Title: LIQUID TREATMENT APPARATUS AND METHODS

Abstract: Apparatus (40) and methods for treatment of liquids by generating hydroxyl radicals through the dissolution of water molecules by hydraulic cavitation.
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LIQUID TREATMENT APPARATUS AND METHODS

Field of the Invention

[0001] The present invention relates to apparatus and methods for effecting the dissolution of water into hydroxy! radicals for the treatment of liquids.

Background of the Invention

[0002] Centrifugal separation of solids carried in a liquid-solid suspension by hydrocyclonic technology involves tangentially feeding the suspension into an open-ended, circular cylinder having an inwardly tapering inner diameter and extracting from its apex heavier solids, while collecting finer solids from its larger opposite end. Individual hydrocyclone cylinders may be relatively small - on the order of about four inches in length and with an inner diameter tapering
to as cyclonettes.

[0003] Typically, the cyclonettes are grouped in a housing, as shown in U.S. Patents No. Re, 25,099; 3,261,467; 3,415,374; 3,486,618; 3,598,731; 3,959,123 and 5,388,708. As indicated by these patents, this technology dates back to at least the mid-1950's. Regardless, the essence of the technology is the same. A spiral flow of the suspension is introduced tangentially along the inwardly tapering inner wall of the cyclonette near its wider end and flows along the inner wall toward the opposite, smaller end. This generates a counter flow, which carries fines out the larger, open end.

[0004] In contrast to hydrocyclonic technology, hydraulic cavitation is directed toward the dissolution of water into hydroxy! radicals for the treatment of liquids. Early work in this field was directed to the generation of hydraulic cavitation by means of sound waves. See, for example, "The Chemical Effects of Ultrasound," by Kenneth S. Suslick, *Scientific American*, February, 1989, pp. 80-86. However, hydraulic cavitation may also be induced by cavitating jets. See "Remediation and Disinfection of Water Using Jet Generated Cavitation," by KM. Kalumuck, et. al., Fifth International Symposium on Cavitation (CAV 2003) Osaka, Japan, November 1-4, 2003.

[0005] Regardless of which cavitation method is employed, the goal is to generate many fine bubbles, which upon their implosion, create intense, but highly localized temperatures and pressures. This energy release then causes a dissolution of the water molecules and the creation of free hydroxyl radicals.
has been well recognized for many years.

For example, the patent literature discloses a multitude of methods and apparatus for this purpose. See, for example, U.S. Patent No. 6,200,486, where fluid jet cavitation is employed for the decontamination of liquids by directing the flow along an interior chamber surface. Note also U.S. Patent 6,221,260, which describes the creation of a central vortex about a longitudinal axis for inducing cavitation pockets in the vortex, and U.S. Patent 6,896,819, which relies upon the formation of a liquid vortex along an inner surface of a cyclone.

Thus, it will be seen that the beneficial effects of cavitation are acknowledged and an understanding of the mechanism involved has been known for decades. However, the inefficiency of the known processes, whether based on ultrasonic or jet cavitation, has restricted commercial acceptance of hydraulic cavitation. There thus remains the apparent conundrum of a highly effective method of water treatment but at an energy cost that thwarts its widespread implementation.

Summary of the invention

The present invention obviates the inefficiency of present day cavitation processes by employing liquid jets, but in a manner contrary to existing jet cavitation technology. Thus, while conventional wisdom focuses on the formation of hollow core jets to create shear zones that in turn generate cavitation, the present invention, in one embodiment, is directed to the formation of a central axial jet and a vacuum chamber that can be sealed by
generated by directing a high velocity jet of fluid through a volume of vapor
under a vacuum created in the chamber through which the jet travels.

[0009] In this embodiment, the present invention employs a high speed jet of liquid, flowing axially and concentrically through a cylindrical chamber to generate a vacuum within a confined space. The invention includes the provision of a liquid-free volume around the jet near the inlet end of the chamber to cause vapor to accumulate. The discharge opening of the chamber is designed so that it will be completely filled by the exiting jet of fluid, so as to seal the chamber and permit maintenance of a vacuum.

