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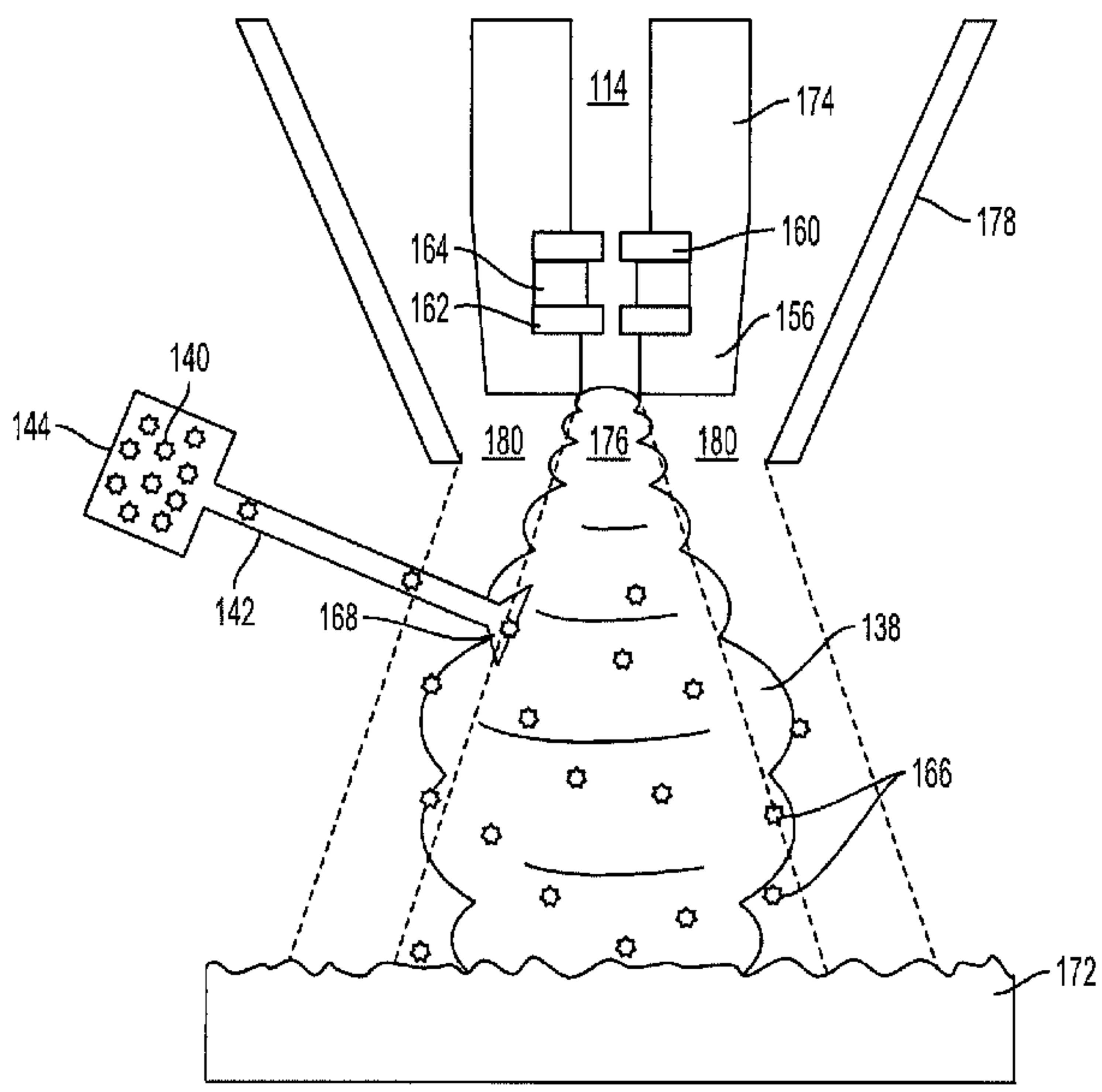

(57) Abrégé/Abstract:
A method of removing material from a surface of a workpiece includes discharging a flow of fluid towards a workpiece at a pressure and a flow rate that facilitates forming a plurality of cavitation bubbles, and introducing abrasive media. The method includes exciting the abrasive media with the cavitation bubbles, removing material from the workpiece by an interaction between the cavitation bubbles and the abrasive media, and the surface of the workpiece.

Abstract

A method of removing material from a surface of a workpiece includes discharging a flow of fluid towards a workpiece at a pressure and a flow rate that facilitates forming a plurality of cavitation bubbles, and introducing abrasive media. The method includes exciting the abrasive media with the cavitation bubbles, removing material from the workpiece by an interaction between the cavitation bubbles and the abrasive media, and the surface of the workpiece.

METHOD AND APPARATUS FOR FLUID CAVITATION ABRASIVE SURFACE FINISHING

Field

This disclosure relates to surface finishing. More specifically, the disclosed embodiments relate to systems and methods for subtractive material finishing, cleaning, and peening with a cavitated fluid.

Introduction

Additive manufacturing methods such as directed energy deposition and powder bed melting have enabled efficient manufacturing of new components with complex shapes and features which are not practical or feasible to manufacture by previous methods. However, the resulting surface finish on products made by additive manufacturing is rougher than parts produced by traditional manufacturing methods. Electron beam powder bed melting can create a surface roughness average (Ra) over **1**,**000** μM, which is more than **10** times the smooth finish required for typical structural airplane components. Machining is cost-prohibitive or not possible for complex additive manufactured components, and surface finishing methods such as grit blasting, chemical milling, and shot peening do not sufficiently improve the surface roughness.

Cavitation peening is a promising new method of mechanically treating a surface. Cavitation bubbles are formed in a fluid by a transition to gas phase resulting from an increase in flow velocity, then collapse as the flow velocity decreases. When a cavitation bubble collapses, a micro-jet is produced that can have a speed of **1**,**500** m/s in some examples. As disclosed in Soyama US**6855208** B**1**, injecting a high speed water jet, or cavitating jet into water produces a cavitation cloud. The cavitation bubbles move in a vortex and the multi-directional impacts of the resultant micro-jets harden a surface better than shot peening. However, while cavitation peening cleans and enhances fatigue strength, surface roughness is not improved sufficiently for many applications.

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Summary

A method of removing material from a surface of a workpiece is disclosed. The method includes discharging a flow of fluid towards a workpiece at a pressure and a flow rate that facilitates forming a plurality of cavitation bubbles, then introducing abrasive media in or around the bubbles. The method may include forming a mixture of the cavitation bubbles and the abrasive media, then directing the mixture toward the surface of the workpiece. The method includes exciting the abrasive media with the cavitation bubbles, removing material from the workpiece by an interaction between the cavitation bubbles, the abrasive media, and the surface of the workpiece.

An apparatus for removing material from a workpiece is also disclosed. The apparatus includes a fluid flow device and an abrasive media dispensing device. The fluid flow device is configured to pump fluid through a nozzle to generate a plurality of cavitation bubbles. The abrasive media dispensing device is configured to deliver abrasive media into the cavitation bubbles.

The present disclosure describes a method and an apparatus for removing material from a workpiece. In some embodiments, the method may include forming a plurality of cavitation bubbles and introducing abrasive media into the bubbles. In some embodiments, the method may include forming a mixture of cavitation bubbles and abrasive media. In some embodiments, the apparatus may include a fluid flow device and an abrasive media dispensing device.

In one embodiment, there is provided a method of material removal. The method involves discharging a flow of fluid towards a workpiece at a pressure and a flow rate that facilitates forming a plurality of cavitation bubbles, introducing abrasive media into the plurality of cavitation bubbles, and exciting the abrasive media with the cavitation bubbles, and removing material from the workpiece based on an interaction between the cavitation bubbles with the abrasive media and the surface of the workpiece.

The method may be carried out in a fluid environment.

The fluid environment may be a body of fluid contained in a tank.

Discharging may include pumping a first fluid stream at a first pressure level, the fluid environment comprising a second stream of fluid surrounding the first stream at a second pressure level, the second pressure level being lower than the first pressure level.

The fluid may comprise water.

The introducing step may include channeling abrasive media from a source into the plurality of cavitation bubbles.

The abrasive media may include particles comprising one or more of (a) metal, (b) glass, (c) ceramic, (d) silica oxide, (e) aluminum oxide, (f) pumice, (g) nut shells, (h) corn cob, and (i) plastic abrasives.

The abrasive media may include particles in a dimensional range of approximately **16** to **1200** ANSI Grit Size.

The method may comprise channeling the abrasive media through a conduit leading from a source of the abrasive media to the plurality of cavitation bubbles.

The method may comprise rotating or otherwise actuating movement of the conduit during the introducing step.

The method may comprise moving the abrasive media through a corkscrew structure in the conduit.

The method may further comprise dispersing the abrasive media through a wide angle nozzle at a distal end of the conduit.

The method may comprise channeling the abrasive media through plural conduits into the plurality of cavitation bubbles.

The discharging step may be performed at a pressure in a range of **50** to **10,000** pounds per square inch.

In another embodiment, there is provided a method of material removal. The method involves forming a mixture of cavitation bubbles and abrasive media, and removing material from a surface on a workpiece by directing the mixture toward the surface.

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The method may further comprise discharging a fluid at high pressure through a nozzle directed toward the workpiece, and introducing abrasive media into cavitation bubbles generated by the discharging step.

The introducing step may include dispersing the abrasive media through a wide angle nozzle directed toward the cavitation bubbles.

In another embodiment, there is provided an apparatus for removing material from workpiece. The apparatus includes a fluid flow device configured to pump fluid through a nozzle generating a plurality of cavitation bubbles directed toward a workpiece, and an abrasive media dispensing device configured to deliver abrasive media into cavitation bubbles generated by the fluid flow device.

