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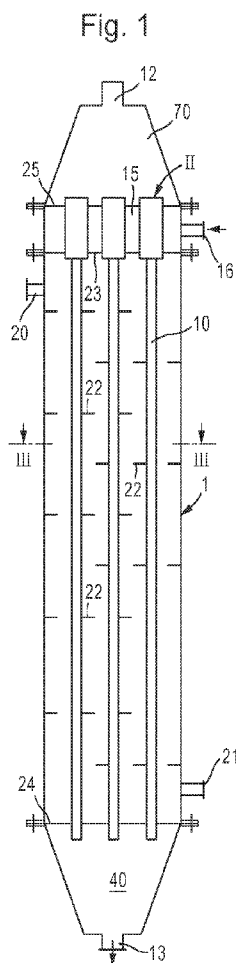
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(54) Title: FILM OZONOLYSIS IN A TUBULAR OR MULTITUBULAR REACTOR

(57) Abstract: The disclosure relates to a method of performing ozonolysis or ozone-based oxidation on a liquid or emulsified reagent using a tubular falling film reactor with one or multiple tubes wherein the combined ozone and carrier gas flow is co-current.





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FILM OZONOLYSIS IN A TUBULAR OR MULTITUBULAR REACTOR

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Provisional Application No. 62/015,311, filed June 20, 2014, and U.S. Provisional Application No. 62/163,022, filed May 18, 2015, both of which are incorporated herein by reference in their entireties.

BACKGROUND

[0002] Ozonolysis or ozone-based oxidation of reagents currently in use in the chemical industry generally rely on processing large amounts of material in either tray-type continuous ozonation systems or in batch systems, *e.g.*, US 2,813,113. The use of either type of established method, however, results in the accumulation of peroxide intermediates that can be unstable and present a significant explosion risk. Alternatively, processing small amounts of material in a continuous fashion can significantly reduce these risks. Solutions to address this important safety issue include the use of microstructured falling film reactors such as those described in US 7,825,277 B2, and available from ThalesNano, Inc. These technologies, however, have not been adapted for use in large-scale (multi-ton) manufacturing processes, owing to challenges with throughput and the operation costs associated with maintaining large numbers of reaction vessel channels and precisely calibrated instruments.

[0003] Other commercial reaction technologies use sparging or aeration techniques to drive interactions between liquid and gaseous reagents, which can introduce local hot spots and requires that the gaseous reagent be present at high pressures. The disclosure described herein addresses the need for a method of industrial-scale ozonolysis that is safer and more efficient than conventional methods.

SUMMARY OF THE DISCLSORE

[0004] The approach to ozonolysis described herein functions using gravity assisted co-current reagent flow to facilitate gaseous reagent diffusion into a liquid or emulsified reagent, which simplifies the reaction setup and minimizes the mechanical energy required, all while achieving a scalable and continuous process that does not allow for the accumulation of large amounts of hazardous intermediates, thus rendering the process and equipment described herein suitable for large, industrial-scale ozonolysis.

[0005] In one embodiment of the current disclosure a monotubular or multitubular reactor is used for ozonolysis or ozone-based oxidation in which:

- (a) homogeneity of the reagent-containing film and thermal exchange is maximized,
- (b) selection of the optimum size of the individual tubes is based on the best compromise between maximum internal diameter (for optimum throughput) and minimum height (for reduced head loss) while maintaining mechanical simplicity (for reduced maintenance), and
- (c) distribution of the gaseous ozone-containing reagent with negligible head loss is conditioned by the reagent-containing film thickness and corresponding flow rate such that the conversion and temperature profiles are optimized along the tube length.

[0006] The parameters above can be optimized both theoretically and empirically, and can be used to ensure excellent results without the need for calibration when changing the flow rate and/or composition of the liquid or emulsified reagent.

[0007] In some embodiments, the method of performing ozonolysis or ozone-based oxidation on a liquid or emulsified reagent entails using a tubular falling film reactor with one or multiple tubes wherein the combined ozone and carrier gas flow is co-current.

[0008] In some embodiments, the diameter of the tube(s) is between 5 mm and 5 m.

[0009] In some embodiments, the diameter of the tube(s) is between 5 mm and 50 mm.

[0010] In some embodiments, the diameter of the tube(s) is between 5 mm and 30 mm.

[0011] In some embodiments, the diameter of the tube(s) is between 10 mm and 25 mm.

[0012] In some embodiments, the diameter of the tube(s) is 25 mm.

[0013] In some embodiments, the diameter of the tube(s) is 10 mm.

[0014] In some embodiments, the diameter of the tube is between 50 mm and 5 m.

[0015] In some embodiments, the diameter of the tube is between 0.5 m and 5 m.

[0016] In some embodiments, the diameter of the tube is between 50 mm and 5 m and an annular element is added to the center of the tube to regulate gas flow and to add additional film surface area.

[0017] In some embodiments, the length of the tube(s) is between 1 and 20 m.

[0018] In some embodiments, the length of the tube(s) is between 1 and 7 m.

[0019] In some embodiments, the length of the tube(s) is 1.7 m.

[0020] In some embodiments, the length of the tube(s) is 6 m.

[0021] In some embodiments, the length of the tube(s) is between 7 and 20 m.

[0022] In some embodiments, the distribution of gas within the tube(s) may be controlled by annular spaces for gas flow within the tube(s).

[0023] In some embodiments, multiple falling film tube reactors are used in series to process a continuous stream of liquid or emulsified reagent.

