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WATER-BASED BERNOULLI PAD FOR BIOFOULING MITIGATION

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of the United States Provisional Application Serial No. 63/227,430, filed on July 30, 2021, entitled "Water-Based Bernoulli Pad for Biofouling Mitigation" by the inventors, Kristina M. Kamensky, Aren M. Hellum, Ranjan Mukherjee, and Christin Murphy, the complete disclosure of which is incorporated herein by reference in its entirety.

STATEMENT OF GOVERNMENT INTEREST

[0002] The invention described herein was made in the performance of official duties by employees of the U.S. Department of the Navy and may be manufactured, used, or licensed by or for the Government of the United States for any governmental purpose without payment of any royalties thereon.

BACKGROUND OF THE INVENTION

1) FIELD OF THE INVENTION

[0003] The present invention is directed to a biofouling mitigation device and, in particular, to one that uses the Bernoulli principle to maintain contact with an object for cleaning.

2) DESCRIPTION OF THE RELATED ART

[0004] Past devices, often referred to as "contactless grippers" or "Bernoulli grippers," use high velocity airflow and various geometries to adhere to an object without physical contact. Such grippers rely on the Bernoulli airflow principle. A high velocity airstream has a low static pressure. With careful design, the pressure in the high velocity airstream can be lower than atmospheric pressure. This can cause a net force on the object in the direction normal to the side with lower local pressure. A Bernoulli gripper takes advantage of this by maintaining a positive pressure at the gripper face compared to the ambient pressure, while maintaining an air gap between the gripper and the object being held.

[0005] Confined radial outflow has been of scientific interest because of the characteristic venturi effect that occurs due to axial jet flow turning into a smaller cross-sectional area at the gap between the pad and a workpiece. FIG. 1 shows a diagram of a Bernoulli pad 200 with a stem 202 and an object 204. The diagram provides a cross-sectional view. In FIG. 1, a can be flow of fluid indicated by arrows 206 through the stem 202 can travel between pad 200 and a surface 208. The flow extends out the edge of pad 200 as indicated by arrows 210. As shown in FIG. 1, the pad 200 has diameter D and the stem 202 has diameter d . Using Bernoulli's principle, the sudden constriction in flow

generates a partial vacuum before asymptotically reaching atmospheric pressure at the outer edge of the pad 200. Pad 200 is positioned at an equilibrium height h above the object 204. If the fluid can impinge directly on the opposing surface, the pressure profile will have a positive pressure region in the middle of the pad 200. Taking the integral of this pressure field with respect to the radial location, quantifies the total force normal to the object 204 generated by the flow field. One of ordinary skill in the art would understand that the applied force F_a is the sum of all forces acting on the freely moving component (e.g., pad 200), which are not produced by the fluid flow between the pad 200 and the surface 208 of the object 204. Bernoulli pads are used in the prior art as grippers for handling electronic components using a gas as a working fluid.

[0006] There is a need for surface cleaning in marine environments. An initially clean surface submerged in a marine environment, if left undisturbed, will have a biofilm form thereon from environmental microorganisms. This biofilm leads to biofouling as larger organisms attach to the surface. For example, a vessel hull that is continuously immersed in seawater experiences biofouling that depends on the season, location, and the length of time the vessel remains stationary. The extent of biofouling depends upon the surface characteristics of the hull and the ability to clean it. Biofouling causes economic losses,

a higher carbon footprint, and facilitates the spread of invasive species.

OBJECTS OF THE INVENTION

[0007] A first object is to provide a contactless underwater surface cleaning device.

[0008] Another object is to provide a device that utilizes fluid wall shear stress to dislodge biofouling.

[0009] Yet another object is to have device that is readily controllable to be moved over an underwater surface.

SUMMARY OF THE INVENTION

[0010] According to an embodiment of the invention, there is provided a non-contact cleaning device. The non-contact cleaning device includes a plate having a top surface and a bottom surface. An aperture is centrally located in the plate. The device includes a nozzle capable of being connected to the aperture on the top surface of the plate. A source of high-pressure liquid is connected to the nozzle. Flow of high-pressure liquid through the nozzle travels radially outward from the center of the aperture and provides shear forces between the high-pressure liquid and a work surface. The flow of high-pressure liquid maintains a gap at an equilibrium distance between the bottom surface of the plate and the work surface.