The apparatus may comprise a tank for containing a body of fluid, and a stage for supporting a workpiece in the body of fluid, the fluid flow device being directed toward the stage.

The fluid flow device may include a nozzle having an inner channel configured to supply a first stream of fluid at a first pressure level sufficient to generate a plurality of cavitation bubbles, and an outer channel configured to supply a second stream of fluid at a second pressure level, the second pressure level being below the first pressure level, and wherein the second stream of fluid substantially surrounds the first stream of fluid.

Features, functions, and advantages may be achieved independently in various embodiments of the present disclosure, or may be combined in yet other embodiments, further details of which can be seen with reference to the following description and drawings.

Brief Description of the Drawings

Fig. 1a is an isometric view of a jet engine nacelle compression pad created by a machining process.

Fig. 1b is an isometric view of a jet engine nacelle compression pad created by an additive manufacturing process.

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Fig. **2** is a block diagram of an example of a fluid cavitation abrasive surface finishing apparatus.

Fig. **3** is a diagrammatic illustration of an example of an abrasive media source.

Fig. **4** is a diagrammatic illustration of the creation of an abrasive cavitation cloud, by an apparatus of the type shown in Fig. **2**.

Fig. **5** is a diagrammatic illustration of a workpiece undergoing surface finishing in the abrasive cavitation cloud of Fig. **4**.

Fig. **6** is a block diagram of another example of a fluid cavitation abrasive surface finishing apparatus.

Fig. **7** is a diagrammatic illustration of a surface undergoing finishing by an apparatus of the type shown in Fig. **6**.

Figs. **8**A-**8**D are schematic diagrams of abrasive media of different sizes being used to remove surface roughness from a surface of a work piece.

Fig. **9** is a flow chart illustrating a method of material removal.

Description

Overview

Various embodiments of a surface finishing method and apparatus having a fluid flow device and abrasive media are described below and illustrated in the associated drawings. Unless otherwise specified, a surface finishing apparatus and/or its various components may, but are not required to, contain at least one of the structure, components, functionality, and/or variations described, illustrated, and/or incorporated herein. Furthermore, the structures, components, functionalities, and/or variations described, illustrated, and/or incorporated herein in connection with the present teachings may, but are not required to, be included in other surface finishing apparatuses. The following description of various embodiments is merely exemplary in nature and is in no way intended to limit the disclosure, its application, or uses. Additionally, the advantages provided by the embodiments, as described below, are illustrative in nature and not all embodiments provide the same advantages or the same degree of advantages.

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Fig. **1**a shows a jet engine nacelle compression pad **2** made by machining a block of titanium. Raw material for the pad may weigh about **15** pounds, while the pictured finished component may weight only **1.5** pounds. By contrast, Fig. **1**b shows a compression pad **4** for the same jet engine nacelle, produced by additive manufacturing. All raw material may be used in this design, and the design flexibility may allow a more structurally efficient configuration.

However, as built, the compression pad shown in Fig. **1**b is not acceptable for use as a structural part in an engine. The additive manufacturing process produces a surface roughness average (Ra) of over **1,000** μM. It should be noted that the compression pad has been designed with such complexity that machining may be cost prohibitive or even impossible.

The improvement in manufacturing efficiency and design freedom offered by additive manufacturing is highly desirable across a wide range of disciplines, to reduce costs and enable new technologies. Surface roughness is a major obstacle to the adoption of such techniques, which may be overcome by fluid cavitation abrasive surface finishing.

Examples, Components, and Alternatives

The following sections describe selected aspects of exemplary apparatuses for removing material from a workpiece as well as related systems and/or methods. The examples in these sections are intended for illustration and should not be interpreted as limiting the entire scope of the present disclosure. Each section may include one or more distinct embodiments, and/or contextual or related information, function, and/or structure.

*Example **1**:*

Fig. **2** is a block diagram of an exemplary apparatus for fluid cavitation abrasive surface finishing, generally indicated at **10**. A high-pressure pump **12** supplies pressurized water **14** along a conduit **16**. A branching conduit **18** is regulated by a control valve **20**. Such placement of the control valve allows precise control of the pressure and flow rate of water supplied along conduit **16** to a nozzle **22**.

Nozzle **22** is disposed in a pressurized tank **24** filled with water **26**. Lid **28** of tank **24** may open to allow overflow from the tank into a catchment container **30**. The lid may be coupled to tank **24** by a spring, or may be constrained by a weight, in order to maintain pressure in the tank. Water also drains from tank **24** along a conduit **32**, regulated by a control valve **34**.

High pressure water **14** is injected by nozzle **22** into water **26** of tank **24** as a cavitating jet, which is directed toward a workpiece **36** submerged in tank **24**. An interaction between the cavitating jet and water **26** form a swirling cavitation cloud **38**, including a plurality of cavitation bubbles. Workpiece **36** may be disposed such that cavitation cloud **38** surrounds some or all of the workpiece, and collapsing cavitation bubbles impact a surface of the workpiece. The collapsing impact force of a cavitation bubble is determined in part by the pressure of injected water **14**, the pressure of water **26** in tank **24**, the ratio between the two pressures, and the temperature of water **14** and water **26** of tank **24**. High pressure water **14** may be between **50** and **10,000** pounds per square inch, or any effective pressure. Preferably, water **14** may be at approximately **4,000** pounds per square inch when water **26** of tank **24** is at atmospheric pressure.

To optimize these parameters, a pressure and temperature sensor may be included in tank **24**, or in any of conduits **12**, **18**, or **32**. Control valves **20**, **34** and lid **28** as well as high pressure pump **12** and a temperature control system may be connected to an electronic controller or other such component to allow precise, coordinated control of pressure and temperature conditions throughout apparatus **10**.

In the pictured example, the cavitated fluid is water. However, any desired fluid may be used. Properties such as viscosity of the fluid used may affect collapsing force of cavitation bubbles and a fluid may be chosen to improve impact, or decrease the pressure required for a desired impact level. Any effective fluid flow device may be used to pump pressurized fluid through nozzle **22**.

As shown in Fig. **2**, an abrasive media **40** is introduced into cavitation cloud **38** between nozzle **22** and workpiece **36**. The abrasive media is supplied by a conduit **42** from a hopper, or abrasive media source **44**. An example of source **44** is shown in more detail in Fig. **3**. The source includes a sealed compartment **46** with multiple hoppers **48**, each hopper housing a different type of abrasive media or abrading material. In the pictured example, compartment **46** includes **6** hoppers with **6** abrasive media of decreasing grit size. Source **44** may include any desired types of media or number of types of media. The media may be of any grit size, preferably within a range of approximately **16** to **1200** ANSI grit size.

Each hopper **48** includes a hopper door **50** that may be opened to introduce the desired media into conduit **42**. Door **50** may be controlled manually, or may be actuated by an electronic controller integrated with other components of apparatus **10**. Other simple switching mechanisms exist that may transition between delivery of different media, and any effective mechanism may be used.

An air hose **52** is connected to source **44** to pressurize sealed compartment **46**. Abrasive media **40** may thereby flow more freely and easily, and be urged into and along conduit **42**. In some examples, water or another fluid may be used in place of air to pressurize sealed compartment **46**. In other examples, a mechanism such as a push-rod may be used to induce abrasive media **40** to move through conduit **42**. The abrasive media may be loose or may be in the form of a paste, or suspension.

Conduit **42** also includes a corkscrew structure **54**, to induce a rotational or swirling motion to the media before the media is introduced to cavitation cloud **38**, as shown in Fig. **4**. In some examples, conduit **42** may be rotated other otherwise moved relative to cavitation cloud **38** while abrasive media **40** is being introduced to the cloud.

Nozzle **22** is show in more detail in Fig. **4**, including a nozzle cap **56** disposed in a guide pipe **58**. A cavitator **60** is spaced from a nozzle plate **62** by spacer **64**, and positioned in nozzle cap **56** to alter flow of high pressure water **14** through nozzle **22**. The change in flow rate of water **14** and interaction with tank water **26** may result in cavitation cloud **38**. The plurality of cavitation bubbles comprising the cloud may swirl in a vortex, or tornado-like shape.

Conduit **42** from abrasive media source **44** introduces a plurality of particles **66** of abrasive media **40** into cavitation cloud **38**. Abrasive media **40** may gain speed, momentum, and kinetic energy from the cavitation cloud and mix with the cavitation bubbles. In the pictured example, abrasive media **40** is introduced by a wide-angle nozzle **68**, having at least a portion of outwardly diverging surfaces, at a distal end of conduit **42**. As shown in Fig. **3**, abrasive media **40** is rotated by corkscrew **54** to facilitate mixing with cavitation cloud **38**. Wide-angle nozzle **68** is disposed proximate an end of guide pipe **58** to saturate the greatest possible portion of cavitation cloud **38** with abrasive media **40**.

In other examples, abrasive media **40** may be fed into cavitation cloud **38** by multiple conduits that are disposed at locations distributed around the cloud. In Fig. **4**, nozzle **68** is shown oriented at an acute angle relative an axis defined by guide pipe **58**. In other examples, nozzle **68** may be oriented perpendicular the axis or at an oblique angle. Any type of nozzle may be used with conduit **42**. Source **44** may also include any appropriate delivery system or dispensing device for the abrasive media being used in apparatus **10**.

In the pictured example, abrasive media **40** is introduced at an edge of cavitation cloud **38**, into the swirling cavitation bubbles. In other examples, abrasive media **40** may be introduced near a center of cavitation cloud **38**, or into water **26** of tank **24** just outside of cavitation cloud **38**, or at any point that promotes effective mixing of the abrasive media and the cavitation bubbles.