[0024] In some embodiments, the method of performing ozonolysis or ozone-based oxidation on a liquid or emulsified reagent with a gaseous reagent (e.g., comprising ozone and one or more carrier gases) includes:

- (a) feeding the liquid or emulsified reagent from a common liquid or emulsified reagent feeding chamber that is maintained completely full through annular slots and into a plurality of parallel and substantially identical tubes, as to form a liquid or emulsified reagent film on the internal surface of each tube;
- (b) feeding the gaseous reagent through the annular slots and into the tubes from a gaseous reagent feeding chamber, the feeding pressure of the gaseous reagent being substantially the same as the pressure loss from the gaseous reagent flow through the tubes containing the liquid or emulsified reagent film, but less than the feeding pressure of the liquid reagent;
- (c) cooling the tubes by flowing a liquid coolant through a housing surrounding the tubes; and
- (d) collecting reaction product(s) and gaseous reagent exhaust in one or more product containers connected to the end of the tubes opposite that connected to the annular slots.

[0025] In some embodiments, the length of the tubes used in this method is between 1 and 20 m.

[0026] In some embodiments, the length of the tubes used in this method is between 1 and 7 m.

[0027] In some embodiments, the length of the tubes used in this method is 1.7 m.

[0028] In some embodiments, the length of the tubes used in this method is 6 m.

[0029] In some embodiments, the length of the tubes used in this method is between 7 and 20 m.

[0030] In some embodiments, the internal diameter of the tubes used in this method is between 5 mm and 5 m.

[0031] In some embodiments, the internal diameter of the tubes used in this method is between 5 mm and 50 mm.

[0032] In some embodiments, the internal diameter of the tubes used in this method is between 5 mm and 30 mm.

[0033] In some embodiments, the internal diameter of the tubes used in this method is between 10 mm and 25 mm.

[0034] In some embodiments, the internal diameter of the tubes used in this method is 25 mm.

[0035] In some embodiments, the internal diameter of the tubes used in this method is 10 mm.

[0036] In some embodiments, the internal diameter of the tubes used in this method is between 50 mm and 5 m.

[0037] In some embodiments, the internal diameter of the tubes used in this method is between 0.5 m and 5 m.

[0038] In some embodiments, the feeding pressure of the gaseous reagent used in this method is between 0.1 and 5 bar.

[0039] In some embodiments, the feeding pressure of the gaseous reagent used in this method is between 0.1 and 0.5 bar.

[0040] In some embodiments, the feeding pressure of the gaseous reagent used in this method is between 0.2 and 0.4 bar.

[0041] In some embodiments, the feeding overpressure of the liquid or emulsified reagent with respect to the feeding pressure of the gaseous reagent is between 5 and 15 cm of liquid column.

[0042] In some embodiments, the carrier gas contains, at least in part, gaseous reagent exhaust from one or more product containers.

[0043] In some embodiments, the reagent is a liquid.

[0044] In some embodiments, the reagent is an emulsion in water.

[0045] In some embodiments, the liquid or emulsified reagent or reagent mixture is the starting material which is reacted with ozone to yield oxidized product(s).

[0046] In some embodiments, the starting material is an alkene, alkyne, or any other compound that may be oxidized with ozone.

[0047] In some embodiments, the liquid or emulsified reagent comprises hydroxycitronellene, methoxycitronellene, rose ketones (e.g., Ionone), fatty acid methyl esters (FAME), triglycerides, fatty acids, fatty alcohols, fatty esters, diterpenes, sesquiterpenes, monoterpenes, allyl ethers, alpha olefins, rosin acids, tertiary amines, alkanes, amides, carboxylic acids, or compounds containing an aromatic ring.

[0048] In some embodiments, the reagent introduced into the reactor is any compound that is susceptible to ozone oxidation. In some embodiments, the reagent comprises any alkane, amide, carboxylic acid, or aromatic ring.

[0049] In some embodiments, the reaction products may be further reduced or oxidized to generate corresponding carbonyls, alcohols, and/or acids.

[0050] In some embodiments, the liquid or emulsified reagent comprises hydroxycitronellene.

[0051] In some embodiments, the liquid or emulsified reagent is a hydroxycitronellene emulsion in water.

- [0052]** In some embodiments, the liquid or emulsified reagent is a hydroxycitronellene solution in methanol.
- [0053]** In some embodiments, the product of the method described herein is hydroxymelonal.
- [0054]** In some embodiments, the liquid or emulsified reagent comprises methoxycitronellene.
- [0055]** In some embodiments, the liquid or emulsified reagent is a methoxycitronellene emulsion in water.
- [0056]** In some embodiments, the liquid or emulsified reagent is a methoxycitronellene solution in methanol.
- [0057]** In some embodiments, the product is methoxymelonal.
- [0058]** In some embodiments, the liquid or emulsified reagent comprises fatty acid methyl esters (FAME).
- [0059]** In some embodiments, the liquid or emulsified reagent is a FAME emulsion in water.
- [0060]** In some embodiments, the liquid or emulsified reagent is a FAME solution in methanol.
- [0061]** In some embodiments, the product produced by the method described herein comprises methyl azealdehyde and nonanal.
- [0062]** In some embodiments, the liquid or emulsified reagent comprises an unsaturated olechemical such as a triglyceride, a fatty acid, a fatty alcohol, or a fatty acid ester.
- [0063]** In some embodiments, the liquid or emulsified reagent comprises a diterpene such as abietic acid or its ester.
- [0064]** In some embodiments, the liquid or emulsified reagent comprises a mono- or di-unsaturated sesquiterpene.
- [0065]** In some embodiments, the liquid or emulsified reagent comprises a mono- or di-unsaturated monoterpene or terpene derivative such as pinene or limonene.
- [0066]** In some embodiments, the liquid or emulsified reagent comprises an allyl ether of 10 to 30 carbon atoms.
- [0067]** In some embodiments, the liquid or emulsified reagent comprises an alpha olefin of 10 to 30 carbon atoms.
- [0068]** In some embodiments, the liquid or emulsified reagent comprises a rose ketone. In some embodiments the rose ketone is lonone.
- [0069]** In some embodiments, the product of the method described herein is cyclocitral.
- [0070]** In some embodiments, the liquid or emulsified reagent comprises a tertiary amine.
- [0071]** In some embodiments, the product of the method described herein is an *N*-oxide derivative.
- [0072]** In some embodiments, the carrier gas is O₂.

