up spools in combination onto another spool.

[0028] A gas transfer membrane yarn **15** may be provided, in a core **12**, either as a central yarn or as a warp parallel to a central reinforcing yarn **16**; in one or more wraps **18**; or, in another spiral yarn **8**. It is desirable for gas transfer efficiency to have the gas transfer membranes **14** near the outer surface of the cord **10**. However, the gas transfer membranes **14** are typically fragile and they are more likely can be damaged if they form the outer surface of a cord **10**. Accordingly, it is preferable for a reinforcing yarn **16** to be used as an outer wrap **18**. In this case, a gas transfer membrane yarn **15** may be used in the core **12** or in an inner wrap **18**.

[0029] The gas transfer membranes **14** may be porous, non-porous or semi-porous. Composite membranes, for example having a non-porous membrane layer, and a semi-porous or porous support layer, may also be used. Asymmetric membranes, for example having a non-porous region and an integral semi-porous or porous region, may also be used.

[0030] Porous gas transfer membranes **14** may have pores up to the microfiltration range. Wetting is avoided by choosing hydrophobic materials or treating the hollow fibers **14** to make them hydrophobic. Porous hollow fibers **14** may be made, for example, using polyethylene, polyvinylchloride, polypropylene or polysulfone.

[0031] Non-porous gas transfer membranes **14**, including dense wall gas transfer membranes **14**, may be made from a thermoplastic polymer, for example a polyolefin such as polymethyl pentene (Poly (4-methylpentene-1) or PMP), polyethylene (PE) or polypropylene (PP). PMP is sold, for example, by Mitsui Petrochemical under the trade mark TPX. The polymer may be melt spun into a hollow fiber. The gas transfer membranes **14** may be called non-porous if water does not flow through the fiber walls by bulk or advective flow of liquid even though there are small openings through the wall, typically in the range of 4 or 5 Angstroms in the case of melt spun PMP. However, oxygen or other gases may permeate or travel through the fiber walls. In a dense walled hollow fiber **14**, gas travel is primarily by molecular diffusion or dissolution-diffusion which occurs when openings in the fiber walls are generally less than 30 Angstroms. Gas transfer membranes **14** as described in U.S. Pat. No. 7,169,295, which is incorporated by reference, may be used.

[0032] The term porous has been used to refer to any structure having openings larger than in a dense wall, for example having openings of 30 or 40 Angstroms or more, but without openings large enough to be wetted or transport liquid water by advective, Poiseuille or bulk flow. In this specification, membranes with openings in this size range are referred to as semi-porous.

[0033] Gas transfer membranes **14** may alternatively be made by mechanically or thermally treating a melt spun thermoplastic polymer after spinning to increase its permeability to oxygen without making the fiber wettable or capable of permitting advective flow of liquid water. Spinning or post-treatment steps that can be used or controlled to increase permeability include the spinning speed or drawing ratio, the quenching conditions such as temperature or air flow rate, post annealing, if any, stretching and heat setting. The resulting fibers may have a dense layer, with openings ranging from the size of openings in the raw polymer to 30 or 40 Angstroms, on either the inside of the fiber, the outside of the fiber or both, with the remaining parts of the fiber being porous or semi-porous. For example, U.S. Pat. No. 4,664,681, issued on May 12, 1997, to Anazawa et al. describes, in examples 4 and 6, processes for melt-spinning and post-processing PE and PP to produce acceptable fibres while other fibers are made from PMP or polyoxymethylene. Processes described in "Melt-spun Asymmetric Poly (4-methyl-1-pentene) Hollow Fibre Membranes", Journal of Membrane Science, 137 (1997) 55-61, Twarowska-Shmidt et al., also produce acceptable fibres of PMP and may be adopted to produce fibres of other polyolefins such as PE or PP. In one example, the mean pore size of the fibers produced is just over 40 Angstroms. In U.S. Pat. No. 4,664,681, membranes are melt spun, stretched (by producing the membrane at a high draft ratio) under weak cooling and then heat treated. The resulting membranes are asymmetric containing a dense layer with substantially no pore with a diameter of 30 Angstroms or more and a microporous layer having larger pores. The non-porous layer is the outer surface of the fiber and so the fiber is non-wetting.