Fig. **5** shows workpiece **36** supported by a stage **70**, in a swirling mixture of cavitation bubbles and abrasive media **40**. Nozzle **22**, not shown in Fig. **5**, may be directed toward stage **70**. As the bubbles of the mixture collapse, particles **66** of the media may be excited and energized. The micro-jets created by collapsing bubbles may collectively accelerate the motion of particles **66**. As the mixture of bubbles and media contacts a rough surface **72** of workpiece **36**, particles **66** may impact the surface and remove material. That is, abrasive media **40** may be acted on by the high forces of the cavitation cloud to smooth rough surface **72**. The swirling and multi-directional motion of cavitation cloud **38** may bring abrasive media **40** into contact with tight corners, crevices, and internal features of surface **72** as well as exposed upper areas.

Normal cavitation peening may also occur, as the cavitation bubbles interact directly with surface **72** of workpiece **36**. Surface **72** may be thereby peened, improving residual stress and fatigue strength, and cleaned, ready for painting or use.

Example ***2****:*

Fig. **6** is a block diagram of another exemplary apparatus for fluid cavitation abrasive surface finishing, generally indicated at **110**. Components similar to apparatus **10** as described above, are labeled with corresponding reference numbers. As shown, high-pressure pump **112** supplies pressurized water **114** along a conduit **116** to a nozzle **122**. A branching conduit **118** is regulated by a control valve **120**.

Nozzle **122** is directed toward a workpiece **136** that is disposed in an air environment. The nozzle delivers two streams of water, a high pressure inner cavitation jet and a lower pressure outer jet. A cavitation cloud **138** may be thereby generated by nozzle **22**, which may be referred to as a co-flow nozzle.

Abrasive media **140** is introduced into cavitation cloud **138** between nozzle **122** and workpiece **136**. The abrasive media is supplied by a conduit **142** from a source **144**. Fig. **7** illustrates in more detail the resultant mixture of cavitation bubbles and abrasive media **140**.

As shown in Fig. **7**, co-flow nozzle **122** includes an inner nozzle **174** to generate inner cavitating jet **176** and an outer nozzle **178** to generate lower pressure outer jet **180**. Inner nozzle **174** includes a cavitator **160**, a spacer **164**, and a nozzle plate **162** to alter the flow of high pressure water **114** and create cavitation cloud **138**, while outer nozzle **178** has geometry appropriate to lower the pressure of water **114** for outer jet **180**. That is, inner nozzle **174** defines an inner channel for cavitating jet **176**, and an outer channel is for outer jet **180** defined between inner nozzle **174** and outer nozzle **178**. In some examples, co-flow nozzle **122** may be separately supplied with lower pressure water in addition to high pressure water **114** from pump **112** as shown in Fig. **6**.

Referring again to Fig. **7**, as cavitation jet **176** and outer jet **180** leave co-flow nozzle **122**, the outer jet forms a shell of water or fluid environment substantially surrounding the cavitation jet and resulting cavitation cloud **138**. Abrasive media **140** is introduced by a wide-angle nozzle **168**, and energized by the cloud. A portion of a rough surface **172** of workpiece **136** may be finished and peened by abrasive media **140** and cavitation cloud **138**.

In some examples, apparatus **110** may be configured for use while fixed, or stationary. Workpiece **136** may be fully surrounded in cavitation cloud **138**. Alternatively, workpiece **136** may be supported by a moving stage, to bring new portions of surface **72** into cavitation cloud **138** as surface finishing is completed. In other examples, apparatus **110** may be integrated into a wand or other movable structure, to allow an operator to direct nozzle **122** as desired.

In some examples, apparatus **110** may be appropriate for spot-treatment, or finishing of repair work. The apparatus may be configured for transport to a work-site, may include an adaptor or connector to accept pressurized water from a variety of external systems, or may be otherwise made portable. In other examples, apparatus **110** may be appropriate for use on large-scale projects, where it would be prohibitive to submerge workpieces in a tank of fluid.

*Example **3**:*

Figs. **8**a-d illustrate a surface **210** undergoing a multi-stage fluid cavitation abrasive surface finishing process. In Fig. **8**a, a first abrasive media **212** energized by a cavitation cloud interacts with protruding peaks **214** of surface **210**, removing material from the surface and lowering the peaks.

Fig. **8**b shows a second abrasive media **216** interacting with surface **210**, which has been smoothed to some extent. Second media **214** has a smaller grit size than first media **212**, allowing the energized media to further smooth surface **210** and reduce protruding peaks **214**. Similarly, a third abrasive media **218** removes additional material and further smooths surface **210**, as shown in Fig. **8**C. Finally, as shown in Fig. **8**D, surface **210** has been finished to a desired level of smoothness. Any number of different media may be used for such a multi-stage process, in any number of stages.

Abrasive media **212**, **216**, **218** may include particles of any effective material, of any grit size, or may include a mixture of materials. For example, a media may include metal, glass, ceramic, silica oxide, aluminum oxide, pumice, nut shells, corn cob, or plastic abrasive particles. Each media may include particles preferably within a range of approximately **16** to **1200** ANSI grit size.

As previously discussed and shown in Fig. **3**, abrasive media source **44** may be configured to deliver multiple abrasive media. Transition between media may be controlled by an operator or may be timed, actuated by a sensor, or otherwise triggered as part of an automatic multi-stage fluid cavitation abrasive surface finishing process.

A most effective combination of media may be selected from a plurality of materials available in source **44** based on the material and roughness of a particular surface to be finished. Alternatively, source **44** may be stocked with appropriate media for a particular surface at time of processing. For example, a metal surface with Ra **100** μM may be finished with glass abrasives of **100** and **500** grit sizes while a plastic surface with Ra **1,000** μM may be finished with nut shell abrasives of **10** grit size, and then pumice abrasives of **50** and **100** grit sizes.

Manner of Operation / Use

Fig. **9** describes multiple steps of a method, generally indicated at **300**, for surface finishing. Method **300** may be used in conjunction with any of the apparatuses, nozzles, or processes described in reference to Figs. **1-8**. Although various steps of method **300** are described below and depicted in Fig. **9**, the steps need not necessarily all be performed, in some cases may be performed in a different order than the order shown, and in some cases may be performed simultaneously.

First step **302** of method **300** includes discharging a flow of fluid toward a workpiece, in a fluid environment. The fluid may be discharged at a pressure and a flow rate that facilitates step **304**, which includes forming a plurality of cavitation bubbles. The fluid may be discharged from a nozzle, configured to alter pressure and flow rate in a manner that generates a cloud of cavitation bubbles.

The fluid may be discharged at a high pressure, preferably between **50** and **10,000** pounds per square inch. Either or both of the discharged fluid and the fluid environment may be water.

The fluid environment may be a body of fluid contained in a tank, and may also be under pressure. In such a case the workpiece may be submerged in the tank. Alternatively, discharging the flow of fluid may further include pumping a first fluid stream at a first pressure and a second fluid stream at a second, lower pressure. The first fluid stream may be contained by the second fluid stream, which may form the fluid environment.

Discharging the flow of fluid toward the workpiece may include surrounding the workpiece with the generated cloud of cavitation bubbles, or may include directing the flow to a portion of a surface of the workpiece. The workpiece may be supported by a stage, and the nozzle may be directed toward the stage or the workpiece.

Step **306** of method **300** includes introducing abrasive media into the plurality of cavitation bubbles. Introducing the abrasive media may form a mixture of cavitation bubbles and abrasive media that is directed toward the workpiece.

The abrasive media may be channeled through a conduit leading from a source, and may move through a corkscrew structure in the conduit. The media may then be dispersed through a wide-angle nozzle at a distal end of the conduit, the nozzle directed toward cavitation bubbles. The conduit may rotate or otherwise move as the abrasive media is introduced. The abrasive media source may be pressurized to induce movement of the abrasive media through the conduit. In some examples, abrasive media may be channeled through multiple conduits from the abrasive media source or from multiple sources.

The abrasive media may include particles of one or more of metal, glass, ceramic, silica oxide, aluminum oxide, pumice, nut shells, corn cob, and plastic abrasives. Preferably, the included particles may be within a dimensional range of

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approximately **16** to **1200** ANSI grit size. Any effect abrasive media, combination of media, or mixture of media or particles may be used. In some examples, step **306** of introducing abrasive media may be repeated for a series of abrasive media with descending grit sizes.

Step **308** includes exciting the abrasive media with the cavitation bubbles. The cavitation cloud formed by the cavitation bubbles may have a swirling, vortex motion that imparts speed, momentum, and kinetic energy to the abrasive media. The cavitation bubbles may also collapse, collectively accelerating the motion of the abrasive media to achieve a high speed and sufficient kinetic energy to remove material from a surface of the workpiece upon impact, thereby facilitating step **310** of method **300** which includes removing material from the workpiece.

Since the cavitation cloud and bubbles impart a swirling and multi-directional motion to the abrasive media, material may be removed from tight corners, crevices, and internal features of the workpiece. The cavitation bubbles may further perform cavitation peening and cleaning of the surface of the workpiece.

Advantages, Features, Benefits

The different embodiments of the methods and apparatuses for surface finishing described herein provide several advantages over known solutions for finishing material surfaces. For example, the illustrative embodiments of the method described herein allow finishing of complex, irregularly shaped surfaces. Additionally, and among other benefits, illustrative embodiments of the method described herein allow a surface to be smoothed, cleaned, and peened with one process. No known system or device can perform these functions, particularly for such a wide range of surface shapes and materials. Thus, the illustrative embodiments described herein are particularly useful for finishing parts produced by additive manufacturing. However, not all embodiments described herein provide the same advantages or the same degree of advantage.