[0011] According to another embodiment of the invention, an apparatus for biofouling mitigation includes a Bernoulli pad having a top surface and a bottom surface and a centrally located aperture extending through the Bernoulli pad between the top surface and bottom surface. A nozzle is connected on the top surface of the Bernoulli pad to the aperture at a right angle to the axis of the nozzle. The device includes a source of high-pressure liquid. A hose is connected between the source of high-pressure liquid and the nozzle. The hose establishes fluid communication between the source of high-pressure liquid and the nozzle. Flow of high-pressure liquid through the nozzle travels radially outward from the center of the aperture and provides shear forces between the high-pressure liquid and a work surface. The flow of high-pressure liquid maintains a gap an equilibrium distance between the bottom surface of the plate and the work surface.

[0012] According to still another embodiment of the invention, a Bernoulli pad for biofouling mitigation has a circular body having a top surface and a bottom surface. The top surface is configured for connection to a pressurized fluid source. There is a fluid conduit through the circular body with an inlet at the top surface for receiving a pressurized fluid and an outlet at the bottom surface for discharging the pressurized fluid. Flow of pressurized fluid through the body travels radially

outward from the fluid conduit and provides shear forces between the pressurized fluid and a work surface. The flow of pressurized fluid maintains a gap an equilibrium distance between the bottom surface of the circular body and the work surface.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Other objects, features and advantages of the present invention will become apparent upon reference to the following description of the preferred embodiments and to the drawings, wherein corresponding reference characters indicate corresponding parts throughout the several views of the drawings and wherein:

[0014] FIG. 1 is a diagram of a prior art Bernoulli device;

[0015] FIG. 2 is a side view of one embodiment of a cleaning system according to the present invention;

[0016] FIG. 3 is a diagram of a Bernoulli pad according to one embodiment;

[0017] FIG. 4 is a diagram of a Bernoulli pad according to a second embodiment;

[0018] FIG. 5 is a diagram of a Bernoulli pad according to a third embodiment;

[0019] FIG. 6 is a side view of another embodiment of a cleaning system; and

[0020] FIG. 7 is a top view of another embodiment of a cleaning system.

DETAILED DESCRIPTION OF THE INVENTION

[0021] FIG. 2 shows a cleaning system, indicated generally as 10. The cleaning system 10 includes an antifouling tool 12 having a plate 14 and a nozzle 16. The nozzle 16 is joined to an aperture 18 in the center of the plate 14. The plate 14 preferably has a circular outer perimeter. The nozzle 16 can be made from any rigid material. The plate 14 is preferably made from a transparent plastic material such as polycarbonate or acrylic, which allows observation of a surface 100 of a workpiece 102 during operation. Operation typically occurs in an aqueous environment, below a waterline 104. Handles 20 may be mounted on the nozzle 16 to allow movement of the antifouling tool 12 (i.e., nozzle 16 and plate 14) over the surface 100. A source of high-pressure liquid, such as pump 22, is connected to the nozzle 16 by a hose 24. The pump 22 is joined to the hose 24 by a first connector 26. The hose 24 extends from the pump 22 to the nozzle 16. The hose 24 should be sufficiently flexible to allow movement of the antifouling tool 12 over the surface 100. A second connector 28 joins the nozzle 16 to the hose 24. The pump 22 may be connected to a reservoir 30. Liquid from the reservoir 30 can be pumped up to the required pressure and flow rate by the pump 22. The reservoir 30 helps

guard against damage to the pump 22 by ingestion of debris from environmental liquid. In some embodiments, the liquid may be filtered liquid of the same type as the surrounding environment, e.g., seawater. The surface 100 is cleaned by shear forces between the liquid and the surface 100 as the liquid travels radially outward from aperture 18. If scouring of the surface 100 is desired, the liquid can contain a particulate. In some embodiments, the pump 22 and reservoir 30 are located above the waterline 104 and the hose 24 extends from the pump 22 above the waterline 104 to the antifouling tool 12 below the waterline 104.

[0022] Using the handles 20, a diver can move the antifouling tool 12 over the surface 100. In some embodiments, the pump 22 can be connected directly to the nozzle 16; however, with the pump 22 being above the waterline 104, a larger pump can be used, which allows easier maintenance of the pump 22. The lighter-weight antifouling tool 12 is easier to manipulate by a diver than an embodiment having the pump 22 directly connected to the nozzle 16.