[0034] Another alternative process for making gas transfer membranes **14** is to make an asymmetric outside dense skin membrane with a spongy substructure by the non-solvent induced phase separation (NIPS) process. Polymers typically used for this process are polysulfone, cellulose acetate and polyimide. Other alternative methods of making gas transfer membranes **14** may include, for example, meltblown extrusion, flash spinning, and electrospinning.

[0035] In general, silicon rubber or PDMS have very high oxygen permeability but cannot be processed using many textile techniques and are not available in small diameter fibers. PMP has higher oxygen permeability than PE or PP, but it is more expensive. Porous membranes have high oxygen permeability but they are prone to wetting in use. Accordingly, dense wall polymeric gas transfer membranes **14**, for example of PE, PP or PMP, with a wall thickness of 50 microns or less,

preferably 20 microns or less, or polymeric membranes that are not entirely dense walled but have a nonporous or semi-porous layer, are preferred but not essential.

[0036] A yarn **8** in a core **12**, whether it is a gas transfer yarn **15** or a reinforcing yarn **16**, may be called a warp **26**. A wrap **18** is preferably applied around a core **12** or another underlying yarn **8** with some tension to cause its filaments to spread on the surface of the core **12**. Wrapping may be done with a pitch ratio (pitch divided by the diameter of the core) of between 1 and 5. Wrapping can be in one direction only, but is preferably done in both directions. There may be 1 or more, for example between 1 and 3, wraps **18** in one direction. Gas transfer membranes **14** are preferably directly exposed over at least 25% of the surface of the core **12** although oxygen can also travel from a gas transfer membrane **14** through an overlying yarn **8**.

[0037] A cord **10** may consist of only a set of twisted yarns **8**. However, merely twisted yarns **8** may tend to partially untwist and separate in use. Accordingly, it is preferable to use twisted yarns **8** as a core **12** with at least one wrap **18** wrapped around the core **12** in the direction opposite to the twist of the core **12**. A braided core **12** is more stable. Spiral yarns **8** may be added as a braid around a core **12**, but a wrap **18** can be made at a faster line speed with a less complicated machine. A cord structure using one or more wraps **18** also allows for a reinforcing yarn **16** to be used as an outer wrap **18** to help protect an interior gas transfer membrane yarn **15**.

[0038] In the examples of FIGS. **1** to **4** and FIGS. **11** to **14**, gas transfer membrane yarns **15** are made up of 48 dense wall PMP hollow fiber filaments. The filaments have an outside diameter of less than about 70 microns and a wall thickness of less than 20 microns. Reinforcing yarns **16** are either monofilament yarns or multi-filament yarns of polyester (PET).

[0039] In FIG. **1** and FIG. **11**, a first cord **10a** has a core **12** made up of a single monofilament reinforcing yarn **16** and a two multi-filament gas transfer membrane yarns **15** applied as warps **26** parallel to the reinforcing yarn **16**. The core **12** is covered with two wraps **18**, one in each direction, with a wrapping pitch of 1.8. Each wrap **18** is a single multi-filament gas transfer membrane yarn **15**.

[0040] In FIG. **2** and FIG. **12**, a second cord **10b** has a core **12** comprising a reinforcing yarn **16** and a gas transfer membrane yarn **15**. Each of these yarns in the core **12** is an untwisted multi-filament yarn, alternatively called a tow. The second cord **10b** also has two wraps **18**, one in each direction. Each wrap **18** is an untwisted multi-filament reinforcing yarn **16**.

[0041] In FIG. **3** and FIG. **13**, a third cord **10c** has a core **12** comprising a set of multifilament reinforcing yarns **16** braided together. The third cord **10c** also has an inner wrap **18** comprising an untwisted multifilament gas transfer membrane yarn **15** and an outer wrap comprising an untwisted multifilament reinforcing yarn **16**.

[0042] In FIG. **4** and FIG. **14**, a fourth cord **10c** has a core **12** comprising a set of multifilament reinforcing yarns **16** braided together and an untwisted multifilament gas transfer membrane yarn **15** as a warp **26** parallel to the reinforcing yarns **16**. The gas transfer membrane yarn **15** is parallel with the core **12** but not braided with the reinforcing yarns **16**. The third cord **10c** also has a wrap **18** comprising an untwisted multifilament reinforcing yarn **16**.