[0010] The present invention recognizes that although hydrocyclone technology is completely alien to hydraulic cavitation, conventional hydrocyclone apparatus may be modified and thus adapted for implementation of the present invention. For example, a conventional cyclonette may be employed to provide a central axial jet with its conventional, tangential feed opening blocked. Additionally, a multiplicity of cyclonettes may be mounted in a housing, essentially as shown in U.S. Patent No. 5,388,708, but with the cyclonettes fed from the annular, outer chamber and discharging into the inner or central cylindrical chamber.

[0011] Alternatively, the tangentialSy directed inlet port in the cyclonettes of the 708 patent may be employed to inject a second stream of liquid into the cyclonette along its inside wall in a spiral flow path. Vapor within the cyclonette will tend to be dragged axially toward the discharge end by the linear jet and in a spiral path by the second liquid. When the two high-velocity liquid streams
lend to create a turbulent mixing zone that will disrupt the vapor film between
the two liquids and generate bubbles. Increasing the fluid velocities will
increase shear and reduce the size of the bubbles. It will also result in
increased vacuum within the chamber and the generation of more vapor.

With this design cavitation initiates at very low inlet fluid pressure
- on the order of 10 psi or less, with water at 3G°C and atmospheric pressure
discharge. Also, the high shear generated helps reduce bubble size, which in
turn, increases bubble surface to volume ratio and improves chemical reaction
rates. As long as the velocity head of the fluid exiting the chamber exceeds the
static pressure in the discharge zone, a vacuum will be generated within the
chamber. Once pressure within the chamber drops to the vapor pressure of the
liquid, vapor fills the cavity and cavitation occurs. Thus, the amount of vapor
entrained is almost independent of pressure in the discharge zone.

As a modification of this embodiment, the main inlet jet may pass
through a vortex finder of conventional design, except that, in addition to the
flow being directed into the cyclonette from the vortex finder (instead of out of
the cyclonette through the vortex finder), the vortex finder is modified to impart
a spin to the incoming jet in a direction opposite to the direction of the
tangential inlet flow. The result is that the collision of the two streams flowing in
opposite directions creates a shear on the vapor trapped between the two
streams that tears the vapor film into tiny bubbles, leading to increased
cavitation efficiency.
invention, the enhancement of fine bubble generation may be attained by the interposition in the flow path into the cyclonette of a washer-shaped orifice plate. The abrupt decrease in diameter of the flow path through a modified vortex finder, not only accelerates flow and decreases pressure, but generates an intense shear zone that forms a virtual fog of tiny bubbles, the collapse of which, generates localized extreme temperatures and pressures.

**Brief Description of the Drawings**

[0015] FIG 1 is an elevational view, partly in section, displaying an array of cyclonettes modified in accordance with the present invention, to generate hydraulic cavitation;

[0016] FIG. 2 is an elevational view of the extreme lower end of the device of FIG. 1 and with the cooperating inlet and outlet flow manifolds;

[0017] FIG. 3 is a cross-sectional view of a portion of FIG. 1 showing in greater detail the positioning of a modified cyclonette;

[0018] FIG. 4 is a horizontal view in cross-section taken along line 4-4 of FIG. 1;

[0019] FIG. 5 is a view similar to FIG. 4, but with portions removed to show more dearly the physical relationships of modified cyclonettes within an array with respect to each other;
vortex finder;

[0021] FIG. 7 is a view similar to FIG. 6, but showing a modified
cycionette and a modified vortex finder, together with an orifice plate;

[0022] FIG. 8 is a view similar to FIG. 7, but showing the flow of the liquid
through the modified cycionette, vortex finder and orifice plate;

[0023] FIG. 8A is a somewhat diagrammatic view of the liquid flow at
point 8A in FIG. 8 and showing individual bubbles generated as the liquid flows
through the inlet plate;

[0024] FIG. 8B is a view similar to FIG. 8A, but depicting the flow and
bubbles at point 8B in FIG. 8 of the drawings;

[0025] FIG. 8C is a view similar to FIGS. 8A and 8B, but showing the
individual bubbles somewhat dispersed at point 8C in Fig. 8 downstream of
points 8A and 8B in FIG. 8;