[0023] The pump 22 is responsible for driving liquid (e.g., seawater) through the antifouling tool 12, and can have variable power. Power to pump 22 can be controlled by a controller 31. Controller 31 can be preset or operator controlled. Flow of high-pressure liquid from the pump 22 travels through the hose

24 to the nozzle 16. From the nozzle 16, the high-pressure liquid travels radially outward from the center of the aperture 18 and provides shear forces between the high-pressure liquid and the surface 100. The liquid-based Bernoulli pad generates significantly more suction force and wall shear stress than one utilizing a gas. The flow of high-pressure liquid maintains a gap 32 that is an equilibrium distance (h_{eq}) between the bottom surface of the plate 14 and surface 100.

[0024] Referring to FIG. 3, the plate 14 is a circular body having a top surface 36 and a bottom surface 38. The aperture 18 is centrally located in the plate 14. Preferably, the bottom surface 38 of the plate 14 should be uniformly flat to avoid unbalancing the plate 14 or scratching the surface 100. The effective area of the plate 14 can be determined from the flow rate and the size of the nozzle opening i.e., size of the aperture 18. Beyond a mathematically calculable radius from the center of the nozzle 16, the effectiveness of the plate 14 as a Bernoulli pad declines to zero.

[0025] Nozzle 16 includes a fluid conduit 40 that extends through the plate 14. The nozzle 16 is connected to the aperture 18 on the top surface 36 of the plate 14. In some embodiments, the nozzle 16 is connected to the plate 14 at a right angle to the axis of the nozzle 16 with sharp 90° edges 46 to maximize fluid shear at the outlet 44. With abrupt geometry, such as a 90-

degree interface between the nozzle 16 and the plate 14, there will be flow separation and reattachment. This creates a recirculation bubble near the plate 14 which creates an even smaller cross sectional area that most of the flow goes through. For cleaning purposes, this is ideal since the location of the peak wall shear stress directly correlates to where the peak velocity occurs.

[0026] In some embodiments, as shown in FIG. 4, the edges 46 between the nozzle 16 and the plate 14 can be rounded. Rounded edges can provide a larger area of effect. In some embodiments, as shown in FIG. 5, the edges 46 can also be sharpened. Sharpened edges increase shear stress or induce cavitation in the liquid. Because of potentially damaging effects, the presence or absence of cavitation should be calculated before operation at a particular flow rate.

[0027] High-pressure liquid can be provided in a flow direction indicated by arrow A. Upon flow of the high-pressure liquid, the plate 14 maintains a gap 32 an equilibrium distance away from the surface 100 of the workpiece 102. The gap 32 is maintained by Bernoulli effect forces, i.e. a suction force is established that prevents the plate 14 from moving away from the surface 100, and a pressure force prevents the plate 14 from moving towards the surface 100.

[0028] FIG. 6 shows another embodiment of the cleaning system 10 with the antifouling tool 12. The nozzle 16 and plate 14 are mounted to a frame 48. The pump 22 is mounted on the frame 48 and directly connected to the nozzle 16. The pump inlet 50 is positioned away from plate 14 and the surface 100 in order to avoid ingesting debris from the antifouling operation.

Actuators 52 are joined between the frame 48 and axles for wheels 54. A controller 56 is joined to the actuators 52 to control the height between the frame 48 and the surface 100 of the workpiece 102. Height measurements can be provided by one or more sensors 58 joined to the frame 48. Multiple sensors 58 can provide measurement of surface variations. The actuators 52 can also control the distance between the plate 14 and the surface 100. The actuators 52 can be activated to cant the plate 14 with respect to the surface 100 to induce a force on the antifouling tool 12, moving the antifouling tool 12 in a desired direction. In one variation, the wheels 54 can be steerable to allow the antifouling tool 12 to turn on the surface 100. The controller 56 can also activate the pump 22 and control the pump flow rate.

[0029] A UV projector 60 can be mounted on the frame 48 in order to provide additional biocidal action. A buoyancy device 62, such as an air bladder, can be used to make the antifouling tool 12 neutrally buoyant. The buoyancy device 62 can be provided

with a control 64 such as a gas source and a regulator to allow buoyancy control at a variety of depths. The controller 56 can be linked to operate the buoyancy device control 64. This could allow the antifouling tool 12 to float to the surface when predetermined conditions are met.