[0073] In some embodiments, the carrier gas is a mixture of O₂ and N₂. In some embodiments, the carrier gas is about 95% O₂ and 5% about N₂, about 90% O₂ and about 10% N₂, about 85% O₂ and about 15% N₂, about 80% O₂ and about 20% N₂, about 70% O₂ and about 30% N₂, about 60% O₂ and about 40% N₂, about 50% O₂ and about 50% N₂, about 40% O₂ and about 60% N₂, about 30% O₂ and about 70% N₂, about 20% O₂ and 80% N₂, or 10% O₂ and 90% N₂, wherein the term “about” refers to the indicated percentage +/- 2.5%.

[0074] In some embodiments, the carrier gas is about 95% O₂ and about 5% N₂.

[0075] In some embodiments, the carrier gas is air.

[0076] In some embodiments, the liquid or emulsified reagent comprises an alkene.

[0077] In some embodiments, the liquid or emulsified reagent comprises an alkyne.

[0078] In some embodiments, the primary component of the liquid or emulsified reagent is methyl oleate.

[0079] In some embodiments, the liquid or emulsified reagent is derived from soy.

[0080] In some embodiments, the liquid or emulsified reagent is derived from palm oils.

[0081] In some embodiments, the liquid or emulsified reagent is derived from algal oils.

[0082] In some embodiments, waste water can be the reagent introduced into the reactor for the purpose of treating the water.

BRIEF DESCRIPTION OF THE FIGURES

[0083] Figure 1 is a diagram of the vertical cross-section of a multitubular reactor.

[0084] Figure 2 is a diagram of the detail denoted by II in Fig. 1, on a larger scale.

[0085] Figure 3 is a diagram of the cross-section along line III-III in Fig. 1.

DETAILED DESCRIPTION OF THE DISCLOSURE

[0086] The disclosure relates to the ozonolysis or ozone-related reactions which occur on the free surface of a film of a liquid or emulsified reagent or reagent mixture that is subject to the controlled amount of a gaseous reagent comprising ozone (O₃). The liquid or emulsified reagent or reagent mixture is the starting material which is reacted with ozone to yield oxidized product(s). The starting material is generally an alkene, alkyne, or any other compound that may be oxidized with ozone. The reaction products may be further reduced or oxidized to generate corresponding carbonyls, alcohols, and/or acids.

[0087] Performing ozone-based oxidation reactions in industrial-scale tubular falling film reactors (e.g., those originally designed for other processes, such as sulfonation) is

advantageous for a variety of reasons. For example, tubular falling film sulfonation reactors operate by exposing relatively small volumes of liquid reagent(s) to relatively high volumes of reactive gaseous reagent(s) that have been diluted with an inert carrier gas or mixture thereof. Due to their continuous mode of operation, the reactors are efficient and exhibit reasonably high throughput rates per reactor tube, but do not allow for the accumulation of intermediates. Moreover, these reactors handle exothermic processes well because they include excellent heat dissipation features. The method described herein provides a safe and efficient means of performing ozonolysis reactions on an industrial scale by taking advantage of the aforementioned benefits of tubular falling film sulfonation reactors.

[0088] Examples of tubular falling film sulfonation reactors are described in GB 2,043,067 B, which is incorporated herein by reference. Tubular or multitubular co-current reactors are particularly useful due to their relatively low cost and mechanical simplicity. Such reactors can be adapted to use for ozonation reactions.

[0089] An additional safety advantage can be realized over traditional ozonolysis approaches if the reaction is carried out in water or as an emulsion with water. The flashpoint of the liquid reagent(s) can be eliminated or dramatically reduced in the presence of water, thereby minimizing the risk of fire in the event of an uncontrolled exotherm or explosion. Furthermore, the use of an emulsion allows for easier control of the liquid reagent in terms of concentration, distribution within the ozonolysis device tubes, and temperature.

[0090] As shown in Figures 1-3, the reactor 1 contains a set of parallel tubes 10 enclosed in a cylindrical housing, which is connected at one end to a gaseous reagent feeding chamber 70 and at the other end to a product collection chamber 40.

[0091] Gaseous ozone from an external source, such as a corona discharge or electrolysis driven ozone generating device, flows through conduit 12 into the feeding chamber 70 where it enters the tubes 10 and reacts with the liquid or emulsified reagent.

[0092] Reaction product(s) emerge from the tubes 10 into the product collection chamber 40, from which the reaction product(s) are removed via conduit 13 and collected in an external vessel.