[0043] FIG. **5** shows a machine **20** for making a cord **10**. The machine **20** is built on frame **22** that supports the different components and aligns them. One or more warps **26** are supplied to the machine **20** from a creel **24**. The creel **24** has stationary bobbin holders, guides and tensioning devices, as found in other textile equipment. The warps **26** pass through a distributor **28**. The distributor **28** may have a central opening and one or more eyelets around the central opening. A warp **26** is unwound from a bobbin on the creel **24**, positioned to the top of the distributor **28** through a roller and fed vertically down through the distributor **28**. A take up winder (not shown) pulls the cord **10** downwards through the machine **20** and onto a bobbin. The one or more warps **26** form the core **12** of the cord **10**.

[0044] One or more spindles **30**, or other yarn wrapping devices, are located below the distributor **28**. Each spindle **30** is loaded with a yarn and wraps the yarn around the one or more warps **26** of

the core **12** as they pass through the spindle **30**. Due to the downward movement of the core **12**, each wrapped yarn forms a spiral wrap **18**. The machine **20** may also have alignment guides (not shown) to keep the core **12** aligned with the central axis of the spindles **30** and to reduce vibration of the core **12**.

[0045] An example of a suitable spindle **30** is a Temco™ spindle model MSE150 by Oerlikon Textile. Each spindle **30** has an electrical motor and a hollow core and holds a bobbin of wrap yarn. The spindle **30** is positioned so that its central axis coincides with the core **12**. In the machine **20** of FIG. **2**, there are two spindles **30**, one rotating clockwise and the other rotating counter clockwise. The spindles **30** can rotate at an adjustable speed of up to 25,000 rpm to provide a controllable pitch. Alternatively, a rotating creel may be used in place of the spindle **30**. In a rotating creel, bobbins are mounted on a wheel that rotates in one direction around the core **12** without being in contact with it. Each bobbin is preferably equipped with tension control.

[0046] A plurality of cords **10**, for example 100 or more, may be made into a module generally in the manner of making an immersed hollow fiber membrane filtration module. At least one end of each of the cords **10** is potted in a block of a potting material such as thermoplastic or thermosetting resin which is sealed to a pan to form a header. The ends of the gas transfer membranes **14** are made open to the inside of the header, for example by cutting them open after potting. The other ends of the cords **10** may be potted in another header with the ends of the gas transfer membranes **14** open or closed, closed individually, or looped back and potted in the first header. A port in the header allows a gas to be fed to the lumens of the gas transfer membranes **14**. The gas may be fed to the gas transfer membranes **14** in a dead end manner or with exhaust through a second header.

[0047] As one example, the composite fibers **10** may be assembled into modules and cassettes according to the configuration of ZeeWeed 500™ immersed membrane filtration units sold by GE Water & Process Technologies. Sheets of cords **10** are prepared with the composite fibers **10** generally evenly spaced in the sheet. Multiple sheets are stacked on top of each other to form a bundle with adjacent sheets spaced apart from each other. The bundle is potted. After the potting material cures, it is cut to expose the open ends of the gas transfer membranes and sealed to a header pan. Several such modules may be attached to a common frame with their ports manifolded together to form a cassette. Various useful techniques that may be used or adapted for making a module are described in U.S. Pat. Nos. 7,169,295, 7,300,571, 7,303,676, US Publication 2003/01737006 A1 and International Publication Number WO 02/094421, all of which are incorporated by reference. Alternatively, other known techniques for making a hollow fiber membrane module may be used.

[0048] Referring to FIG. **6**, multiple cords **10**, or an undulating cord **10**, are laid out on a flat jig or drum to provide a set of generally parallel segments of cord **10** in a sheet **38**. The segments of cord **10** may be kept evenly spaced from each other in the sheet **38**, for example by a woven filament **40** or a strip of hot melt adhesive **42**. When segments of cord **10** are used, the ends of the cords **10** may be sealed, for example by melting them with an iron or heated cutter along a sealing line **44**. Multiple sheets **38** may be stacked on top of each other, preferably with the ends of adjacent sheets **38** separated by spacers. The end of the set of sheets **38** is dipped in a potting mold **46** filled with a potting resin **48**. The potting resin **48** may be, for example, a polyurethane resin formulated to penetrate into the yarns **8** to seal around the various filaments of the cord **10**.

