

RESONATING NOZZLE SYSTEM

by Inventors

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Background of the Invention

1. Field of the Invention

The present invention relates generally to high velocity liquid jets for eroding a surface. More particularly, the present invention relates to discharging an excited liquid to provide the highest possible rate of erosion of the surface.

2. Description of the Related Art

High velocity liquid jets are being increasingly used in a variety of industries to erode, cut, clean, drill, or bore into solid material. The jets offer a relatively inexpensive and pollution-free cleaning process, which can be used in both air and water mediums. In the aviation industry, liquid jets are used to remove paint from aircraft and various coatings from both aircraft and landing strips. In the naval industry, liquid jets are used to clean the hulls of ships. Liquid jets are also used for general purposes that are adaptable to almost any mechanized industry, such as removing rust and debris from a solid surface. Liquid jets have also been used to remove asbestos from contaminated buildings.

A cavitating jet is an enhanced form of a liquid jet used to achieve higher erosion effect of the jet. A cavitating liquid is a fluid having cavities or bubbles when discharged. One method of generating the cavitation effect is to force the fluid through a restrictive aperture at high speeds. The aperture usually includes a protrusion or a rod (also known as a pintle) to generate vapor-filled bubbles in the liquid jet. The liquid jet is then discharged and the bubbles implode when the liquid jet comes into contact and impinges

against a solid surface. The cavitating liquid thus provides for a much greater erosive and destructive effect on the surface material than a non-cavitating liquid jet would.

U.S. Patent No. 4,389,071 discloses that if a cavitating liquid jet is excited or oscillated at a certain frequency, the liquid jet forms into discrete slugs of fluid upon
5 discharge, which have a heightened level of cavitation in submerged mode. The slugs of fluid have an "intermittent percussive effect" on the solid surface that it impinges upon impact, resulting in an even greater erosive effect than an ordinary cavitating liquid jet. The liquid jet is oscillated either mechanically or by hydrodynamic or acoustic interactions with a specially designed nozzle system.

10 The nozzle system typically includes a resonator chamber. The resonator chamber includes an aperture for receiving the liquid and another aperture for discharging the liquid. The nozzle system may also include a discharge chamber for receiving the liquid from the resonator chamber. The discharge chamber is useful because it was discovered that vortices in the liquid jet are more precisely formed if the jet is discharged from the
15 nozzle system using an additional chamber instead of being discharged directly through the resonator chamber.

As the liquid jet enters the resonator chamber, it enters a shear zone between the jet and the chamber, in which discrete vortices are formed in the liquid. Varying the dimensions of the resonator chamber as well as the size and shape of the receiving and
20 discharging apertures may control the frequency that is applied to the liquid jet. The liquid is then discharged in a round jet of liquid, which eventually forms into a string of liquid spheres that impact and erode material from a solid surface.

One of the major problems with the high velocity liquid jet described in U.S. Patent No. 4,389,071 is that while it is effective in eroding a solid surface, the round jet
25 of liquid that is discharged has a very narrow coverage area because it has a small spot size. With the round jet, only one small area of any surface may be impinged and eroded at one time. For example, when the round jet is used to clean a large surface area, such as the hull of a large ship, it may be a very time consuming process.

Many commercial liquid jet nozzle manufacturers build nozzles that generate a fan shaped jet, in which the liquid jet covers a much larger surface area than that of a standard round jet because the fan shaped liquid jet has a much larger spot size. However, it has been discovered that when the liquid jet is discharged in a fan shape, it is not possible to maintain the frequency generated by the resonating chamber, such as the one described in U.S. Patent No. 4,389,071. Therefore, even though the coverage of the liquid jet is much wider, the erosive effect of the jet is usually lower than that of the oscillating round liquid jet.

Users of fan shaped liquid jets have also attempted to use "super water" instead of plain water. The super water, which includes certain polymers to increase the thickness of the water, has been found to increase erosion rate, however the operating cost of using super water is also about three times more expensive than using plain water, making it a very costly option. In view of the foregoing, it is desirable to have a method and apparatus for a fan shaped high velocity liquid jet that maintains the oscillating frequency necessary in the liquid to generate discrete slugs of fluid with percussive effect.