[0093] A liquid coolant, such as water and/or glycol, flows into the reactor housing through conduit 20, around the tubes 10 and out of the reactor housing via conduit 21. Alternatively, the liquid coolant flows into the reactor housing through conduit 21 and out via conduit 20. The in conduit 20 and out conduit 21 direction of flow for the liquid coolant is preferred, however, because the exothermic reaction between ozone and the liquid or emulsified reagent(s) takes place preferentially at the portion of the tubes 10 that is closest to the feeding chamber 70. Numerous diaphragms 22, located inside the reactor housing and oriented perpendicular to the

tubes 10, increase alter the path and increase the turbulence of the coolant flowing through the reactor housing. The coolant is separated from the gas feeding chamber and the product collection chamber by plates 23 and 24, respectively, which are oriented normal to, and positioned at the ends of the tubes 10.

[0094] Additional configurations for cooling the reactor that are not depicted in Figures 1-3 are also effective and may be employed. For example, the reactor housing interior may contain two separate cooling sections, one to cool the end of the tubes 10 that is connected to the feeding chamber 70 and one too cool the end of the tubes 10 that is connected to the product collection chamber 40, to enhance the overall cooling capacity.

[0095] A third tube plate 25 is positioned between the gas feeding chamber 70 and plate 23 such to define a feeding chamber 15 for the liquid or emulsified reagent(s). One or more conduits 16 are used to feed the liquid or emulsified reagent(s) into the feeding chamber 15, which also contains a device as shown in Figure 2 for introducing the liquid or emulsified reagent(s) into one end of the tubes 10.

[0096] As shown in Fig. 2, each tube 10 has a cylindrical portion 30 with a slightly larger diameter than the remainder of the tube, which is connected to the tube by a frusto-conical section 31. The cylindrical portion 30 contains passages 38 for introducing the liquid or emulsified reagent(s) into the tube 10. The cylindrical portion 30 fits, with suitable clearance, in a cylindrical sleeve 33, the latter of which facilitates for the formation of liquid-tight seals between the cylindrical portion 30 and plates 23 and 25. The cylindrical sleeve 33 contains passages 36 for the liquid or emulsified reagent(s), of suitable size and circumferential distribution as not to generate head losses when allowing passage of the liquid or emulsified reagent(s) into the cylindrical portion 30.

[0097] The outer surface of a second sleeve 50 is in contact with the inner surface of the cylindrical portion 30, except for a central section, owing to the presence of a wide annular groove 51. The inner surface of the cylindrical portion 30 and groove 51 define an annular space for receiving the liquid or emulsified reagent(s) that enter the tube 10 from the passages 36 and 38, which open into groove 51. A seal groove 34 is positioned between the cylindrical sleeve 33 and the frusto-conical section 31. Suitable axial passages 52, shown only diagrammatically in Fig. 2, allow the liquid reagent to discharge into the tube interior from the annular space defined by groove 51. The sleeve 50 comprises a beveled or frusto-conical end with the same opening angle as the frusto-conical section 31.

[0098] Between one end of the second sleeve 50 and the frusto-conical section 31 there is an annular slot oriented according to the generatrices of a truncated cone, the width of this slot being defined by the gap space between sleeve 50 and the frusto-conical section 31. The gap space

between sleeve 50 and the frusto-conical section 31 may be adjusted by a threaded crown 54 screwed into the end of the cylindrical portion 30 that is closest to the gas feeding chamber 70. It is thus possible, by screwing up or down the sleeve 50 in the cylindrical portion 30, to adjust the cross-section of the annular slot between the edge of the sleeve 50 and the frusto-conical section 31. The annular slot, being orientated according to the generatrices of a cone, favors the distribution of the liquid reagent in the form of a film entirely around the inner surface of the tube 10.

[0099] The inner diameter of sleeve 50 is suitably the same as the inner diameter of the tube 10 so that the gaseous reagent coming from the distribution chamber 70 may be brought to brush the free surface of the film 60 without resulting in a significant head loss.

[00100] Starting materials for the method described herein include any compound that may be oxidized by ozonolysis. Specific examples of starting materials for this process include hydroxycitronellene, methoxycitronellene, fatty acid methyl esters (FAME), triglycerides, fatty acids, fatty alcohols, fatty esters, diterpenes, sesquiterpenes, monoterpenes, allyl ethers, alpha olefins, and rosin acids.

[00101] In one embodiment, a tube reactor for ozonolysis includes a tube (see, e.g., 10 in Figure 1) with a 5 to 30 mm internal diameter (e.g., 10 mm) and a length of 1 to 7 m (e.g., 1.7 m). The tube is constructed of a suitable material (e.g., stainless steel) and is connected to a gaseous reagent feeding chamber (see, e.g., 70 in Figure 1) that allows gas to flow through the center of the tube and liquid to be flowed in a film on the wall of the tube through annular slots (e.g., as shown in Figure 2; component II in Figure 1). The tube is enclosed in a jacket (see, e.g., 1 in Figure 1) for circulating liquid coolant around it (see, e.g., 10 in Figure 1), with the end of the tube protruding through a liquid-sealed orifice (see, e.g., 24 in Figure 1). A liquid/gas separation vessel is connected to the bottom of the reaction tube (see, e.g., 10 in Figure 1). The excess gas flows into an ice condenser and then into an ozone destruction unit. The collected liquid product is pumped into sampling containers for analysis by a peristaltic pump.

[00102] In one embodiment, the gas inlet (see, e.g., 12 in Figure 1) is connected to an ozone generator, and the liquid inlet is connected to a stirred feed tank equipped with a peristaltic pump. The liquid inlet pipe is also jacketed and cooled to control the temperature of the feed liquid or emulsified reagent.

[00103] In one embodiment, for emulsion preparation, water is combined with the organic reagent in a ratio (e.g., 5:1) ranging from stoichiometric (i.e., 1:1) to very dilute (e.g., 100:1) in the feed tank and stirred vigorously such that a homogenous emulsion is maintained. Deionized water is used for the emulsions.