[0049] Referring to FIG. **7**, the set of sheets **38** is removed from the potting mold **46** after the potting resin **48** is cured. To expose open ends of the gas transfer membranes **14**, the potting resin **48** is cut through along cutting line **50**. The other end of the set of sheets **38** may be potted in the same manner. Optionally, one or both of the blocks of potting resin **48** may be cut to expose open ends of the gas transfer membranes **14**.

[0050] Referring to FIG. **8**, a header **60** is formed by sealing the block of potting resin **48** to a header pan **52**. The header pan **52** may be made of molded plastic and has an outlet **54**. The block

of potting resin **48** may be held in the header pan **52** by an adhesive or a gasket **56** between the perimeter of the potting resin **48** and the header pan **52**. Optionally, a second potting material **58** may be pored over the potting resin **48**. The second potting material may further seal the cords **10** or the potting resin **48** to the header pan **52**, or may cushion the cords **10** where they exit from the header **60**. A similar header **60** may be made at the other end of the set of sheets **38**.

[0051] Referring to FIG. **9**, a module **66** has two headers **60** with cords **10** extending between them. The headers **60** are preferably vertically aligned and held apart by a frame **62**. The length of the cords **10** between opposing faces of the headers **60** may be slightly greater than the distance between the opposed faces of the headers **60**. In this case, the cords **10** have some slack and can sway. The cords **10** are preferably not connected to each other between the headers **60**. Although one cord **10** may contact another as it sways, the movement of a cord **10** is generally independent of other cords **10**. Multiple modules **60** may be held in a common frame **62**. The frame **62** may also hold an aerator **68** near the bottom of a module **66**.

[0052] When used for wastewater treatment, the cords **10** are immersed in a bioreactor and a gas, for example air, oxygen, hydrogen or another gas, is fed through the lumen of the gas transfer membranes **14**. A biofilm develops on the outside surface of the cords **10**, and anchors itself by filling the gaps between filaments. The resulting membrane biofilm assembly has a generally circular cross section. The cross section of the membrane biofilm assembly has a diameter of about 0.5 to 3 mm determined assuming that the biofilm forms a film extending no more than 0.5 mm beyond the outer diameter of the core **12**. A more typical biofilm thickness is in the range of 0.05 to 0.2 mm. The sum of the circumferences of the gas transfer membranes **14** multiplied by the length of the cord approximates the active gas transfer surface area while the circumference of the outside of the biofilm multiplied by the length of the cord **10** gives the biofilm area. The sum of the circumferences of the gas transfer membranes **14** is preferably at least 1.5 times the circumference of a circle having the outside diameter of the cord **10**. The sum of the circumferences of the gas transfer membranes **14** is also preferably at least 1.5 times the circumference of the attached biofilm when in use.

[0053] Modules of the cords **10** may be deployed in a membrane biofilm reactor (MBfR) by immersing them in an open tank in manner similar to the use of ZeeWeed 500 immersed hollow fibre filtering membranes. Although the cords **10** will be used to support and transport gas to a biofilm and not for filtration, various system design and operating features of the ZeeWeed 500 system can be adapted. As mentioned above, the cords **10** may be potted with an orderly spacing between them. The module configuration with two headers may be used but modified to use one header of each element for introducing the fresh gas and one header for venting exhausted gas. ZeeWeed cassette frames may be used to facilitate deploying multiple modules with the cords **10** oriented vertically into open tanks. Gas sparging by way of bubbles produced below or near the bottom of the modules can be provided at a low rate to renew the liquid around the cords **10**. Gas sparging at a higher rate may be used to help control biofilm thickness either by the direct action of bubbles, bubble wakes or bubble pressure effects on the biofilm, or by causing cords **10** mounted with slack between the headers to sway in the water to produce turbulence or contact between cords **10**. Optionally, gas exhausted from the cords may be recycled for use in gas sparging.

[0054] Referring to FIG. **10**, a module **66** is immersed in a tank **70**. The tank **70** is filled with water to be treated from an inlet **72**. Treated water is removed through an outlet **74**. Optionally, water may recirculate from the outlet **74** to the inlet **72** to provide a flow of water through the module **66**, mix the tank **70**, or to maintain desired conditions in the tank **70**. Air, or another gas, is blown into, or drawn out of, the module **66** by a process gas blower **76**. In the example shown, the gas is blown into one header **60**, travels through the cords **10**, and exhausted from the other header **60**. A throttle valve **78** may be used to increase the gas pressure in the cords **10**. A sparging gas blower **80** blows air or recycled exhaust gas from the module **66**, or both, to the aerator **68** when required for mixing the tank **70** or controlling the thickness of the biofilm on the cords **10**.