[0030] In some embodiments, the cleaning system 10 shown in FIG. 6 can be incorporated into a controllable underwater robot, this is either controlled by a human-in-the-loop or fully autonomous. A power supply 66 is provided for the pump 22. The power supply 66 can be on the frame 48 or tethered above the waterline 104. A buoyancy control device 68 attached to the actuators 52 and the controller 56 helps to achieve and maintain the desired equilibrium gap height and may serve as a way to reach the surface for retrieval. Multiple thrusters (not shown) may be provided to control movement of the cleaning system 10 parallel to the surface 100 in all three axes of space. Appropriate sensors 58 can also be used to indicate orientation.

[0031] FIG. 7 is a top view of cleaning system 10 illustrating use of multiple nozzles 16 and plates 14 to provide an antifouling tool 12 having wider effect and greater ability to maintain contactless grip while in operation (which could occur when navigating complicated geometry). Plates 14 and nozzles 16 (not shown) are joined to a structure 70. The plates 14 can be arranged in an array 72 having many different configurations and

attached to the structure 70 by hinges. In the event that one of the plates 14 in the array 72 reaches an unstable equilibrium point, the flow for that plates 14 can be turned off by an associated controller, and the other plates 14 that have grip will activate movement of the hinge to reorient the plates 14 before initiating flow to reestablish contactless grip. The structure 70 can be either rigid or flexible. A flexible structure 70 will allow the array 72 of plates 14 to bend and conform to the surface 100. Connectors 74 are provided between each nozzle 16 and a manifold 76 for communicating liquid. The manifold 76 is joined to a pump 22 or other source of high-pressure liquid.

[0032] The physical structure of the plate 14 can be either rigid or flexible. The nature of a flexible plate 14 would allow for the height of the gap 32 to be the same constant between the plate 14 and a surface 100 with some curvature, such as certain submerged areas of a vessel's hull. The plate 14 can be specifically buoyed or weighted to give it a preferred vertical orientation in a liquid environment. The plate 14 can be designed to cant with a control signal. The nozzle axis could be angled with respect to the plate 14 to apply a force along the bottom surface 38 of the plate 14. Components of the different embodiments can be mixed and matched to give an optimal antifouling tool 12 for the particular use. The entire

cleaning system 10 can be scaled, to provide a larger effective grooming area, which is defined by the circular area where the wall shear stress reaches a critical value based on biofouling pressure and grooming frequency. A powerful enough pump 22 can induce cavitation, in which the low-pressure region reaches the vapor pressure of water.

[0033] The invention has been described with references to specific embodiments. While particular values, relationships, materials, and steps have been set forth for purposes of describing concepts of the present disclosure, it will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the disclosed embodiments without departing from the spirit or scope of the basic concepts and operating principles of the invention as broadly described. It should be recognized that, in the light of the above teachings, those skilled in the art could modify those specifics without departing from the invention taught herein. Having now fully set forth certain embodiments and modifications of the concept underlying the present disclosure, various other embodiments as well as potential variations and modifications of the embodiments shown and described herein will obviously occur to those skilled in the art upon becoming familiar with such underlying concept. It is intended to include all such modifications, alternatives, and

other embodiments insofar as they come within the scope of the appended claims or equivalents thereof. It should be understood, therefore, that the invention might be practiced otherwise than as specifically set forth herein. Consequently, the present embodiments are to be considered in all respects as illustrative and not restrictive.

[0034] Finally, any numerical parameters set forth in the specification and attached claims are approximations (for example, by using the term "about") that may vary depending upon the desired properties sought to be obtained by the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of significant digits and by applying ordinary rounding.

WATER-BASED BERNOULLI PAD FOR BIOFOULING MITIGATION

ABSTRACT OF THE DISCLOSURE

A non-contact cleaning underwater cleaning device includes a plate having a top surface, a bottom surface with an aperture centrally located in the plate. A nozzle is connected to the plate at the aperture on the top surface. A source of high-pressure liquid is joined to the nozzle. Radial outflow of liquid between the plate and a submerged work place generates wall shear stress to dislodge biofouling. Other embodiments include a frame and wheels for positioning the cleaning device proximate to a surface.