[0026] FIG. 9 is a view similar to FIG. 6, but showing a modified flow path
through the body of a cycionette;

[0027] FIG. 10 is a view similar to FIG. 9, but with the extension of the
vortex finder removed; and

[0028] FIG. 11 is a view similar to FIG. 7, but showing the orifice plate
positioned downstream from the position shown in FIG. 7, closer to the throat
area of the modified cycionette.
Description of the Preferred Embodiments

[0029] Turning initially to FIG. 6 of the drawings, a more or less conventional cyclonette 10 is shown with a vortex finder 12 installed in the left hand end of the cyclonette as it appears in FIG. 6 of the drawings. For a purpose to be presently described, the left-hand end of the cyclonette may be provided with an annular groove 14 into which an O-ring 16 may be seated. To the right of the O-ring 16, as seen in FIG. 6 of the drawings, a second annular groove 18 may be formed to receive a second O-ring 20 of more or less rectangular cross-sectional configuration, interiorly of the cyclonette 10, a flow path is provided comprising a throat portion 22, an inwardly tapering flow channel 24, and a terminal flow channel 26 of narrower constant diameter. At its left-hand end, as seen in FIG. 6, the cyclonette 10 may be provided with an internally threaded socket 28 receiving the complementary external threads 30 of the vortex finder 12. The vortex finder has a uniformly inwardly tapering wall 32 and an extension 34 projecting into the throat portion 22 of the cyclonette. Lastly, the cyclonette may be provided with a passageway 36 extending through a wall of the cyclonette 10 into the throat section 22.

[0030] With reference now to FIG. 1 of the drawings, a housing 40 is shown comprising cylinders 42, each having outwardly projecting annular flanges 44 to permit two or more cylinders 42 to be clamped together by bolts.
are shown in Fig. 1 of the drawings, it will be apparent that more or less cylinders may be employed, depending on the desired length of the annular outer chamber. At its upper end, the annular outer chamber is capped by a closure plate 50 having a lifting ring 52. The closure plate 50 is clamped to the upper end of the uppermost cylinder 42 in a manner similar to the clamping between adjacent cylinders by means of bolts 46.

[0031] With reference now to FIGS. 1 and 2 of the drawings, it will be seen that the lowermost cylinder 42 is attached at its lower end by means of bolts 46 to a manifold system 54. At its upper end, the manifold system 54 has an outwardly projecting annular flange 56 to which the lowermost cylinder 42 is damped by the bolts 46 as shown in Fig. 2 of the drawings. The manifold system 54 comprises three concentric flow channels, namely, an outer feed channel 58, a central, outwardly-flowing channel 60, and an intermediate channel 62, which may or may not be used during the practice of the present invention, as will be described in more detail.

[0032] As seen in Fig. 1 of the drawings, positioned concentrically within the outer cylinders 42 are intermediate cylinders 64 and inner cylinders 66, which are each superimposed upon each other and clamped by the clamping action between the outer cylinders, the top plate 50 and the lower annular rim 56 of the manifold system 54. It will thus be apparent with reference to FIGS. 1 and 2 of the drawings that the outer and intermediate cylinders form the annular outer chamber 68 communicating with the outer feed manifold 58, an
intermediate chamber 72 communicating with the manifold 62.

[0033] As best seen in FIG. 3 of the drawings, adjoining sets of intermediate and inner cylinders may be provided with annular grooves 74 and 76 to receive any convenient seating means. Intermediate cylinders 64 are also provided with closely spaced openings 78 to receive cyclonettes which may be of more or less conventional design of a type shown in FIG. 6 of the drawings or of various modified forms which will be described presently in more detail, in any case, the cyclonettes are secured in any convenient manner in the openings 78 with the opposite ends of the cyclonettes being received in openings 80 in the cylinders 66. In FIG. 3 of the drawings the openings 78 are shown as having internal threads, which could receive complementary external threads on the exterior of the cyclonettes. In this regard, O-rings, such as those shown at 16 and 20 in FIG. 6 of the drawings, may be utilized to create seals with the cylinders 64 and 66, respectively.