Summary of the Invention

The present invention fills these needs by providing an efficient and economical method and apparatus for generating an oscillating fan shaped high velocity liquid jet. It should be appreciated that the present invention can be implemented in numerous ways, including as a process, an apparatus, a system, a device or a method. Several inventive embodiments of the present invention are described below.

In one embodiment of the present invention, a liquid jet nozzle system is provided. The liquid jet nozzle system includes a resonator chamber to receive and to oscillate a liquid jet. The resonator chamber includes a first aperture having an angle of entry to receive the liquid jet. The angle of entry is preferably between about 22.5° to about 45.0°. The first aperture may also include an angle of exiting between about 22.5° to about 60.0°. The liquid jet is then excited at a frequency to generate an oscillating

liquid jet. A discharge chamber is coupled to the resonator chamber to receive the oscillating liquid jet through a second aperture. The second aperture preferably includes an angle of exiting between about 10.0° and 45.0°. The discharge chamber then discharges the oscillating liquid in a fan shape.

- 5 In another embodiment of the present invention, a method for eroding a surface is provided. The method begins when a liquid jet is received, preferably at a pressure of above about 4,000 pounds per square inch. The liquid jet is then excited to generate a frequency in the liquid, becoming an oscillating liquid jet. The frequency is preferably above about 3.3 kilohertz and preferably generated by forming vortices in the liquid jet.
- 10 The oscillating liquid jet is then discharged in a fan shape, preferably forming discrete slugs of liquid. The discharged jet maintains its frequency and erodes the surface with high impact from the slugs.

- In yet another embodiment of the present invention, a liquid jet nozzle system is provided. The liquid jet nozzle system includes a resonator chamber to excite a liquid jet
- 15 at a frequency, preferably above about 3.3 kilohertz, to generate an oscillating liquid jet. The system also includes a discharge chamber having a pair of tapered walls that preferably take the form of a hemisphere. The discharge chamber is coupled to the resonator chamber to receive the oscillating liquid jet from the resonator chamber. The liquid jet is then discharged in a fan shape through a third aperture. To generate the fan
- 20 shape, the third aperture is located within a groove located on a bottom surface of the discharge chamber.

Other aspects and advantages of the invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the invention.

25 **Brief Description of the Drawings**

The present invention will be readily understood by the following detailed description in conjunction with the accompanying drawings. To facilitate this description, like reference numerals designate like structural elements.

Figure 1 illustrates an oscillating fan jet nozzle system in accordance with one embodiment of the present invention.

Figure 2 illustrates the resonator chamber in accordance with one embodiment of the present invention.

5 Figure 3 illustrates the contracting section of the discharge chamber in accordance with one embodiment of the present invention.

Figure 4 illustrates the bottom surface of the nozzle housing in accordance with one embodiment of the present invention.

Figure 5 is a chart of an erosion rate of the oscillating fan shaped liquid jet nozzle
10 system compared with other liquid jets in accordance with one embodiment of the present invention.

Figure 6 is a flow chart of a method for generating an oscillating fan shaped liquid jet in accordance with one embodiment of the present invention.

15 Detailed Description of the Preferred Embodiments

A method and apparatus for generating an oscillating fan shaped high velocity liquid jet is provided. In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be understood, however, to one skilled in the art, that the present invention may be practiced
20 without some or all of these specific details. In other instances, well known process operations have not been described in detail in order not to unnecessarily obscure the present invention.

Figure 1 illustrates an oscillating fan jet nozzle system 10 in accordance with one embodiment of the present invention. Nozzle system 10 includes a nozzle housing 12 for
25 receiving a liquid jet and from which the jet is discharged. Nozzle housing 12 includes a resonator chamber 14 and a discharge chamber 16. Resonator chamber 14 includes a first

aperture 18 and a second aperture 20. Resonator chamber 14 is coupled to discharge chamber 14 through second aperture 20. Discharge chamber 14 also includes a contracting section 22 having a third aperture 24.

A liquid jet is received by nozzle system 10 through nozzle housing 12 and preferably at a pressure of between above about 4,000 pounds per square inch (psi). However, one of skill in the art will recognize that much higher pressures may be used as long as the vortices (to be described below) formed in the liquid jet are maintained. After entering nozzle system 10, the liquid jet enters resonator chamber 14 through first aperture 16. Resonator chamber 14 includes a body of relatively stationary liquid, which aids in creating vortices in the liquid jet.