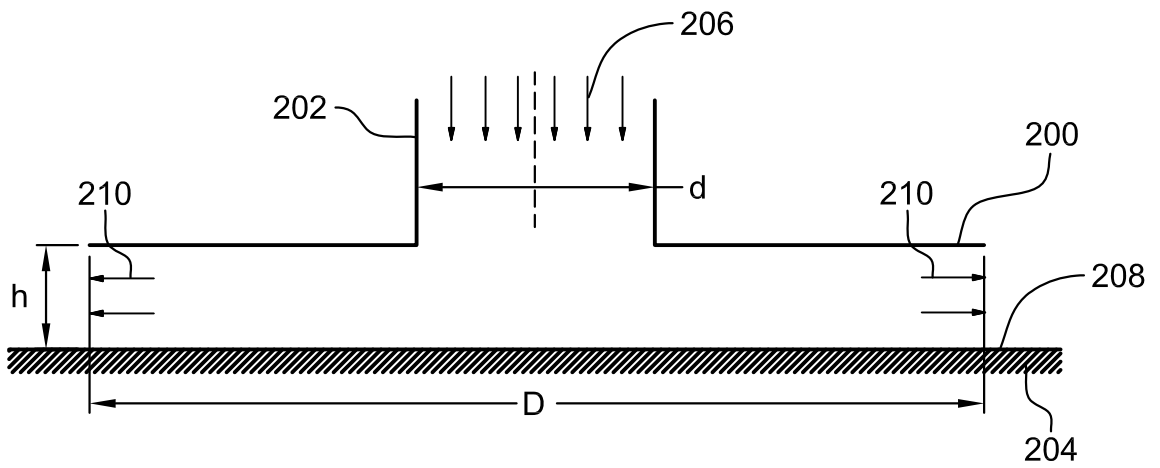


FIG. 1
-PRIOR ART-

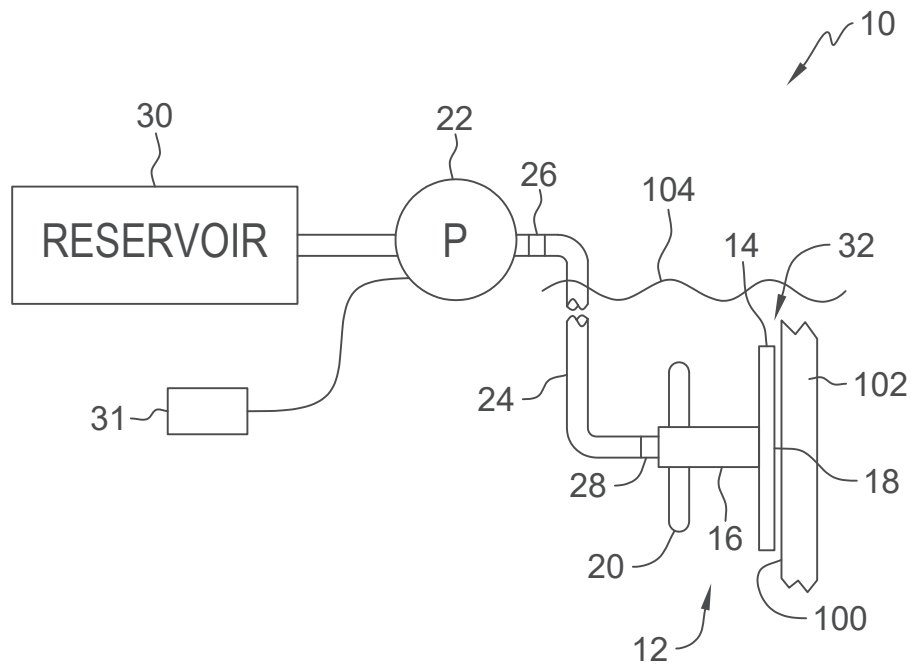