[0034] However, the particular manner of securing the cyclonettes in the intermediate and interior cylinders 64 and 66 does not form a part of the present invention, and any convenient means may be utilized. In any case, the positioning of a cyclonette, regardless of its specific configuration, in the manner shown in FIG. 3 permits the liquid delivered through the outer manifold 58 and into the annular outer chamber 68 to flow into an insert 82 and then into the upstream end of the cyclonette and out its downstream end where it is immersed in the liquid being treated, which is being collected in the inner or central cylindrical chamber 70 and then out through the manifold 60.
the present invention that hundreds, perhaps even a thousand or more of cyclonettes, will be arrayed in a single housing 40. Preferably, each cyclonette, as depicted at 10' in FIG. 5 of the drawings, is disposed opposite another, resulting in direct impingement of the flow from one cyclonette upon the opposite flow from an opposing cyclonette.

[0036] As indicated, previous, conventional utilization of a cyclonette and vortex finder insert as shown in U.S. Patent No. 5,388,708, for example, would result in flow, with reference to FIG. 2 of the drawings, into the intermediate manifold 62 and thence, with reference to FIG. 1, into the intermediate chamber 72. From there the flow would pass into the passageway 36 as seen in FIG. 6 of the drawings, and then spiral around the surface of the throat 22 and thereafter, around the surface of the tapered flow channel 24 to the right as seen in FIG. 6 of the drawing. This would set up a counter flow to the left as seen in FIG. 6 and out the vortex finder 12 of the fines fraction of the suspension while the heavier fractions of the suspension passed on out the narrower flow channel 26 of the cyclonette.

[0037] In contrast, in accordance with the present invention, the feed flow in manifold 58, as shown in FIG. 2 of the drawings, is just the opposite of conventional operation. That is, instead of accepting the fines in an outward flow, the manifold 58 is in fact the feed manifold for the system, delivering the liquid to be treated to the upstream or left-hand end of the vortex finder, as shown in FIG. 6 of the drawings, from whence the flow is ejected in an axial jet out the extension 34 of the vortex finder and into the tapering flow channel 24.
bubbles, each of which, upon implosion, create highly localized areas of extreme pressures and temperatures.

[0038] This in turn results in a dissolution of the water molecules into, inter alia, aggressive hydroxyl radicals. While in its most straightforward form the passageway 36 in the upstream end of the cyclonette will not be utilized, in a modification of the basic form of the invention, a supply of the liquid being treated may be fed via the intermediate manifold 62 and the intermediate chamber 72 into the passageways 36 to provide an additional flow and hence an intensifying of the shear zone to enhance the formation of the tiny bubbles as liquid flows through the tapering flow channel 24 of the cyclonette 10.

10039] Depending upon the desired effect, the passageway 36 may be disposed tangentially with respect to the throat 22, radially, or even substantially axially. It should also be noted that, in addition to utilizing the passageway 36 for the supplemental flow of the liquid being treated, different fluids, gaseous or liquid, could be injected through the passageway 36 to alter the physical or chemical character of the liquid being treated. For example, a pH-adjusting fluid could be supplied through the passageway 36.

[0040] FIG. 9 of the drawings shows a cyclonette 10', similar to that of FIG. 6, but with the flow channels 24 and 26 replaced by flow channels 90 and 92. The reduced diameter at point 94 results in an increase in velocity and a corresponding reduction in static pressure. The pressure within the chamber is directly related to the velocity head at this point. The outwardly tapering flow channel 92 results in a gradual decrease in fluid velocity, permitting efficient
discharge zone.

[0041] As seen in FIG. 10 of the drawings, a cyclonette 10' is provided, but the vortex finder 12 of FIGS. 6 and 9 of the drawings, is replaced by vortex finder 12' in which the extension 34 protruding into the throat portion 22 is eliminated. As a result, the immediate transition from the downstream end of the modified vortex finder 12' into the larger diameter throat portion 22 provides an additional shear zone for the generation of the clesirabie fine bubbles.