Conclusion

The disclosure set forth above may encompass multiple distinct embodiments with independent utility. Although each of these embodiments has been disclosed in its preferred form(s), the specific embodiments as disclosed and illustrated herein are not to be considered in a limiting sense, because numerous variations are possible. To the extent that section headings are used within this disclosure, such headings are for organizational purposes only, and do not constitute a characterization of any particular concept. The subject matter of the embodiments includes all novel and nonobvious combinations and subcombinations of the various elements, features, functions, and/or properties disclosed herein. The following claims particularly point out certain combinations and subcombinations regarded as novel and nonobvious. Other combinations and subcombinations of features, functions, elements, and/or properties may be claimed in applications claiming priority from this or a related application. Such claims, whether directed to different concepts or to the same concept, and whether broader, narrower, equal, or different in scope to the original claims, also are regarded as included within the subject matter of the concepts disclosed herein.

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EMBODIMENTS IN WHICH AN EXCLUSIVE PROPERTY OR PRIVILEGE IS CLAIMED ARE DEFINED AS FOLLOWS:

1. A method of material removal, comprising:

discharging a flow of fluid towards a workpiece at a pressure and a flow rate that facilitates forming a plurality of cavitation bubbles,

introducing abrasive media into the plurality of cavitation bubbles,

exciting the abrasive media with the cavitation bubbles, and removing material from the workpiece based on an interaction between the cavitation bubbles with the abrasive media and a surface of the workpiece.

2. The method of claim **1**, wherein the method is carried out in a fluid environment.

3. The method of claim **2**, wherein the fluid environment is a body of fluid contained in a tank.

4. The method of claim **2**, wherein the discharging step includes pumping a first fluid stream at a first pressure level, the fluid environment comprising a second stream of fluid surrounding the first stream at a second pressure level, the second pressure level being lower than the first pressure level.

5. The method of any one of claims **1-4**, wherein the fluid comprises water.

6. The method of any one of claims **1-5**, wherein the introducing step includes channeling abrasive media from a source into the plurality of cavitation bubbles.

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7. The method of any one of claims **1-6**, wherein the abrasive media includes particles comprising one or more of (a) metal, (b) glass, (c) ceramic, (d) silica oxide, (e) aluminum oxide, (f) pumice, (g) nut shells, (h) corn cob, and (i) plastic abrasives.

8. The method of any one of claims **1-7**, wherein the abrasive media includes particles in a dimensional range of approximately **16** to **1200** ANSI Grit Size.

9. The method of any one of claims **1-8**, further comprising:

channeling the abrasive media through a conduit leading from a source of the abrasive media to the plurality of cavitation bubbles.

10. The method of claim **9**, further comprising:

rotating or otherwise actuating movement of the conduit during the introducing step.

11. The method of claim **10**, further comprising:

moving the abrasive media through a corkscrew structure in the conduit.

12. The method of claim **9**, further comprising:

dispersing the abrasive media through a wide angle nozzle at a distal end of the conduit.

13. The method of any one of claims **1-12**, further comprising:

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channeling the abrasive media through plural conduits into the plurality of cavitation bubbles.

14. The method of any one of claims **1-13**, wherein the discharging step is performed at a pressure in a range of **50** to **10,000** pounds per square inch.

15. A method of material removal, comprising:

forming a mixture of cavitation bubbles and abrasive media, and

removing material from a surface on a workpiece by directing the mixture toward the surface.

16. The method of claim **15**, comprising:

discharging a fluid at high pressure through a nozzle directed toward the workpiece, and

introducing abrasive media into cavitation bubbles generated by the discharging step.

17. The method of claim **16**, wherein the introducing step includes dispersing the abrasive media through a wide angle nozzle directed toward the cavitation bubbles.

18. An apparatus for removing material from a workpiece, comprising:

a fluid flow device configured to pump fluid through a nozzle generating a plurality of cavitation bubbles directed toward the workpiece, and

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an abrasive media dispensing device configured to deliver abrasive media into cavitation bubbles generated by the fluid flow device.

19. The apparatus of claim **18**, further comprising:

a tank for containing a body of fluid, and

a stage for supporting the workpiece in the body of fluid, the fluid flow device being directed toward the stage.

20. The apparatus of claim **18** or **19**, wherein the fluid flow device includes a nozzle having an inner channel configured to supply a first stream of fluid at a first pressure level sufficient to generate a plurality of cavitation bubbles, and an outer channel configured to supply a second stream of fluid at a second pressure level, the second pressure level being below the first pressure level, and wherein the second stream of fluid substantially surrounds the first stream of fluid.

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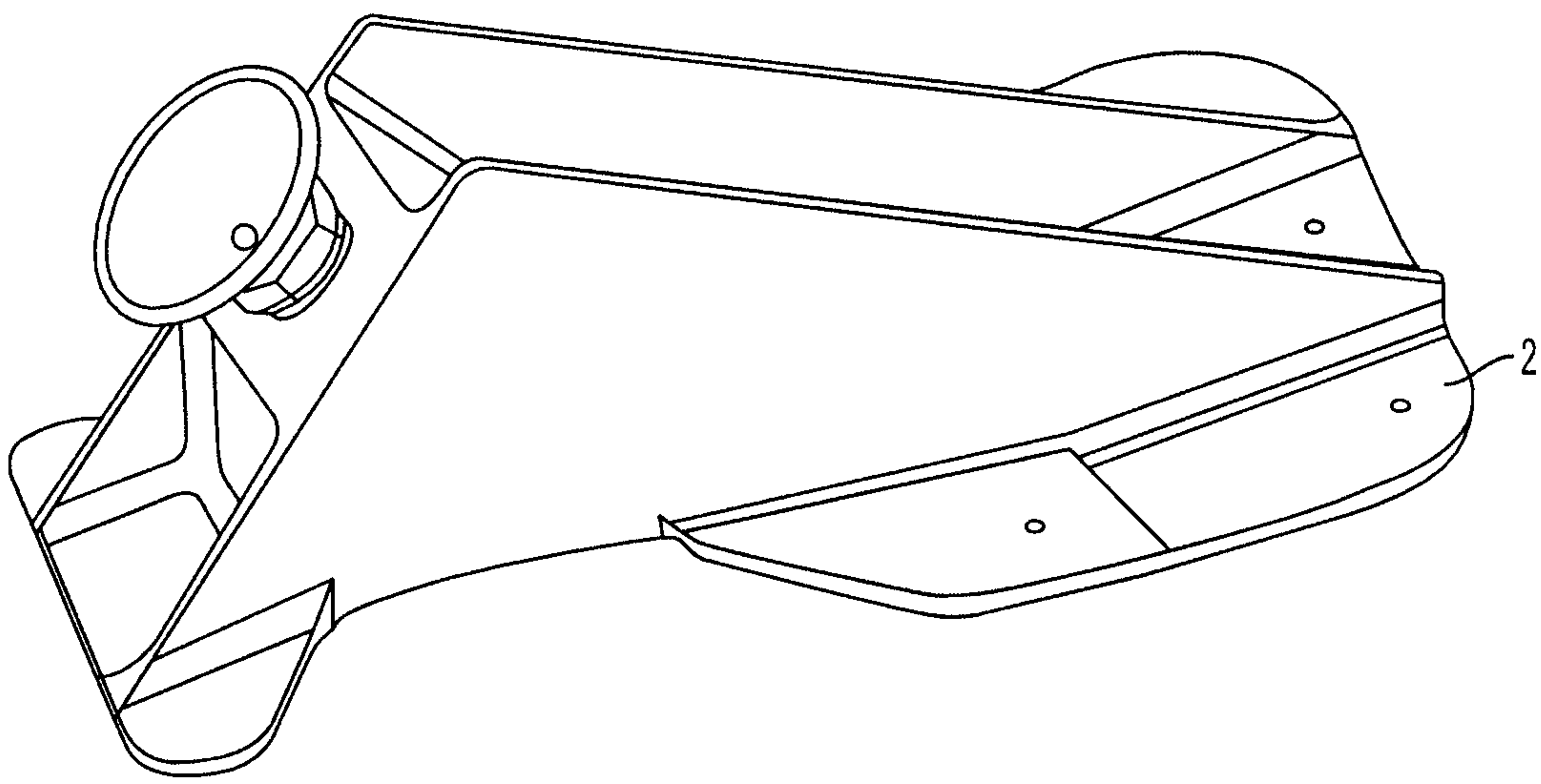