FIG. 2

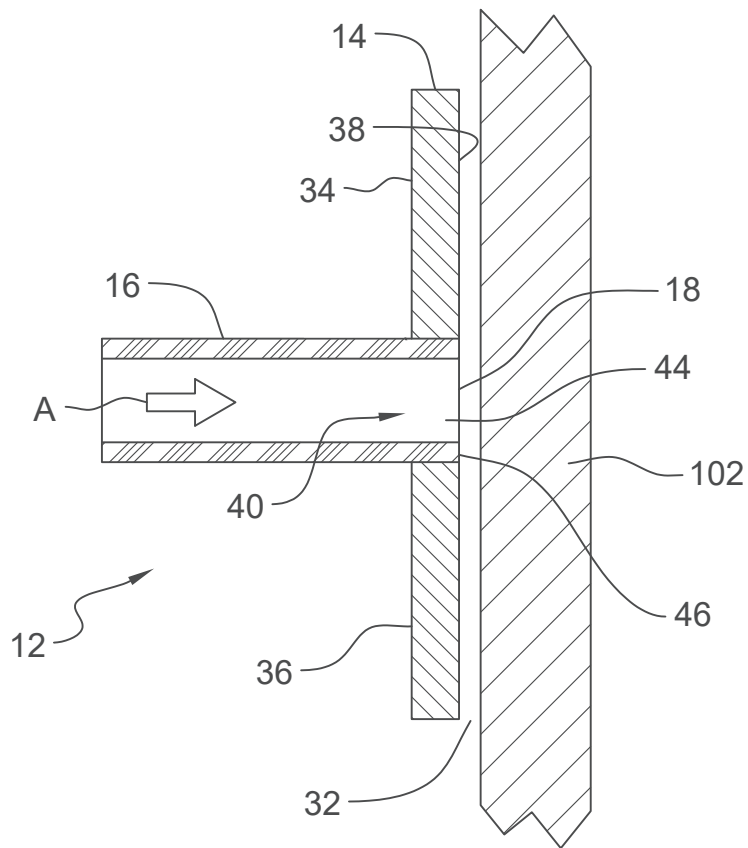


FIG. 3