The liquid jet is excited to oscillate at its natural frequency by forming vortices in resonator chamber 14 before being output to discharge chamber 16. It has been discovered that discharge chamber 16 best maintains the frequency of the liquid jet if its length (l_1) ranges from about 40% to about 60% of the acoustic wavelength in the liquid jet. The acoustic wavelength of the jet depends upon the oscillation frequency of the jet. For example, if the liquid jet is received by nozzle system 10 from about 5,000 psi to about 6,000 psi, then the acoustic wavelength of the liquid ranges from about 50 millimeters (mm) to about 70 mm. Therefore, length (l_1) in this case preferably ranges from about 25 mm to about 35 mm.

After exiting resonator chamber 14, the excited oscillating liquid jet then enters contracting section 22 and is discharged from nozzle system 10 through third aperture 24. Even after exiting nozzle system 10, the oscillating liquid jet maintains its frequency of oscillation. The oscillating liquid jet then forms into discrete fan shaped slugs providing for maximum erosion power upon contact with a solid surface.

Figure 2 illustrates the resonator chamber 14 in accordance with one embodiment of the present invention. As previously discussed, a liquid jet enters resonator chamber 14 through first aperture 18 and is discharged through second aperture 20. The apertures possess several features that allow resonator chamber 14 to generate a frequency in the liquid jet. One requirement of the chamber is that it must provide for a sharp angle of

entry for the liquid jet to generate a liquid jet with the clearest vortices. From experimentation, it has been discovered that the clearest vortices are generated when angle θ_1 of first aperture 18 preferably ranges from about 22.5° to about 45.0°. At the same time, angle θ_2 of first aperture 18 preferably ranges from 22.5° to about 60.0°.

5 The liquid jet thus collides with the stationary liquid inside resonator chamber 14 to generate vortices. The vortices of the liquid jet then partially collide with the walls of second aperture 20 to forcing the liquid jet to resonate at a certain frequency. Angle ϕ of second aperture 20 preferably ranges from about 10.0° to about 45.0°. Resonator chamber 14 preferably oscillates the liquid jet at above about 3.3 kHz. This frequency
10 range assures that the oscillating liquid jet will maintain a steady cavitation effect and frequency after discharge while achieving maximum erosion power. In addition, the ratio of the width of the width (w_2) and the width (w_1) of second aperture 20 preferably ranges from about 1.06 to about 1.25. Width (w_1) is preferably about 2.3 mm to about 3.3 mm wide. The length (l_2) of resonator chamber 14 preferably ranges from about 3.7
15 millimeters to about 6.7 millimeters.

Figure 3 illustrates contracting section 22 of discharge chamber 16 in accordance with one embodiment of the present invention. Contracting section 22 includes a pair of tapered walls 28 and 30 leading to third aperture 24 on a bottom surface 25 of nozzle housing 12. Third aperture 24 is preferably located inside a groove 26. The liquid jet is
20 transmitted hydrodynamically within discharge chamber 16 to contracting section 22, which has the purpose of maintaining the frequency in the liquid jet. The oscillating liquid jet is then discharged from third aperture 24 while coming into contact with groove 26, forming discrete slugs of liquid, each of which has an elliptical shape, resulting in a oscillating fan shaped liquid jet. The slugs of liquid had an optimum Strouhal number of
25 about 0.45 to about 0.75 when the oscillating fan jet nozzle system was tested at a liquid jet pressure of 5,000 psi to 6,000 psi. The Strouhal number of the liquid jet may be calculated by the formula: $f \cdot d / v$, where f is the frequency of the liquid, d is the diameter of the slug of liquid jet, and v is the velocity at which the liquid is discharged.

As illustrated in Figure 3, most of the surfaces in contracting section 22 are very smooth to facilitate the flow of the liquid jet and maintain the frequency of the jet generated in resonator chamber 14. The shape of tapered walls 28 and 30 may form a cone where an angle θ is preferably greater than about 40.0° and preferably less than about 100.0° . Alternatively, tapered walls 28 and 30 may take a logarithmic shape (*i.e.* $y=e^x$). Although a logarithmic shape for tapered walls 28 and 30 appeared to generate the best experimental results, the most cost efficient and preferred shape is that of a hemisphere as illustrated.