[0055] Optionally, the aerator **68** may comprise a supply pipe **82** and a transducer **84**. The transducer **84** collects gas ejected from the supply pipe in a pocket below a shell **86**. The pocket of gas grows larger as gas is accumulated as shown in the first two compartments of the shell **86**, counting from the left side of the shell **86**. When the pocket of gas extends to the bottom of J shaped tube, as in the third compartment of the shell **86**, the gas is released through the J shaped tube as shown in the last compartment of the shell **86**. In this way, large bursts of bubbles are released periodically without requiring a large volume of gas to be continuously pumped into the tank **70**. Excessive scouring gas consumes energy and may disturb desirable anoxic or anaerobic conditions in the tank **70**. Periodic large bursts of bubbles can be more effective for renewing the water around the cords **10** or removing biofilm from the cords **10** than the same amount of gas supplied as a continuous stream of bubbles.

[0056] In some prior MBfRs, silicon rubber or polydimethylsiloxane (PDMS) are coated over a flat substrate to make a flat sheet membrane. While silicon and PDMS are highly permeable to oxygen, such a flat sheet membrane can provide a surface area for oxygen transfer to surface area of biofilm ratio of only about **1**. Further, with reasonably large sheets it is difficult to renew water to be treated along the edges of the sheet or remove excess biofilm from the edges of the sheet. Accordingly, the sheets are often separated by a substantial spacing and the total biofilm area in a tank may be low.

[0057] In U.S. Pat. No. 7,169,295 a membrane supported biofilm reactor has modules made with fine hollow fiber membranes. The fine hollow fibers have a thin wall which allows for good gas transfer efficiency even when heat spun polymers are used. However, the fine hollow fibers are also easily damaged. A tow module described in U.S. Pat. No. 7,169,295, although useful in some applications, has loose and exposed hollow fibers which are prone to damage and to being clumped together by biofilm in other applications. Sheet modules described in U.S. Pat. No. 7,169,295 are more resilient and can provide a surface area for oxygen transfer to surface area of biofilm ratio of more than **1**. However, like silicon flat sheet module, these sheet modules are still subject to total biofilm area limitations.

[0058] The cords **10** described above provide a useful alternative gas transfer module configuration. The use of fine hollow fiber gas transfer membranes **14** allows for good gas transfer efficiencies even when using melt spun polymers and a surface area for oxygen transfer to surface area of biofilm ratio of more than **1**. The fine hollow fiber membranes are not loose and exposed. Yet since the cords **10** can move generally independently and do not form a solid sheet, fresh liquid and bubbles used to scour the biofilm to control its thickness can reach cords **10** located in the interior of a module.

[0059] Movement of the cords **10**, or contact between cords **10**, may also help control biofilm thickness. Further, the total biofilm surface area can be increased relative to a sheet form module.

[0060] In a calculated example, a cord **10** comprises a core **12** and two wraps **18**, one in each direction, of gas transfer membrane yarns **15**. The outside diameter of the cord is 1 mm. The wrapping pitch is 5 core diameters resulting in a wrap **18** helix length of 1.18 times the cord length. The cord **10** has 57 meters of 70 micron outside diameter PMP gas transfer membrane **14** per meter of cord **10** length. The surface area of the gas transfer membranes per unit length of cord is 3.04 times the outer surface area of the cord, calculated based on the circumference of a 1 mm circle.

[0061] A biofilm on the cord **10** is assumed to have a thickness of 0.2 mm giving a membrane biofilm assembly diameter of 1.4. The cords **10** are potted in a module in a rectilinear grid with a 0.7 mm gap between their outside surfaces. With biofilm attached, the gap between adjacent cords in a line is 0.4 mm. Using ZeeWeed module moldings, a module **66** has 16 rows of 340 cords **10** each, or 5440 cords **10**. The exposed length of each cord is 1.9 m giving a biofilm area per module of 45.5 square meters. Using a ZeeWeed frame, a cassette with a 3.7 square meter footprint and 2.5 meter height has 64 modules **66** and a total biofilm surface area of 2910 square meters. The biofilm surface area is 315 square meters per cubic meter of cassette volume and 786 square meters per square meter of cassette footprint.