[0042] In yet another modification of the hydraulic cavitation device of the present invention, as shown in FIG. 7, the cyclonette 10' is combined with an insert 96 having a straight sided internal bore 98 and external threads 99, which are complementary to internal threads 28' in the modified cyclonette 10'. The insert 96 captures and holds in place within the cyclonette 10' a washer-shaped orifice plate 100 having a central orifice 102. This embodiment has shown to be most productive in the formation of multiple tiny bubbles, as the liquid being treated must first constrict from the larger diameter of the insert flow passage 98 to the restricted orifice 92 and then expand again into the throat 22 of the cyclonette 10'. In this embodiment, as in those of FIGS. 9 and 10, the passageway 36 may be used for the addition of a flow of the liquid being treated or a chemical or physical modifying substance in either a tangential, radial or substantially axial direction into the throat 22 of the cyclonette 10 or 10'.

[0043] In some cases, it may be found desirable to eliminate the throat 22, as shown in FIG. 11 of the drawings, and convey the flow through the
into the radially outwardly tapering flow channel 92. In this embodiment, as in the embodiments of FIGS. 7 and 8, the orifice plate 100 is held in place in the cyclonette 10' by the insert 96, which permits orifice plate 100 to be easily replaced for wear or the like.

[0044] Turning now to FIGS. 8, 8A, 8B and 8C, it will be seen that a liquid 110 being delivered to the upstream end of a modified cyclonette 10', via the outer manifold 58 and outer annular chamber 68, passes through an insert 96 and thence through the orifice 102 of the orifice plate 100 and into the throat portion 22. This creates an intense shear zone, resulting in a myriad of fine bubbles and droplets, some of which are dispersed at point 8A in the flow channel 90 as depicted diagrammatically in FIG. 8A. As the flow proceeds downstream through the ever-narrowing flow channel, the droplets move closer together and entrain pockets of vapor. Some of the kinetic energy of the liquid is utilized to accelerate and compress the pockets of vapor into bubbles until downstream flow channel 92 is reached. Beyond point 8B, as the fluid moves to a zone of lower pressure, the bubbles tend to expand. Lastly, at point 8C, the bubbles have assumed a size and configuration as shown in FIG. 8C of the drawings.

[0045] Thus, it will be seen that the cavitation-generating technology of the present invention utilizes a vacuum chamber maintained within the individual cyclonettes by immersing their discharge ends in the liquid being treated and directing a high velocity jet of the liquid being treated to pass
achieved.

10046] From the above, it will be apparent that the present invention provides an efficient method of harnessing the water molecule dissolution powers of hydraulic cavitation with the consequent release of aggressive hydroxy! radicals and highly effective liquid treatment. Additionally, the present invention utilizes conventional hydrocyclones and modifications thereof by operating them in a manner completely contrary to their intended purpose.
1. Apparatus for treating a body of liquid comprising:
   a plurality of cyclonettes, each including an upstream and a downstream end and an internal, unidirectional flow channel extending through said cyclonettes from said upstream end to said downstream end;
   a feed channel communicating with said upstream ends of said cyclonettes and feeding said liquid to said upstream ends thereof; and
   an outwardly-flowing channel communicating with and immersing said downstream ends of said cyclonettes in said liquid and conveying said liquid away from said downstream ends of said cyclonettes.

2. The apparatus of claim 1 wherein:
   said flow channel includes a first portion tapering inwardly in a downstream direction.

3. The apparatus of claim 2 wherein:
   said flow channel comprises a second portion of constant diameter extending in a downstream direction from a downstream end of said first portion.

4. The apparatus of claim 2 wherein:
   said flow channel includes a second portion extending from a downstream end of said first portion and tapering outwardly in a downstream direction.

5. The apparatus of claim 1 further comprising:
   a throat portion of substantially constant internal diameter positioned upstream of said upstream end of said unidirectional flow channel.
a vortex finder received in each of said cyclonettes adjacent said upstream end thereof,

7. The apparatus of claim 6 wherein:
   a throat portion of substantially constant diameter is positioned upstream of said upstream end of said unidirectional flow channel, and
   said vortex finder has an extension projecting into said throat portion.