[00104] In one embodiment, a mixture of O₂ and N₂ gas is used to feed the ozone generator and to comprise the ozone carrier gas for the ozonolysis reaction.

[00105] In one embodiment, conversions of starting materials are determined by gas chromatography (GC) and are calculated on the basis of the disappearance of starting material. Samples are prepared by extracting the organic components of the emulsion into a homogenous organic solvent phase. Analysis of the composition of the aforementioned organic phase is accomplished by gas chromatography.

[00106] In one embodiment, the ratio of water to organic reagent ranges from 1:1 to 100:1 (e.g., 5:1), the ozone concentration ranges from 2.5% to 10% (e.g., 5%), the gas flow rate ranges from 10 to 20 L/min (e.g., 15 L/min), the ozone mass flow rate ranges from 32.6 to 135 g/h (e.g., 65.9 g/h), the emulsion flow rate ranges from 1 to 5 kg/h (e.g., 2 kg/h), and the cooling temperature ranges from 0 to 20 °C (e.g., 10 °C), to yield starting material conversion percentages ranging from 13.70% to 52.63% (e.g., 26.76%).

[00107] In another embodiment, 1-6 pilot tube reactors (e.g., 3) can be connected in series, with gas and liquid being separated at the bottom of each tube. Tubes can be from 1-6 m in length (e.g., 1.7 m), and the tubes can range in diameter from 5-50 mm (e.g., the first 2 tubes being 25 mm in diameter and the 3rd tube being 10 mm in diameter). The organic liquid feed can be flowed in a solution of reagent and nonanoic acid in ranges from 1:1 to 100:1 (e.g., 3:1) through the first tube to the second and third tube in series at rates ranging from 1-99 kg/hr (e.g., 4.2 kg/hr). The gas can be flowed co-currently at ozone concentration in ranges from 0.5% to 10% (e.g., 5.1%) from the 3rd tube through the 2nd to the 1st tube at a flow rate from 10 to 1500 L/min (e.g., 150 L/min), and the cooling jacket temperature can be maintained between 0 and 50 °C (e.g., 15°C) to yield conversion percentages between 93-100% (e.g., 97.6%).

Examples

Example 1.

Film Ozonolysis in a Monotubular Reactor

Ozonolysis Reactor Details

[00108] A pilot tube reactor was used for ozonolysis, including a tube with a 10 mm internal diameter and a length of 1.7 m (e.g., 10 in Figure 1). The tube was constructed of 316 stainless steel and was connected to a gaseous reagent feeding chamber (e.g., 70 in Figure 1) that allowed gas to be flowed through the center of the tube and liquid to be flowed in a film on the

wall of the tube through annular slots (e.g., as shown in Figure 2; component II in Figure 1). The tube was enclosed in a steel jacket (e.g., 1 in Figure 1) for circulating cooling fluid around the reaction tube (e.g., 10 in Figure 1) with the end of the tube protruding through a liquid-sealed orifice (e.g., 24 in Figure 1). A liquid/gas separation vessel was connected to the bottom of the reaction tube (e.g., 10 in Figure 1). The excess gas flowed through to an ice condenser followed by an ozone destruction unit. The collected liquid product was pumped through a peristaltic pump to sampling containers for analysis.

[00109] The gas inlet (e.g., 12 in Figure 1) was connected to an Ozonia Ozat CFS-2G ozone generator and the liquid inlet was connected to a stirred feed tank equipped with a peristaltic pump. The liquid inlet pipe was also jacketed and cooled to control the temperature of the feed liquid reagent.

Ozonolysis Reagent and Product Details

[00110] Methoxycitronellene was >99% pure and was obtained from reaction of methanol with dihydromyrcene. Fatty acid methyl esters (FAME) was obtained from multiple sources including soy, palm, and algal oils and consisted of 72-89% methyl oleate as the primary component.

[00111] When methoxycitronellene is reacted, the major product is methoxymelonal. When FAME is reacted, the major products are methyl azelaldehyde and nonanal.

[00112] For the emulsion preparation, water was combined with the organic reagent in a 5:1 ratio in the feed tank and stirred vigorously such that a homogenous emulsion was maintained. Deionized water was used for all of the emulsions.

[00113] A mixture of 95% O₂ and 5% N₂ gas was used to feed the ozone generator and to comprise the carrier gas for O₃ to the reaction.

[00114] Conversions of starting materials were determined by GC (Agilent 6890N) and were calculated based on the disappearance of the starting material on a gross adjusted basis. Samples were prepared by extracting the organic components of the emulsion into a homogenous ethyl acetate solvent phase and analyzing the composition of said organic phase by gas chromatography.

[00115] Example reaction conditions and product distributions are outlined in Tables 1 and 2. Reactions were performed at various O₃ concentrations and mass flow rates.

Table 1. Methoxycitronellene in a water-based emulsion was oxidized by ozonolysis at different ozone concentrations and flow rates to yield the starting material conversion percentages shown.

Sample	Ratio of Water to Organic Reagent	O ₃ Conc (w/w) %	Gas Flowrate L/min	O ₃ Mass Flow g/h	Emulsion Flow kg/h	Cooling Temp °C	Conversion of Starting Material %
1	5:1	2.5	15	32.6	2	10	13.70
2	5:1	2.5	15	32.6	2	10	15.79
3	5:1	5	15	65.9	2	10	26.76
4	5:1	5	15	65.9	2	10	24.71
5	5:1	10	15	135	2	10	48.89
6	5:1	10	15	135	2	10	52.63

Table 2: FAME (89% methyl oleate) in a water-based emulsion was oxidized by ozonolysis at different ozone concentrations and flow rates to yield the starting material conversion percentages shown.