FIG. 1A

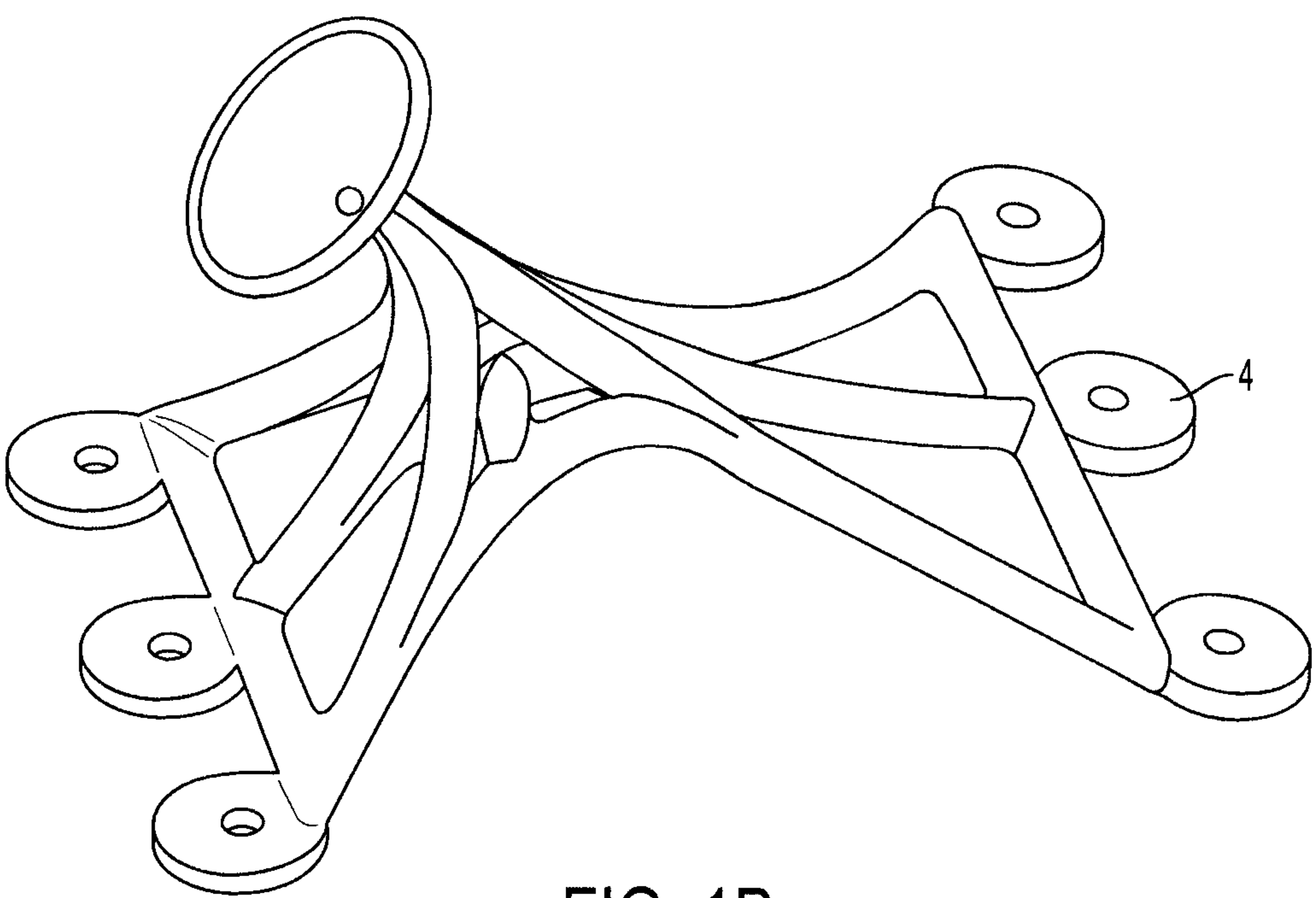

FIG. 1B

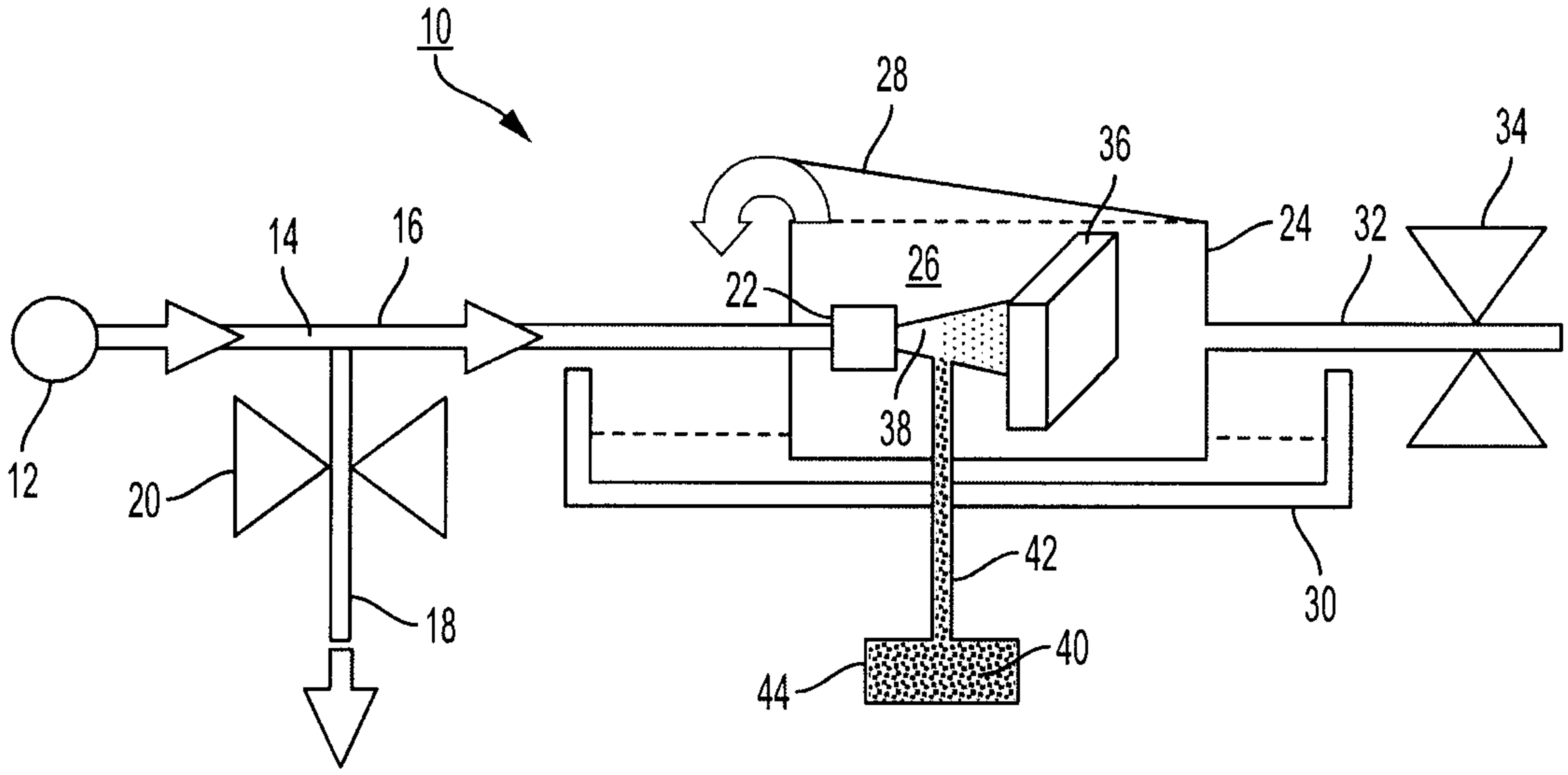
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FIG. 2

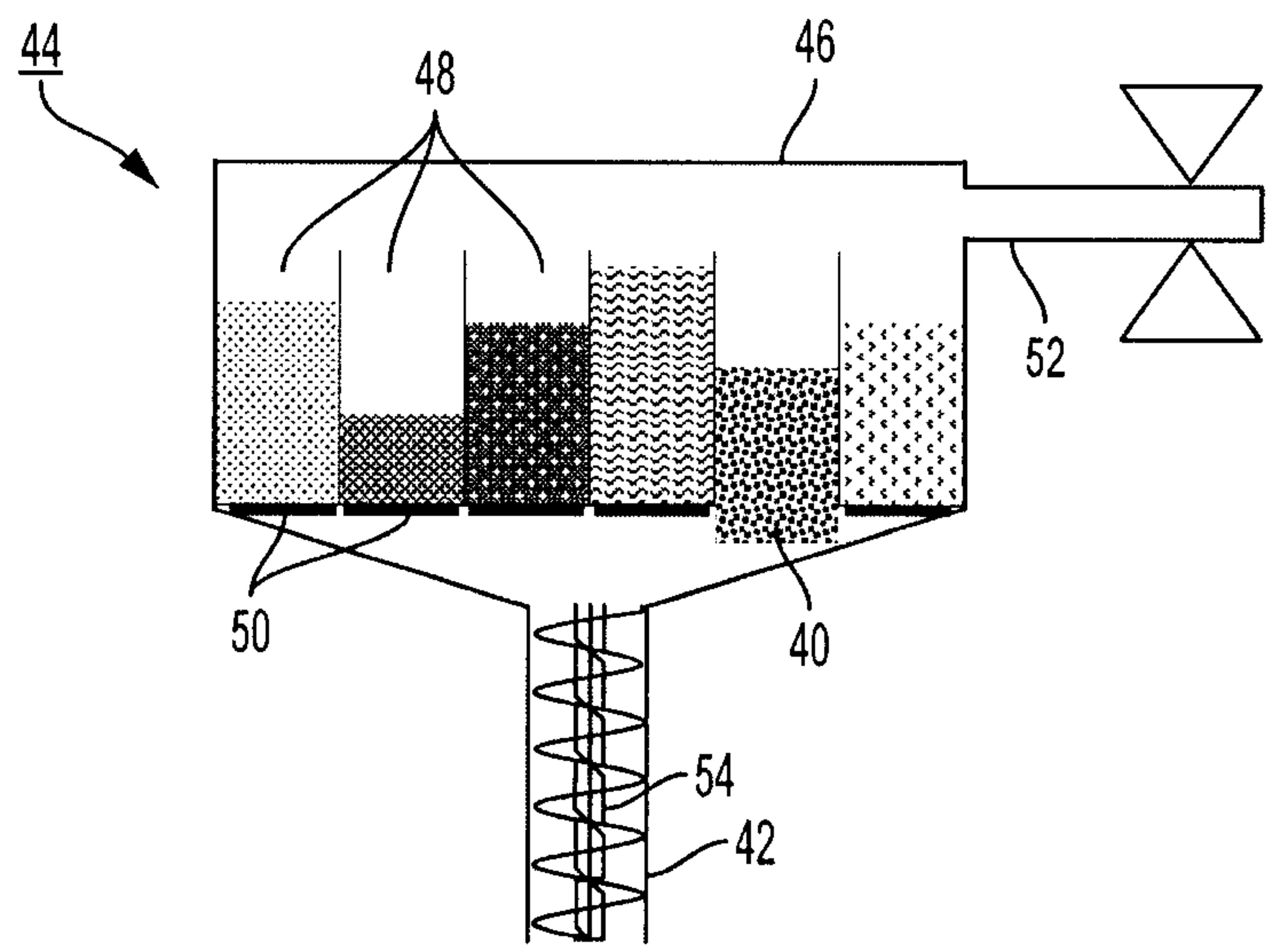
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FIG. 3