[0062] In comparison, a comparable sheet form module made with similar gas transfer membranes **14** can have a 1 mm thick fabric with a similar gas transfer surface area to biofilm surface area of 3.34. The sheets are made into a module with horizontally apposed vertical headers. The module is 2 m long with 1.8 m of exposed membrane length. The sheets and module are 1 m high. The module is 0.3 m wide and can be operated in a 1.5 m deep tank. The centre-to-centre spacing between adjacent sheets is 8 mm. The biofilm surface area is 250 square meters per cubic meter of cassette volume and 250 square meters per square meter of cassette footprint.

[0063] As illustrated by the comparison above, the cord **10** module can have more biofilm area per unit volume of module than a sheet form module. Further, tall sheet modules that rely on bubbles for liquid renewal or scouring have been known in the context of filtering membranes to be prone to a chimney effect whereby bubbles and liquid flow are concentrate near the vertical midline of the sheets. This limits the height of sheet modules. It is expected that a cord **10** module can be higher without a similar chimney effect which allows for an additional decrease in tank footprint and land consumption per unit biofilm area.

[0064] This written description uses examples to disclose the invention and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art.

## Claims

1. A process comprising the steps of, immersing a gas transfer membrane in water; flowing a gas into a first end of the gas transfer membrane to transfer oxygen to a biofilm on an outer surface of the gas transfer membrane; withdrawing an exhaust gas from a second end of the gas transfer membrane; transferring the exhaust gas from the gas transfer membrane to an aerator; and, producing bubbles comprising the exhaust gas in the water from the aerator.
2. The process of claim 1 wherein the water is anoxic or anaerobic.
3. The process of claim 1 wherein the gas transfer membrane is oriented vertically and the bubbles are produced below or near the bottom of the gas transfer membrane.
4. The process of claim 1 wherein the gas transfer membrane is a hollow fiber membrane.
5. The process of claim 1 wherein the bubbles further comprise ambient air.
6. The process of claim 1 wherein the bubbles are provided at a rate sufficient to help control the thickness of the biofilm.
7. The process of claim 1 wherein the bubbles are provided at a lower rate to renew liquid around the gas transfer membrane.
8. The process of claim 1 wherein the bubbles are provided intermittently.
9. The process of claim 1 wherein the aerator comprises a transducer adapted to produce periodic bursts of bubbles from a continuous supply of gas.
10. The process of claim 1 wherein the exhaust gas is pumped from the gas transfer membrane to the aerator.
11. The process of claim 1 wherein exhaust gas from a plurality of gas transfer membranes is collected in a header before being transferred to the aerator.
12. The process of claim 1 further comprising providing a suspended biomass in the water.
13. The process of claim 1 wherein the gas transfer membrane is part of a cord comprising, a core extending along the length of the cord generally parallel with a longitudinal axis of the cord, the core comprising a plurality of hollow fiber gas transfer membranes parallel with the longitudinal axis of the cord; and, at least one spiral filament wrapped around the core.
14. The process of claim 13 wherein the core comprises one or more reinforcing filaments.
15. The process of claim 13 wherein the at least one spiral filament wrapped around the core comprises a multifilament reinforcing yarn.

- 16.** An apparatus comprising, a) a gas transfer membrane having a first end and a second end opposite the first end; b) a source of a gas in fluid communication with the first end of the gas transfer membrane; c) an aerator in fluid communication with the second end of the gas transfer membrane; and, d) a sparging gas blower having an inlet connected to the second end of the gas transfer membrane and an outlet connected to the aerator to blow an exhaust gas collected from the second end of the gas transfer membrane, or a mixture of the exhaust gas and air, to the aerator.
- 17.** The apparatus of claim 16 wherein the aerator produces bubbles effective to control the thickness of a biofilm on the gas transfer membranes.
- 18.** The apparatus of claim 16 wherein the gas transfer membrane is a hollow fiber membrane.
- 19.** The apparatus of claim 18 wherein the gas transfer membrane is oriented vertically in a module and the aerator is located below the module.
- 20.** An apparatus comprising, a) a gas transfer membrane having a first end and a second end opposite the first end; b) a source of a gas in fluid communication with the first end of the gas transfer membrane; and, c) an aerator in fluid communication with the second end of the gas transfer membrane, wherein the aerator comprises a transducer adapted to produce burst of bubbles from a continuous supply of gas.
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