Sample	Ratio of Water to Organic Reagent	O ₃ Conc. (w/w) %	Gas Flowrate L/min	O ₃ Mass Flow g/h	Emulsion Flow kg/h	Cooling Temp °C	Conversion of Starting Material %
1	5:1	4	15	52.5	2	25	42.4
2	5:1	4	15	52.5	2	25	38.8
3	5:1	6.4	15	85	2	25	46.5
4	5:1	6.4	15	85	2	25	50.4
5	5:1	9.5	15	128	2	25	50.9
6	5:1	9.5	15	128	2	25	51.3

Example 2.

Ozonolysis Reactor 2 Details

[00116] A second arrangement of involving 3 pilot tube reactors connected in series was used. All 3 tubes were 1.7 m in length, with the first 2 tubes being 25 mm in diameter and the 3rd tube being 10 mm in diameter. All tubes were equipped with a film distribution head, a cooling jacket, and a gas liquid separator at the bottom. The organic, liquid feed was flowed from the first tube through the second and third tube in series. The gas was flowed co-currently from the 3rd tube through the 2nd to the 1st tube. The cooling jacket temperature was maintained at 15 °C.

[00117] In one instance, this reactor was used to process a 75% mixture of vegetable fatty acid in nonanoic acid. The major components of the vegetable fatty acid were estimated as follows: 77.65% oleic acid, 11.64% linoleic acid, 1.98% stearic acid, 4.4% palmitic acid, 2.9% myristic acid. The O₃ was generated using pure O₂ and a generator composed of 2 Pinnacle Quadblocks in a custom cabinet. The results of this run are presented in Table 3.

Table 3. Ozonolysis of vegetable fatty acid in a film ozonolysis reactor. Sample 1 was taken at 10 minutes, Sample 2 at 15 minutes, and Sample 3 at 20 minutes. Conversion was based on disappearance of starting material on GC FID as compared to an internal standard.

Sample	Ratio of Vegetable Fatty Acid to Nonanoic Acid	O ₃ Conc. (w/w) %	Gas Flowrate L/min	O ₃ Mass Flow g/h	Liquid Flow kg/h	Cooling Temp °C	Conversion of Starting Material (oleic/linoleic) %
1	3:1	5.1	150	672	4.2	15	95.5/98.1
2	3:1	5.1	150	672	4.2	15	94.0/97.6
3	3:1	5.1	150	672	4.2	15	93.7/97.3

[00118] In another instance, this reactor was used to convert a 25% solution of dihydromyrcenol in water to hydroxymelonal. The results of this run are shown in Table 4.

Table 4. Ozonolysis of dihydromyrcenol, i.e., hydroxycitronellene, in the film ozonolysis reactor to generate hydroxymelonal. Samples were taken every 5 minutes. Conversion was based on GC FID results.

Sample	Dihydromyrcenol to Water Ratio	O ₃ % (w/w)	Gas flow (L/min)	O ₃ Mass Flow (g/hr)	Liquid Flow (ml/min)	Cooling Temp (°C)	Conversion of Starting Material (%)
1	3:1	7.8	80	555.8	80	5-15	99.8
2	3:1	7.8	80	555.8	80	5-15	99.5
3	3:1	7.8	80	555.8	80	5-15	98.5
4	3:1	7.8	80	555.8	80	5-15	97.2
5	3:1	7.8	80	555.8	80	5-15	98.3

[00119] Similar results were obtained for the conversion of β -lonone to generate cyclocitral.

INCORPORATION BY REFERENCE

[00120] The entire disclosure of each of the patent documents and scientific articles referred to herein is incorporated by reference for all purposes.

EQUIVALENTS

[00121] The disclosure can be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The foregoing embodiments are therefore to be considered in all respects illustrative rather than limiting on the disclosure described herein. Scope of the disclosure is thus indicated by the appended claims rather than by the foregoing description, and all changes that come within the meaning and range of equivalency of the claims are intended to be embraced therein.

What is claimed is:

1. A method of performing ozonolysis or ozone-based oxidation on a liquid or emulsified reagent using a tubular falling film reactor with one or multiple tubes wherein the combined ozone and carrier gas flow is co-current.
2. The method of claim 1, wherein the diameter of the tube(s) is between 5 mm and 5 m.
3. The method of claim 2, wherein the diameter of the tube(s) is between 5 and 30 mm.
4. The method of claim 2, wherein the diameter of the tube(s) is between 5 and 50 mm.
5. The method of claim 2, wherein the diameter of the tube(s) is between 50 mm and 5 m.
6. The method of claim 1 where the tube diameter is between 50 mm and 5 m and an annular element is added in to regulate gas flow and to add additional film surface area.
7. The method of any one of claims 1-6, wherein the length of the tube(s) is between 1 and 20 m.
8. The method of claim 7, wherein the length of the tube(s) is between 1 and 7 m.
9. The method of claim 8, wherein the length of the tube(s) is 1.7 m.
10. The method of claim 8, wherein the length of the tube(s) is 6 m.
11. The method of claim 7, wherein the length of the tube(s) is between 7 and 20 m.
12. The method of any one of claims 1-11, wherein the distribution of gas within the tube(s) may be controlled by annular spaces for gas flow within the tube(s).
13. The method of any one of claims 1-12, wherein multiple falling film tube reactors are used in series to process a continuous stream of liquid or emulsified reagent.
14. A method of performing ozonolysis or ozone-based oxidation on a liquid or emulsified reagent with a gaseous reagent comprising ozone and one or more carrier gases, the method comprising:
 - (a) feeding the liquid or emulsified reagent from a common liquid or emulsified reagent feeding chamber that is maintained completely full through annular slots and into a plurality of parallel and substantially identical tubes, as to form a liquid or emulsified reagent film on the internal surface of each tube;
 - (b) feeding the gaseous reagent through the annular slots and into the tubes from a gaseous reagent feeding chamber, the feeding pressure of the gaseous reagent being substantially the same as the pressure loss from the gaseous reagent flow through the tubes containing the liquid or emulsified reagent film, but less than the feeding pressure of the liquid or emulsified reagent; and
 - (c) cooling the tubes by flowing a liquid coolant through a housing surrounding the tubes.