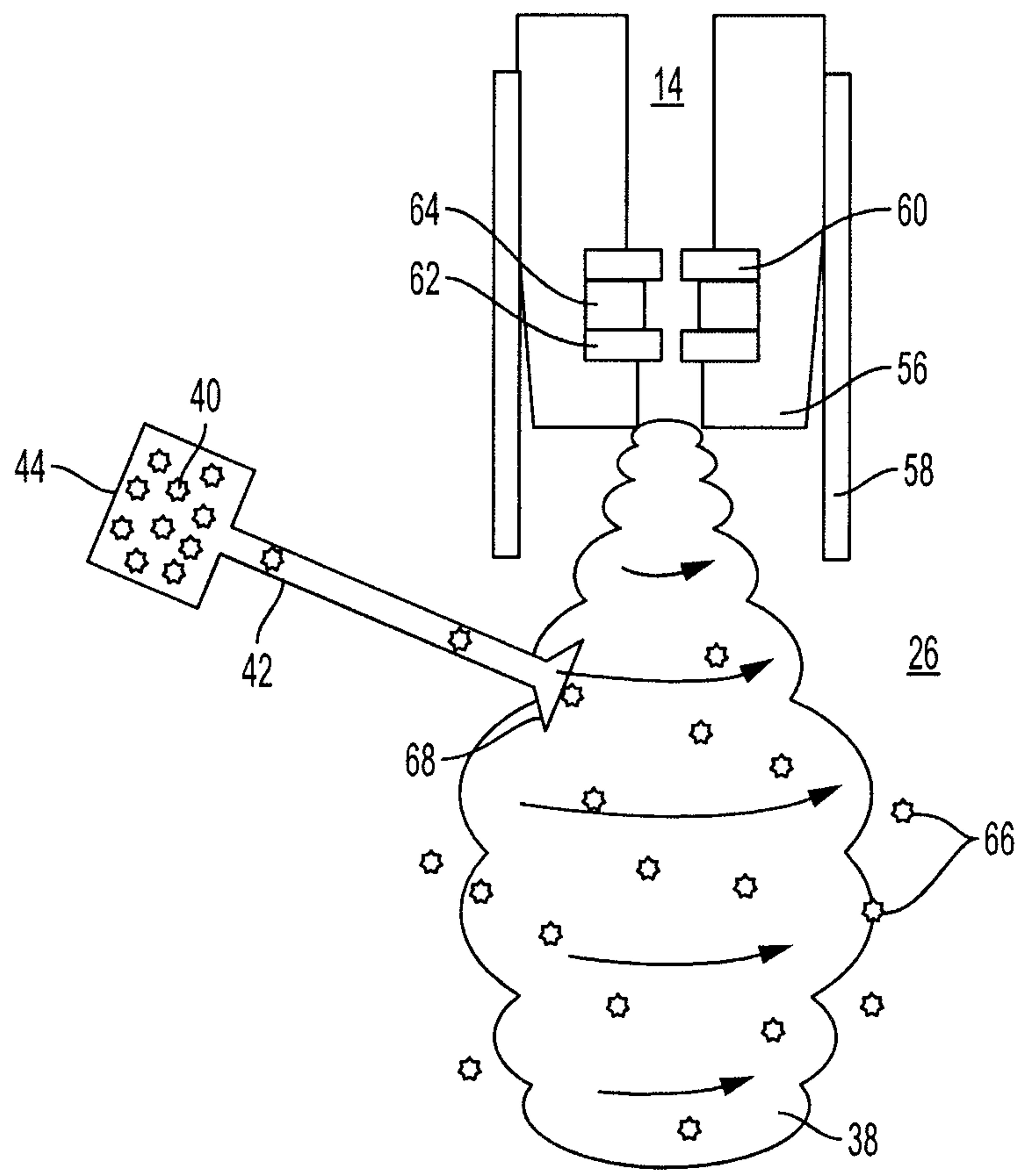

FIG. 4

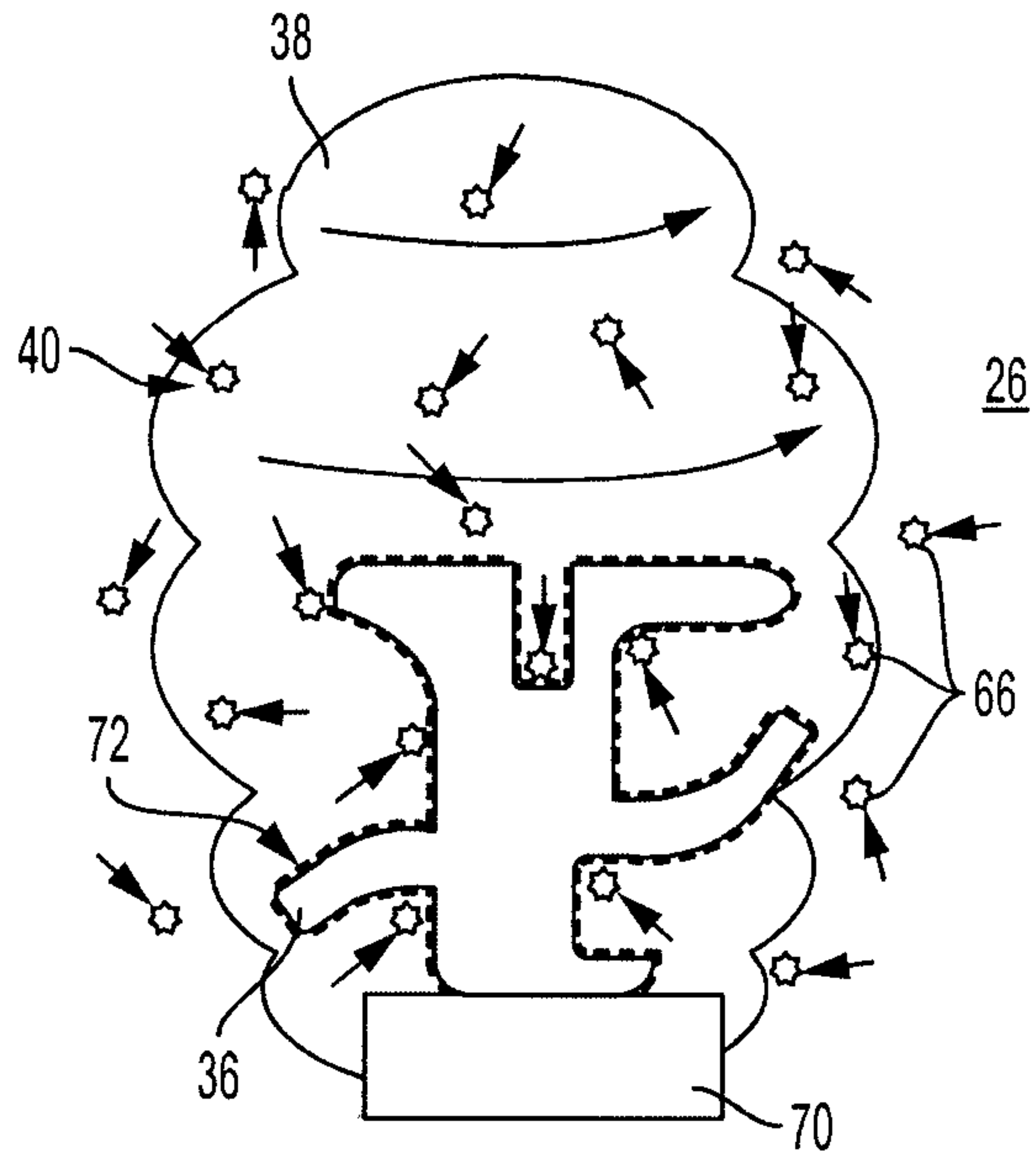

FIG. 5

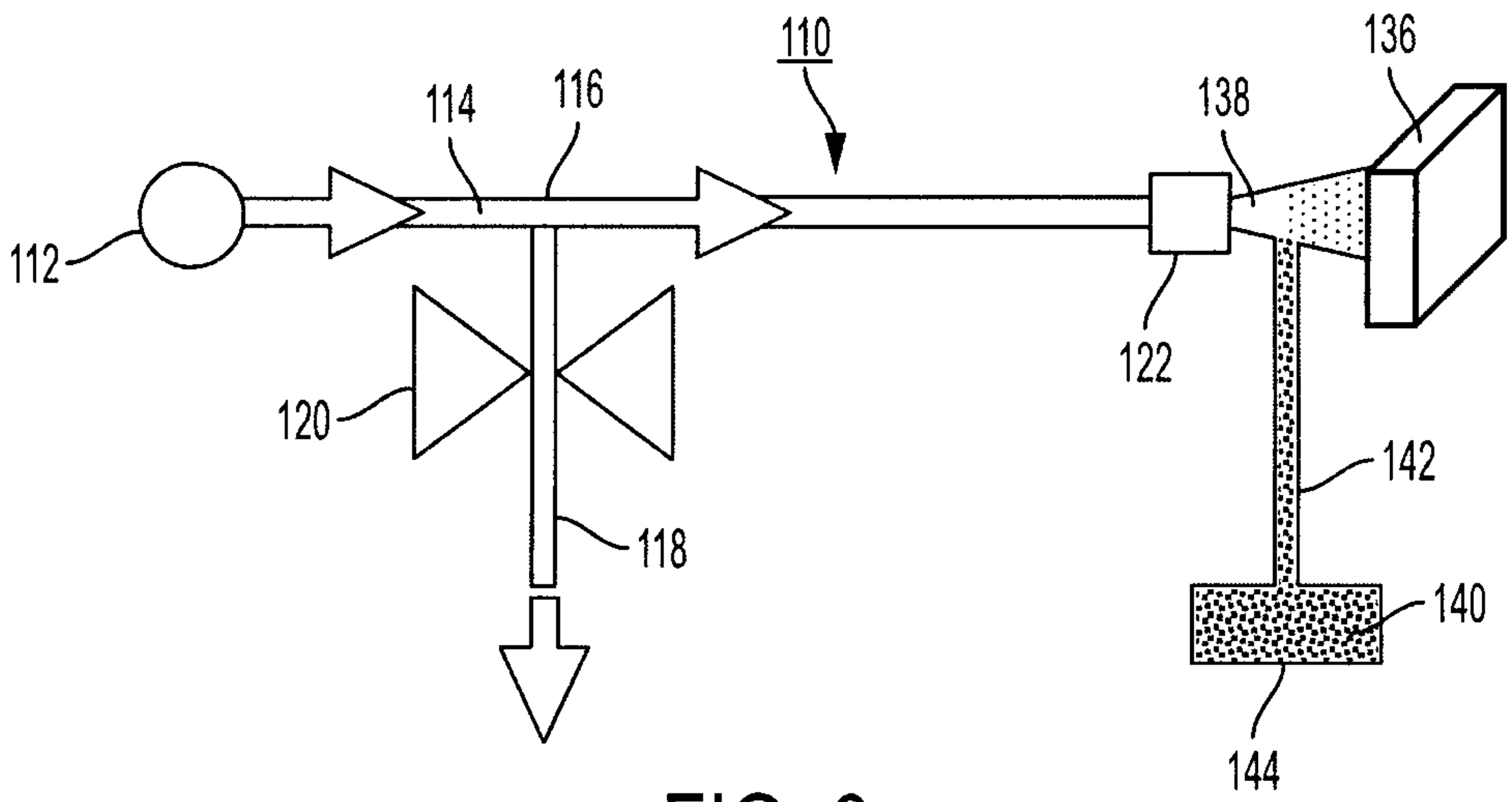