8. The apparatus of claim 1 further comprising:
   an orifice plate having an orifice defined therethrough positioned in each of said cyclonettes adjacent said upstream end of said unidirectional flow channel; and
   said orifice having a diameter smaller than that of said flow channel at said upstream end thereof.

9. The apparatus of claim 8 further comprising:
   an insert received adjacent an upstream end of each of said cyclonettes and removably positioning said orifice plates in said cyclonettes.

10. The apparatus of claim 1 further comprising:
    first and second, concentric, cylindrical casings defining therebetween said feed channel, and
    said plurality of cyclonettes being mounted in said second cylindrical casing.

11. The apparatus of claim 1 wherein:
    said outwardly-flowing channel comprises a central chamber concentric with said first and second cylindrical casings.
a passageway extending through a wall of each of said cydonettes.

13. The apparatus of claim 12 wherein:
a substantially constant diameter throat portion is disposed within each of said cydonettes upstream at said upstream end of said unidirectional flow channel; and
said passageway extends into said throat portion,

14. The apparatus of claim 1 further comprising:
a throat portion of substantially constant diameter upstream of said upstream end of said unidirectional flow channel; and
an orifice plate positioned within each of said cydonettes adjacent an upstream end of said throat portions thereof.

15. The apparatus of claim 14 further comprising:
a removable insert received within each of said cydonettes adjacent an upstream end thereof and removably positioning said orifice plate within each of said cydonettes,

16. Apparatus for treating a body of liquid comprising:
outer, intermediate and inner cylinders positioned concentrically with respect to each other;
said outer, intermediate and inner cylinders defining an outer annular chamber, an intermediate chamber, and an inner, central chamber;
a plurality of cydonettes, each having a unidirectional flow channel extending therethrough from adjacent an upstream end to adjacent a downstream end thereof mounted in said intermediate cylinder with said upstream ends of said cyclonette communicating with said annular outer
central chamber;

an outer feed channel supplying liquid being treated to said outer annular chamber; and

a central, outwardly-flowing channel receiving liquid treated by said cyclonettes and immersing downstream ends thereof in said liquid being treated.

17. The apparatus of claim 16 wherein:

each of said cyclonettes has a substantially constant diameter throat portion adjacent an upstream end of said cyclonettes; and

a vortex finder having an inner wall tapering inwardly in a downstream direction is received in each of said cyclonettes with an extension of said vortex finder projecting into said throat portion of said cyclonette.

18. The apparatus of claim 16 further comprising:

an orifice plate positioned within each of said cyclonettes and having an orifice therethrough of substantially smaller diameter than the internal diameter of an adjacent portion of said cyclonette.

19. A method of treating a body of liquid comprising:

directing said liquid through a cyclonette,

said cyclonette having an upstream end, a downstream end, and a unidirectional flow channel extending from said upstream end to said downstream end, and

a portion of said flow channel adjacent said upstream end tapering inwardly in a downstream direction.
immersing said downstream end of said cyclonette in the liquid being
treated thereby maintaining a vacuum in said flow channel.

21. The method of claim 20 further comprising:

directing said liquid from said downstream end of said portion of said
flow channel through a second portion of said flow channel having an inner
diameter tapering outwardly in a downstream direction.

22. The method of claim 19 further comprising:

injecting a portion of the liquid being treated into said cyclonette adjacent
said upstream end.

23. In combination with a body of liquid being treated, a hydraulic cavitation
generator comprising:

a tubular member having an upstream end, a downstream end and an
interior wall defining an axial flow path through said tubular member,
said axial flow path converging from adjacent said upstream end to
adjacent said downstream end;

means of communicating with said body of liquid and said tubular
member for directing a flow of liquid from said body thereof into said upstream
end of said tubular member,
said flow of liquid being characterized as a single liquid jet oriented
substantially centrally of said axial flow path and spaced from said interior wall,
thereby defining an annular area about said jet; and

said downstream end of said tubular member being submerged in said
body of liquid,

whereby said jet creates a shear zone as said jet exits said downstream
body of liquid.

24. The combination of claim 23 further comprising:

   an opening through said tubular member adjacent said upstream end,

entering said axial flow path substantially tangentially of said interior wall.