15. The method of claim 14, further comprising (d) collecting reaction product(s) and gaseous reagent exhaust in one or more product containers connected to the end of the tubes opposite that connected to the annular slots.
16. The method of claim 14, wherein the length of the tubes is between 1 and 20 m.
17. The method of claim 16, wherein the length of the tubes is between 1 m and 7 m.
18. The method of claim 17, wherein the length of the tubes is 1.7 m.
19. The method of claim 17, wherein the length of the tubes is 6 m.
20. The method of claim 16, wherein the length of the tubes is between 7 m and 20 m.
21. The method of any one of claims 14 through 16, wherein the internal diameter of the tubes is between 5 mm and 5 m.
22. The method of claim 21, wherein the internal diameter of the tubes is between 5 mm and 30 mm.
23. The method of claim 21, wherein the internal diameter of the tubes is between 5 mm and 50 mm.
24. The method of claim 21, wherein the internal diameter of the tubes is between 50 mm and 5 m.
25. The method of any one of claims 14 through 24, wherein the feeding pressure of the gaseous reagent is between 0.1 and 5 bar.
26. The method of claim 25, wherein the feeding pressure of the gaseous reagent is between 0.1 and 0.5 bar.
27. The method of claim 26, wherein the feeding pressure of the gaseous reagent is between 0.2 and 0.4 bar.
28. The method of any one of claims 14 through 27, wherein the feeding overpressure of the liquid or emulsified reagent with respect to the feeding pressure of the gaseous reagent is between 5 and 15 cm of liquid column.
29. The method of any one of claims 14 through 28, wherein the carrier gas contains, at least in part, gaseous reagent exhaust from one or more product containers.
30. The method of claim 1 as described herein with reference to the accompanying drawings and examples.
31. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises hydroxycitronellene.
32. The method of claim 31, wherein the liquid or emulsified reagent is a hydroxycitronellene emulsion in water.
33. The method of claim 31, wherein the liquid or emulsified reagent is a hydroxycitronellene solution in methanol.

34. The method of any one of claims 31 through 33, wherein the product is hydroxymelonal.
35. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises methoxycitronellene.
36. The method of claim 35, wherein the liquid or emulsified reagent is a methoxycitronellene emulsion in water.
37. The method of claim 35, wherein the liquid or emulsified reagent is a methoxycitronellene solution in methanol.
38. The method of any one of claims 35 through 37, wherein the product is methoxymelonal.
39. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises fatty acid methyl esters (FAME).
40. The method of claim 39, wherein the liquid or emulsified reagent is a FAME emulsion in water.
41. The method of claim 39, wherein the liquid or emulsified reagent is a FAME solution in methanol.
42. The method of any one of claims 39 through 41, wherein the product comprises methyl azealdehyde and nonanal.
43. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises an unsaturated olechemical such as a triglyceride, a fatty acid, a fatty alcohol, or a fatty acid ester.
44. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises a diterpene.
45. The method of claim 44, wherein the diterpene is abietic acid or its ester.
46. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises a mono- or di-unsaturated sesquiterpene.
47. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises a mono- or di-unsaturated monoterpene or terpene derivative.
48. The method of claim 47, wherein the mono- or di-unsaturated monoterpene or terpene derivative is pinene or limonene.
49. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises an allyl ether of 10 to 30 carbon atoms.
50. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises an alpha olefin of 10 to 30 carbon atoms.
51. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises a tertiary amine.
52. The method of claim 51, wherein the product is an N-oxide derivative.

53. The method of any one of claims 1 through 29, wherein the liquid or emulsified reagent comprises a rose ketone.
54. The method of claim 53, wherein the rose ketone is Ionone.
55. The method of claim 54, wherein the product is cyclocitral.
56. The method of any one of claims 1 through 29, wherein waste water is the reagent introduced into the reactor for the purpose of treating the waste water.
57. The method of any one of claims 1 through 29, wherein the reagent introduced into the reactor is any compound that is susceptible to ozone oxidation.
58. The method of claim 57, wherein the reagent is selected from the group consisting of an alkane, an amide, a carboxylic acid, and a compound containing an aromatic ring.
59. The method of any one of claims 1 through 29, wherein the carrier gas is O₂.
60. The method of any one of claims 1 through 29, wherein the carrier gas is air.
61. The method of any one of claims 1 through 29, wherein the carrier gas is a mixture of O₂ and N₂.
62. The method of claim 61, wherein the carrier gas is about 95% O₂ and about 5% N₂.