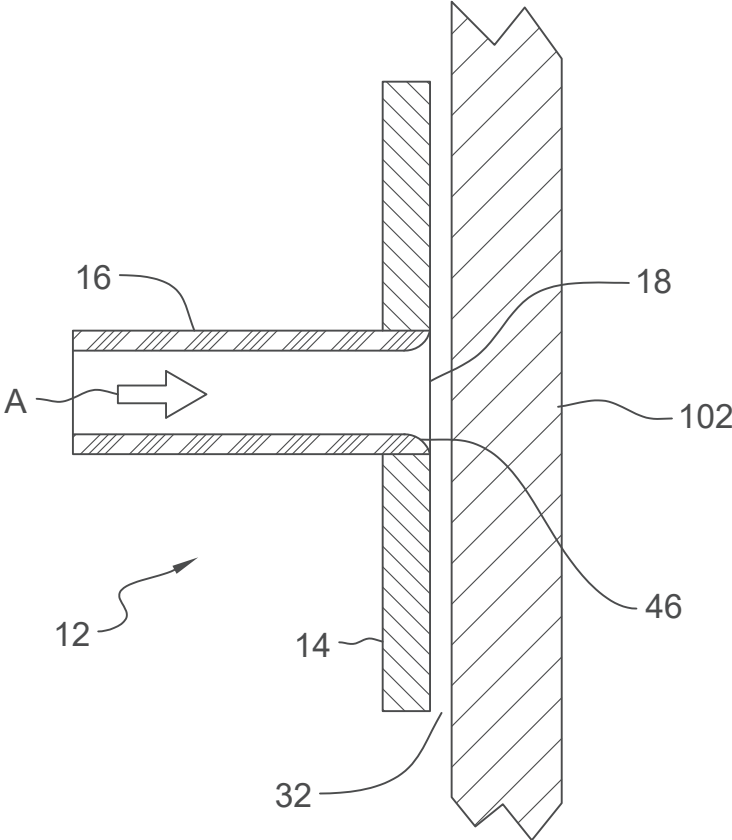


FIG. 4

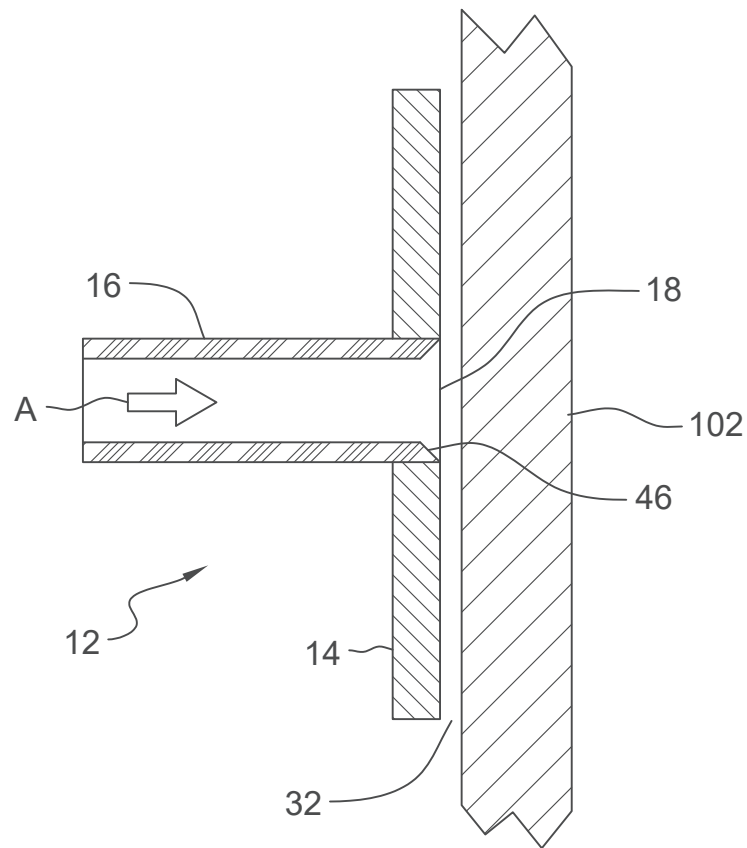


FIG. 5