Third aperture 24 and groove 26 also incorporate many features that aid in the discharge of an oscillating fan shaped liquid jet. The top portion of aperture 24 preferably has a width (w_3) ranging from about 2.0 mm to about 2.5 mm. The lower portion of aperture 24 includes tapered walls 32 and 34 which narrowing the width (w_4) of aperture 24 to about 1.55 mm. An angle ϕ of aperture 24 generated by tapered walls 32 and 34 is preferably between about 74.0° and about 130.0° . Groove 26 preferably has a depth of about 0.70 mm to about 0.85 mm.

Figure 4 illustrates bottom surface 25 of nozzle housing 12 in accordance with one embodiment of the present invention. Bottom surface 25 includes third aperture 24 located inside groove 26. The width (w_5) of third aperture 24 is preferably about 1.65 mm and the width (w_6) of groove 26 is preferably about 1.8 mm to about 2.0 mm. The depth of groove 26 into the surface of nozzle housing 12 determines the shape of the discharged liquid fan jet. Therefore, the larger the radius of groove 26, the narrower the fan shape angle of the discharged liquid jet. From experimental results, a radius ranging between about 1.00 mm to about 1.23 mm results in a discharged liquid jet having a fan shape angle of about 25° to about 45° .

Figure 5 is a chart of the erosion rate of the oscillating fan shaped liquid jet compared with other liquid jets in accordance with one embodiment of the present invention. As illustrated, the erosion rate of the present invention is far superior to the erosion rate of other commercial liquid jet nozzle systems, whether or not the discharge is in a round or fan shape. The only partial exception is the super water fan, which requires

an extremely expensive supply of super water. Furthermore, the effectiveness of the super water fan dwindles quickly relative to the effectiveness of the present invention if the jet spot size is increased.

Figure 6 is a flow chart of a method for eroding a surface in accordance with one embodiment of the present invention. Method 36 begins at a block 38 when a liquid jet is received by an oscillating liquid fan jet nozzle system. The liquid is preferably pressurized at above 4,000 psi to achieve the appropriate velocity for the jet. The liquid jet is then excited to generate an oscillating liquid jet in a block 40. The jet is preferably excited to a frequency above about 3.3 kHz. Finally, the oscillating liquid jet is discharged in a block 42, preferably forming a set of discrete slugs to erode the surface in a block 44. Each of the slugs preferably has a Strouhal number of about 0.30 to about 0.75. The discharge occurs in a fan shape having a much greater spot size than a round jet because each of the slugs has an elliptical shape.

Other embodiments of the invention will be apparent to those skilled in the art from consideration of the specification and practice of the invention. Furthermore, certain terminology has been used for the purposes of descriptive clarity, and not to limit the present invention. The embodiments and preferred features described above should be considered exemplary, with the invention being defined by the appended claims.

What is claimed is:

CLAIMS

1. A liquid jet nozzle system, comprising:

a resonator chamber having a first aperture forming a first angle of entry to
5 receive said liquid jet, wherein said resonator chamber is to excite a liquid
jet at a frequency to generate an oscillating liquid jet; and

a discharge chamber having an end surface, the discharge chamber being
coupled to said resonator chamber to receive said oscillating liquid jet, said
discharge chamber further comprising a contracting section, the contracting
10 section including a first tapered wall narrowing the discharge chamber to a
first portion, and a second tapered wall further narrowing the first portion to
a second portion, the first portion and the second portion forming a
discharge aperture approximating the end surface.

wherein said discharge chamber is to discharge said oscillating liquid jet in a
15 fan shape through the discharge aperture.

2. A liquid jet nozzle system as recited in claim 1, wherein the angle of entry is
between about 22.5° and about 45.0°.

3. A liquid jet nozzle system as recited in claim 2, wherein the first aperture includes
20 an angle of exiting, wherein said angle of exiting is between about 22.5° and about
60.0°.