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FIG. 6

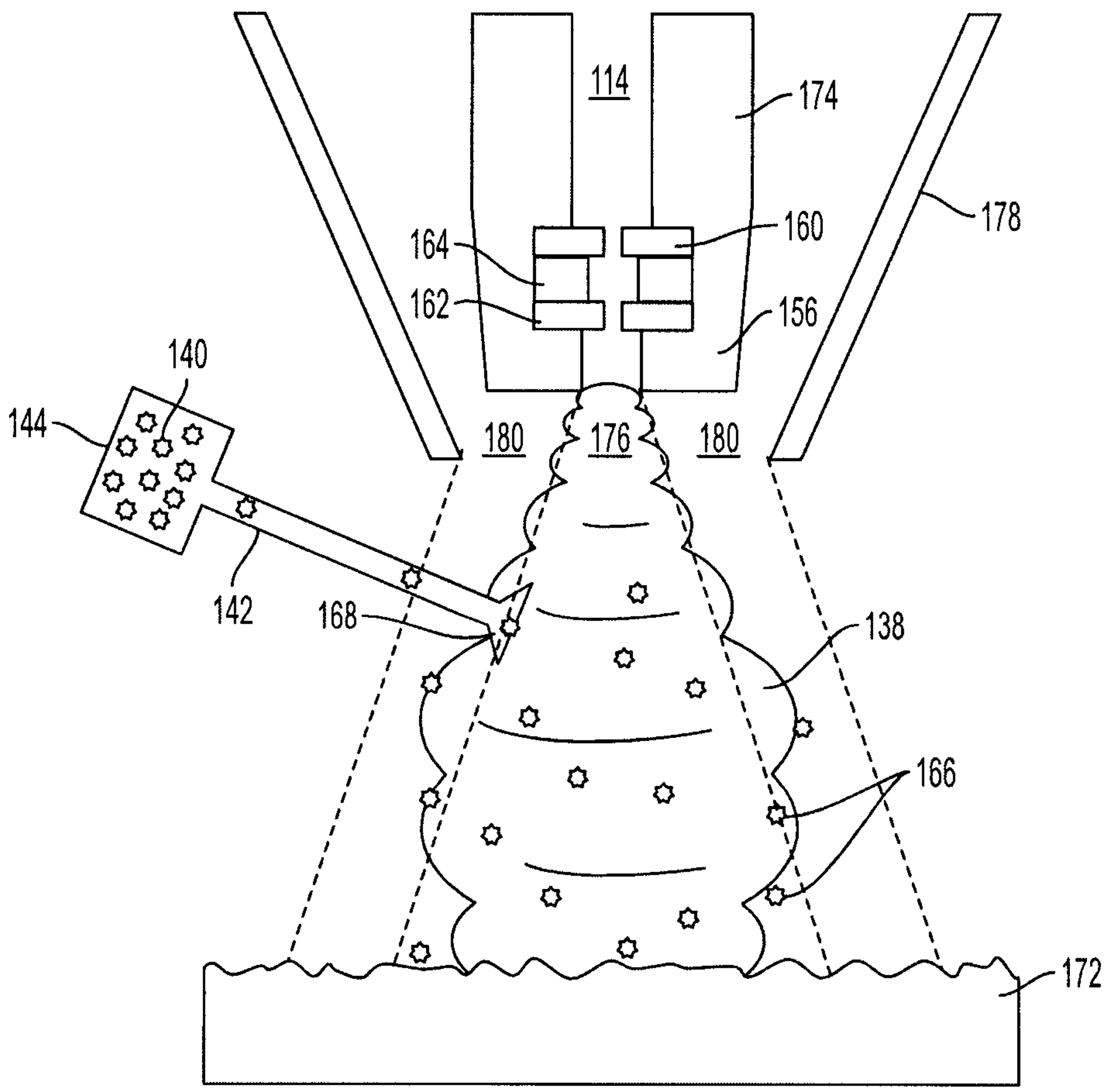
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FIG. 7