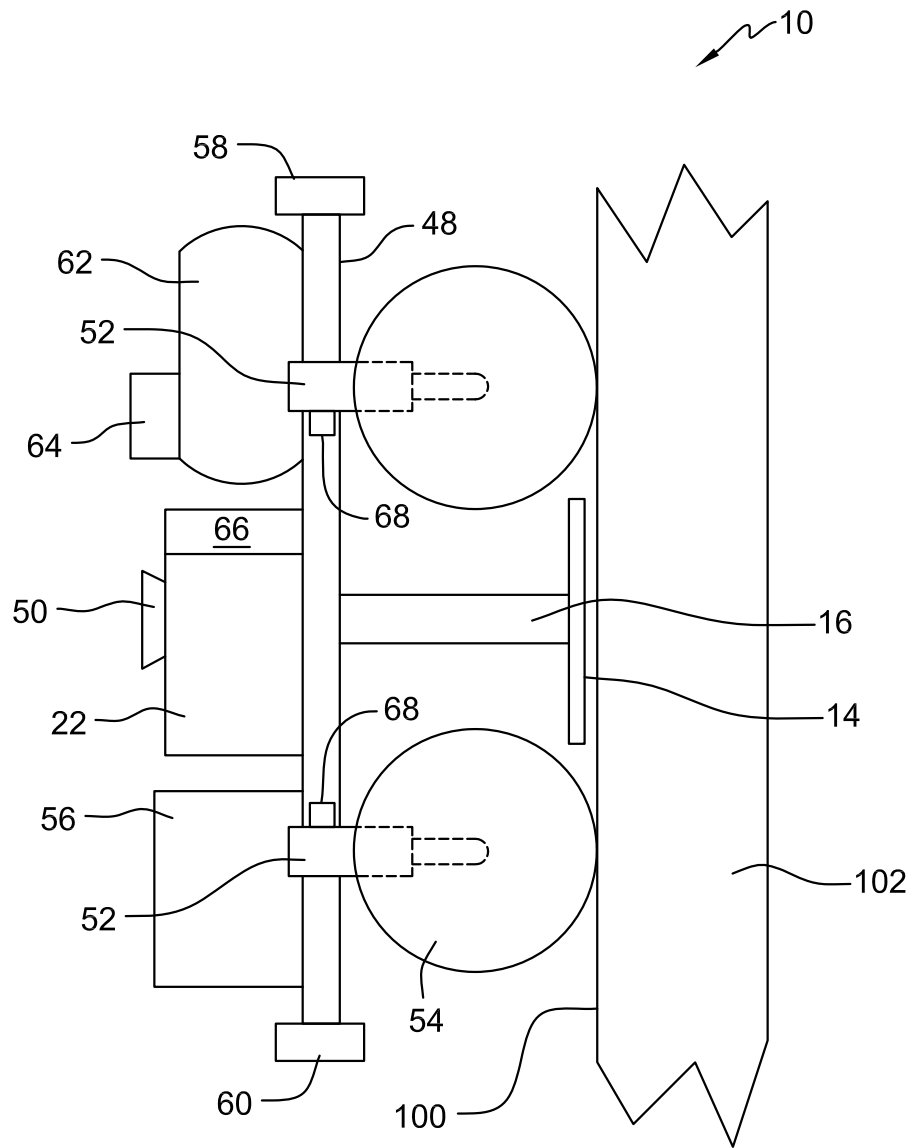


FIG. 6

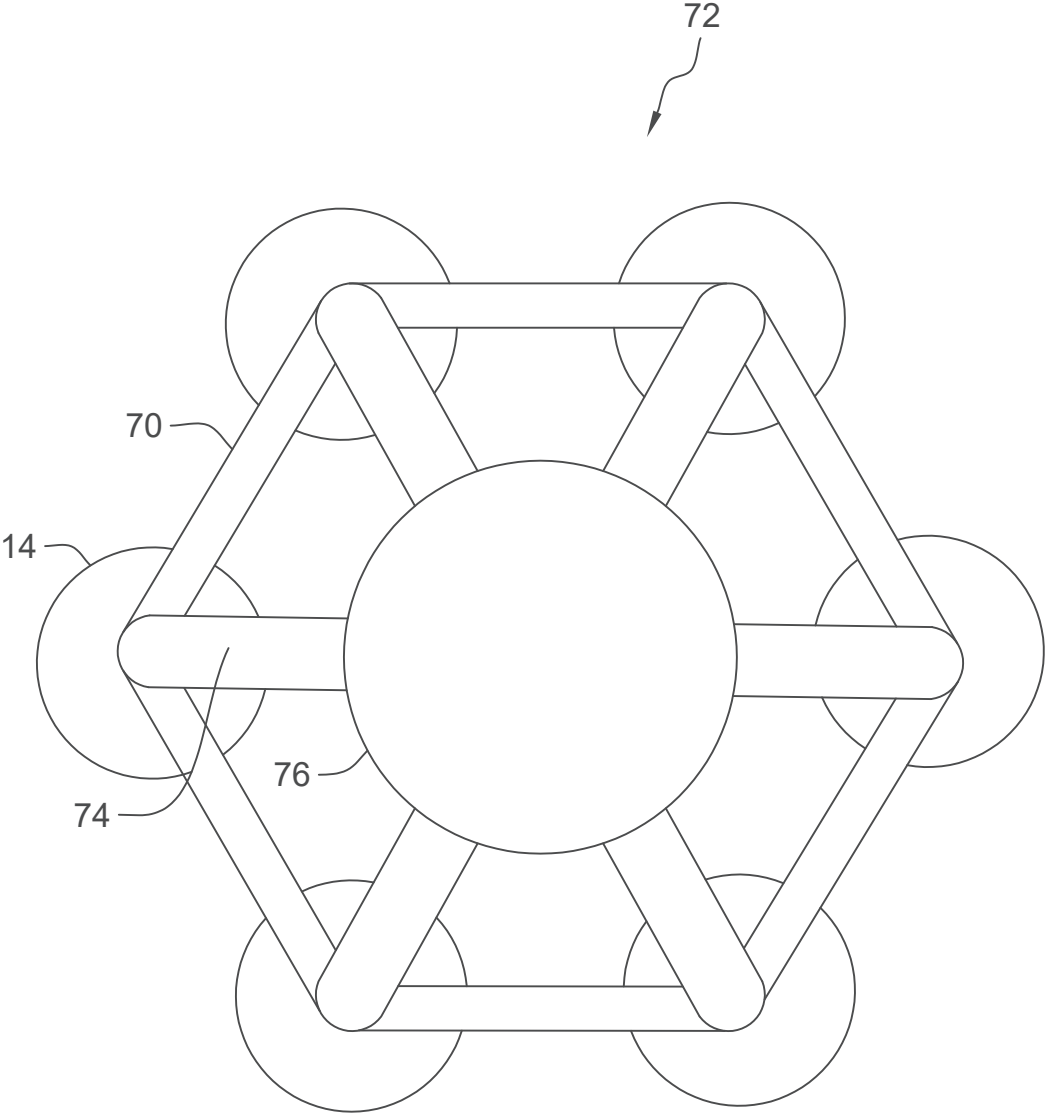


FIG. 7