4. A liquid jet nozzle system as recited in claim 3, wherein the resonator chamber
25 includes a second aperture to discharge the liquid jet into the discharge chamber,
wherein said second aperture forms an angle of exiting between about 10.0° and
about 45.0°.

5. A liquid jet nozzle system as recited in claim 2, wherein a length of the discharge
30 chamber is between about 40% and about 60% of an acoustic wavelength of the
liquid jet.

6. A liquid jet nozzle system as recited in claim 5, wherein the length of the discharge chamber is between about 25 millimeters and about 35 millimeters.
7. A liquid jet nozzle system as recited in claim 1, wherein the first tapered wall forms a hemisphere.
8. A liquid jet nozzle system as recited in claim 1, wherein the first tapered wall forms a cone.
9. A liquid jet nozzle system as recited in claim 8, wherein the cone has an angle of more than 40°.
10. A liquid jet nozzle system as recited in claim 5, wherein the frequency is above about 3.3 kilohertz.
11. A method for eroding a surface with an oscillating liquid jet, comprising:
receiving a liquid jet through a first aperture of a resonator chamber, the first aperture having a sharp angle of entry;
exciting said liquid jet to generate the oscillating liquid jet having a frequency;
discharging said oscillating liquid jet through a discharge chamber formed of a first tapered wall narrowing the discharge chamber to a first portion and a second tapered wall further narrowing the first portion to a second portion, wherein said oscillating liquid jet is discharged in a fan shape and maintains said frequency; and
eroding said surface with said oscillating liquid jet.
12. A method for eroding a surface as recited in claim 11, wherein said frequency is above about 3.3 kilohertz.
13. A method for eroding a surface as recited in claim 12, wherein said liquid jet is excited from vortices that are formed in the liquid jet.

14. A method for eroding a surface as recited in claim 13, further comprising forming discrete slugs of liquid from the oscillating liquid jet.
15. A method for eroding a surface as recited in claim 14, wherein the slugs of liquid have a Strouhal number of between about 0.30 and about 0.75.
16. A method for eroding a surface as recited in claim 15, further comprising pressurizing the liquid jet at above about 4,000 pounds per square inch.
17. A liquid jet nozzle system, comprising:
a resonator chamber having a first aperture forming a sharp angle of entry to receive a liquid jet and to excite the liquid jet at a frequency to generate an oscillating liquid jet; and
a discharge chamber having a first tapered wall narrowing the discharge chamber to a first width and a second tapered wall narrowing the first width to a second width, wherein said discharge chamber coupled to said resonator chamber to receive said oscillating liquid jet and wherein said discharge chamber is to discharge said oscillating liquid jet through the first width and the second width in a fan shape.
18. A liquid jet nozzle system as recited in claim 17, wherein the first tapered wall forms a hemisphere.
19. A liquid jet nozzle system as recited in claim 17, wherein the first tapered wall forms a cone.
20. A liquid jet nozzle system as recited in claim 19, wherein the cone has an angle of more than 40°.
21. A liquid jet nozzle system as recited in claim 17, wherein the angle of entry is between about 22.5° and about 45.0°.

22. A liquid jet nozzle system as recited in claim 21, wherein the first aperture includes an angle of exiting, wherein said angle of exiting is between about 22.5° to about 60.0°.
- 5 23. A liquid jet nozzle system as recited in claim 22, wherein the resonator chamber includes a second aperture to discharge the liquid jet into the discharge chamber, wherein said second aperture includes an angle of exiting between about 10.0° to about 45.0°.
- 10 24. A liquid jet nozzle system as recited in claim 17, wherein a length of the discharge chamber is about 40% to about 60% of an acoustic wavelength of the liquid jet.
25. A liquid jet nozzle system as recited in claim 24, wherein the length of the discharge chamber is about 25 millimeters to about 35 millimeters.
- 15 26. A liquid jet nozzle system as recited in claim 17, wherein the frequency is above about 3.3 kilohertz.
- 20 27. A liquid jet nozzle system as recited in claim 17, further comprising a third aperture located in a groove on a bottom surface of the discharge chamber, wherein the oscillating liquid jet is discharged from the liquid jet nozzle system through said aperture.
- 25 28. A liquid jet nozzle system as recited in claim 27, wherein the groove has a radius of about 1.00 millimeters to about 1.23 millimeters.