Fig. 1

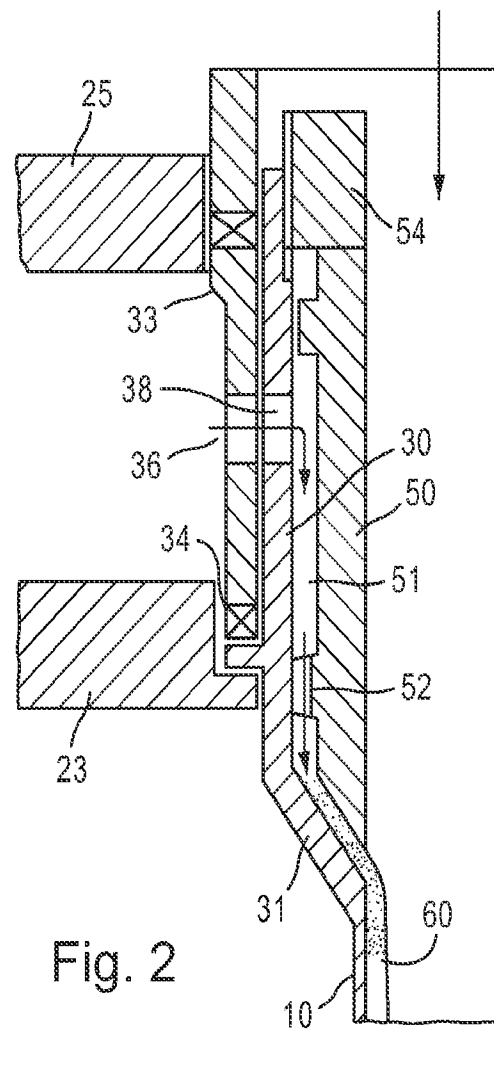
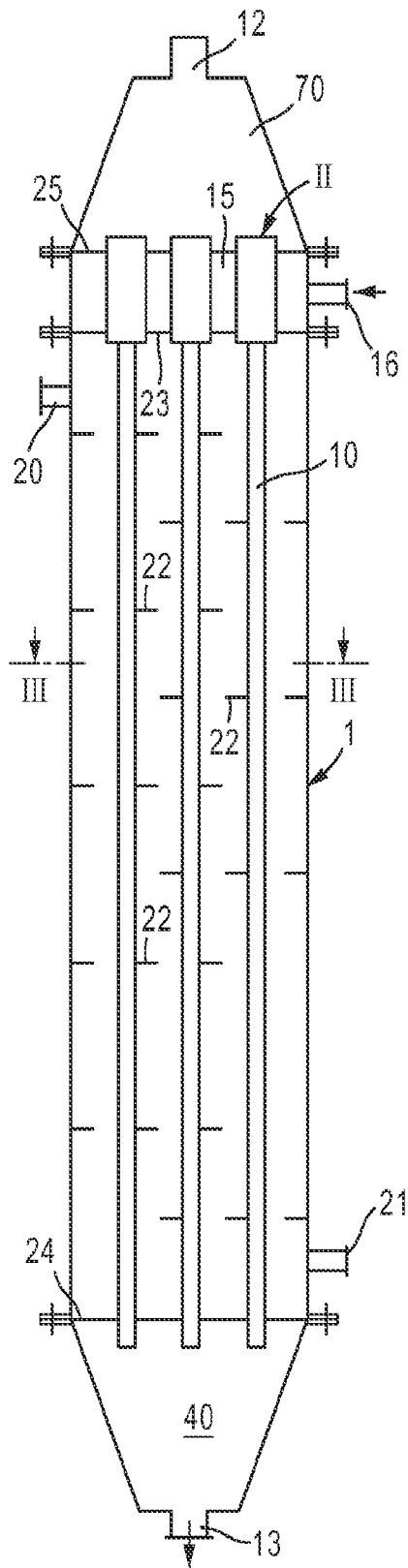


Fig. 2

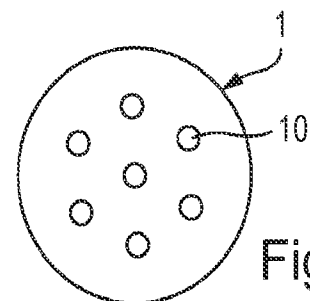


Fig. 3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/36589

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - C07C 51/16; B01J 19/00; C08G 4/00; C08L 59/00 (2015.01)

CPC - B01J 19/1887; C07B 41/08; C07C 31/34

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC(8): C07C 51/16, 45/00; B01J 19/00, 19/18, 19/24; C08G 4/00; C08L 59/00; C095 159/00 (2015.01)

CPC: B01J 19/247, 19/1887; C07B 41/08; C07C 31/34, 45/00, 51/16; C08G 4/00; C08L 59/00; C09J 159/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSeer (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, Other Countries (INPADOC), RU, AT, CH, TH, BR, PH), ProQuest, PatentsGoogle, Google Scholar Keywords: Ozonolysis, ozone-based oxidation, co current, concurrent, tubular falling film reactor, one or multiple tubes, liquid, fluid, emulsified reagent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 8,221,708 B2 (SEEBAUER, F et al.) 17 July 2012; figure 1; column 2, lines 36-48; column 3, lines 36-38; column 5, lines 26-35, 59-65	1-11, 14-24
Y	US 6,512,131 B1 (BEST, B et al.) 28 January 2003; column 6, lines 30-55	1-11, 14-24
Y	US 7,968,742 B2 (AIGNER, R et al.) 28 June 2011; column 5, lines 26-35, 59-65	9-11, 18-20

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search.

18 August 2015 (18.08.2015)

Date of mailing of the international search report

18 SEP 2015

Name and mailing address of the ISA/

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P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/US15/36589

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 12-13, 25-62
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.