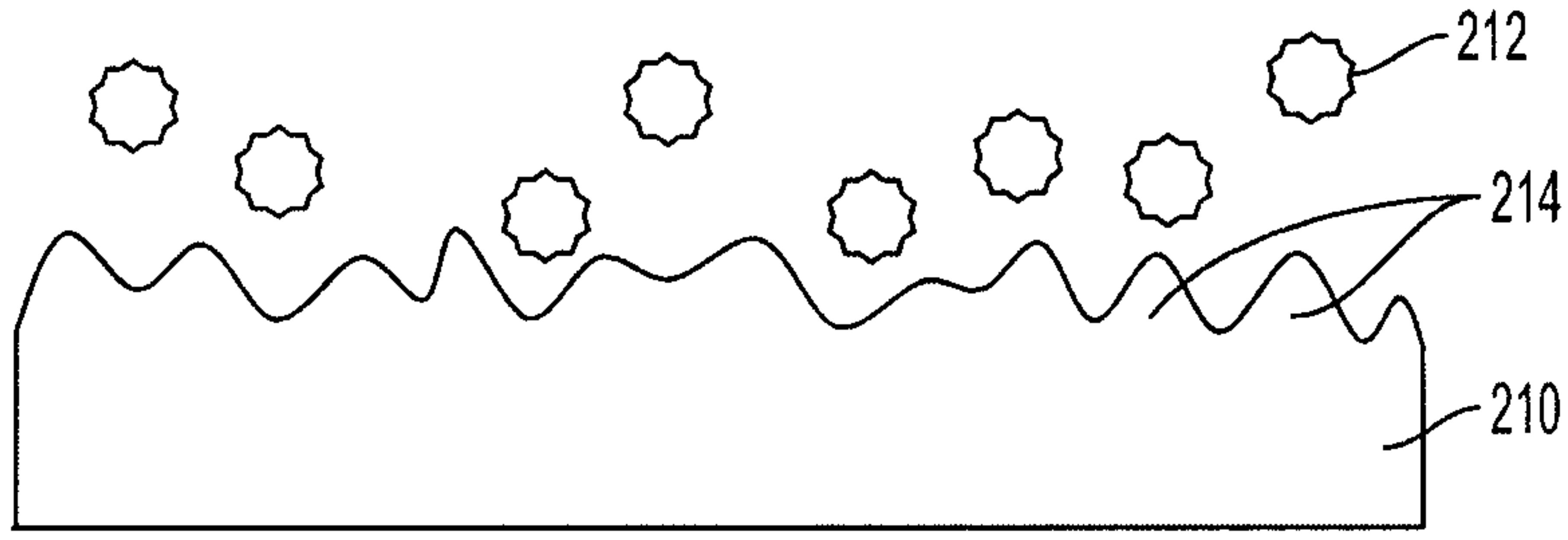


FIG. 8A

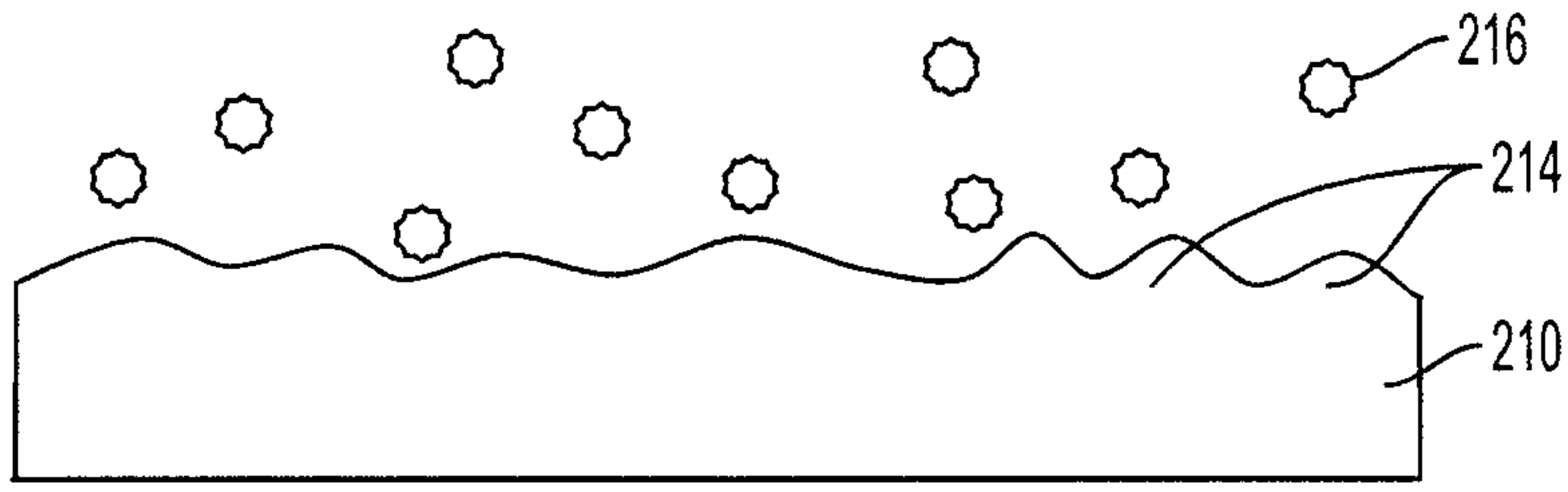


FIG. 8B

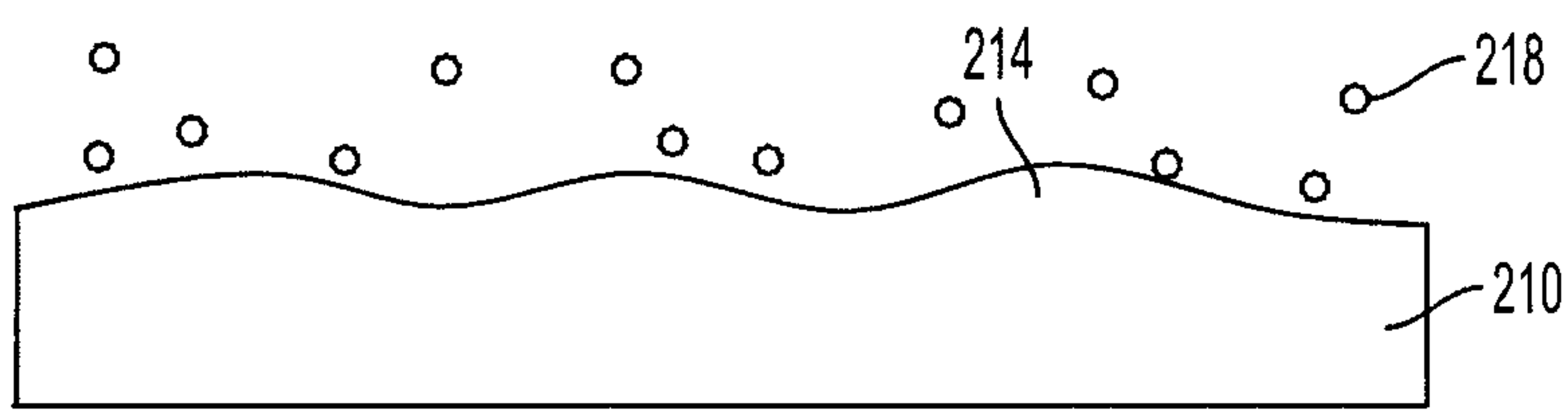


FIG. 8C

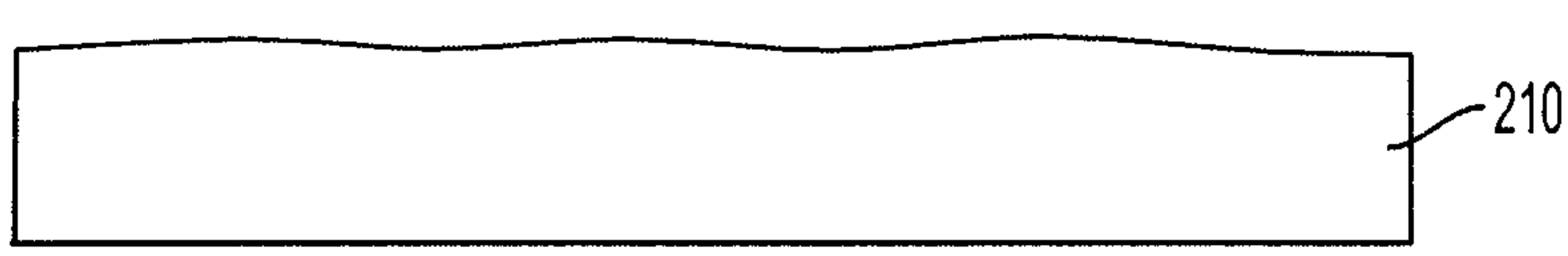
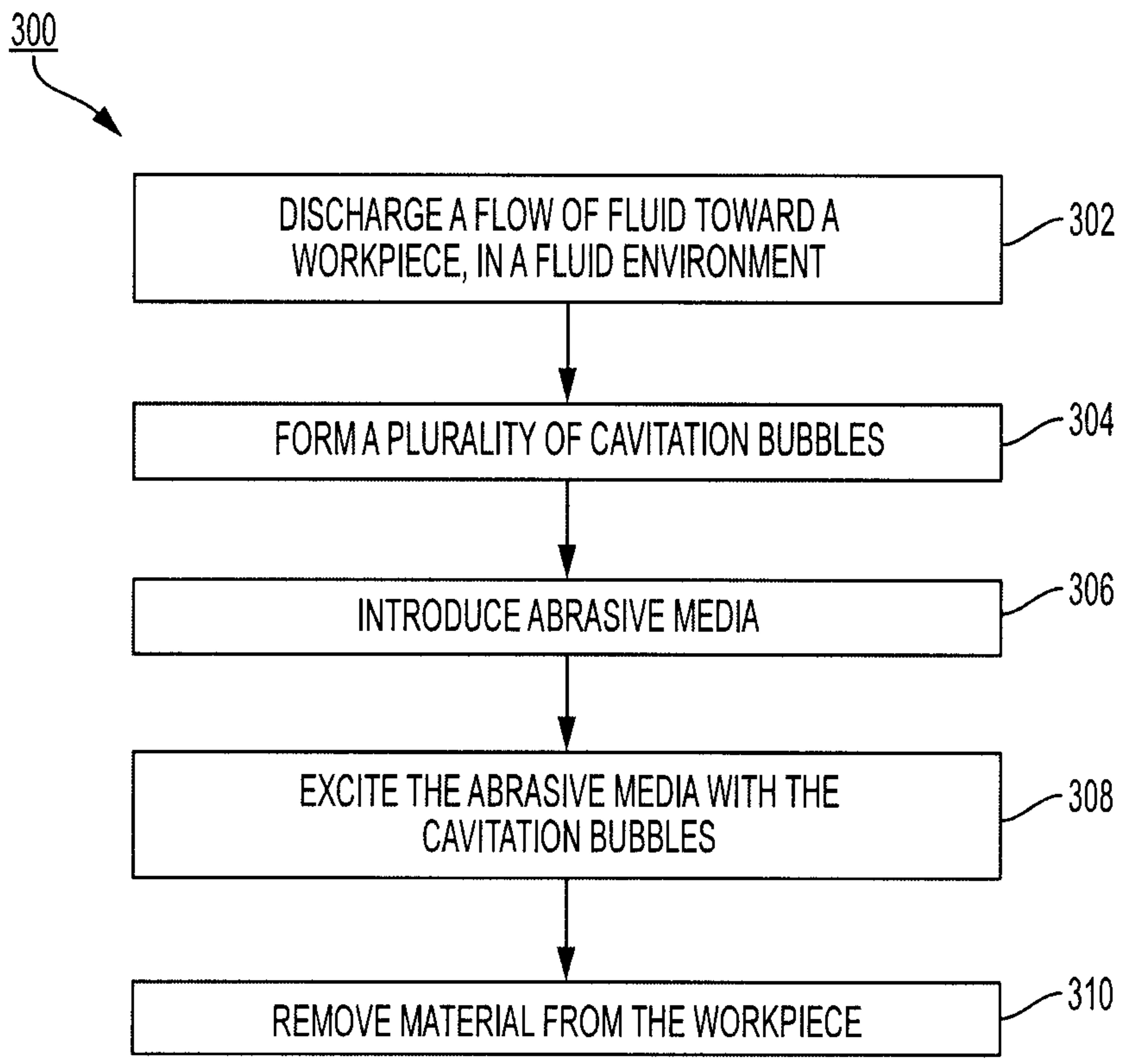


FIG. 8D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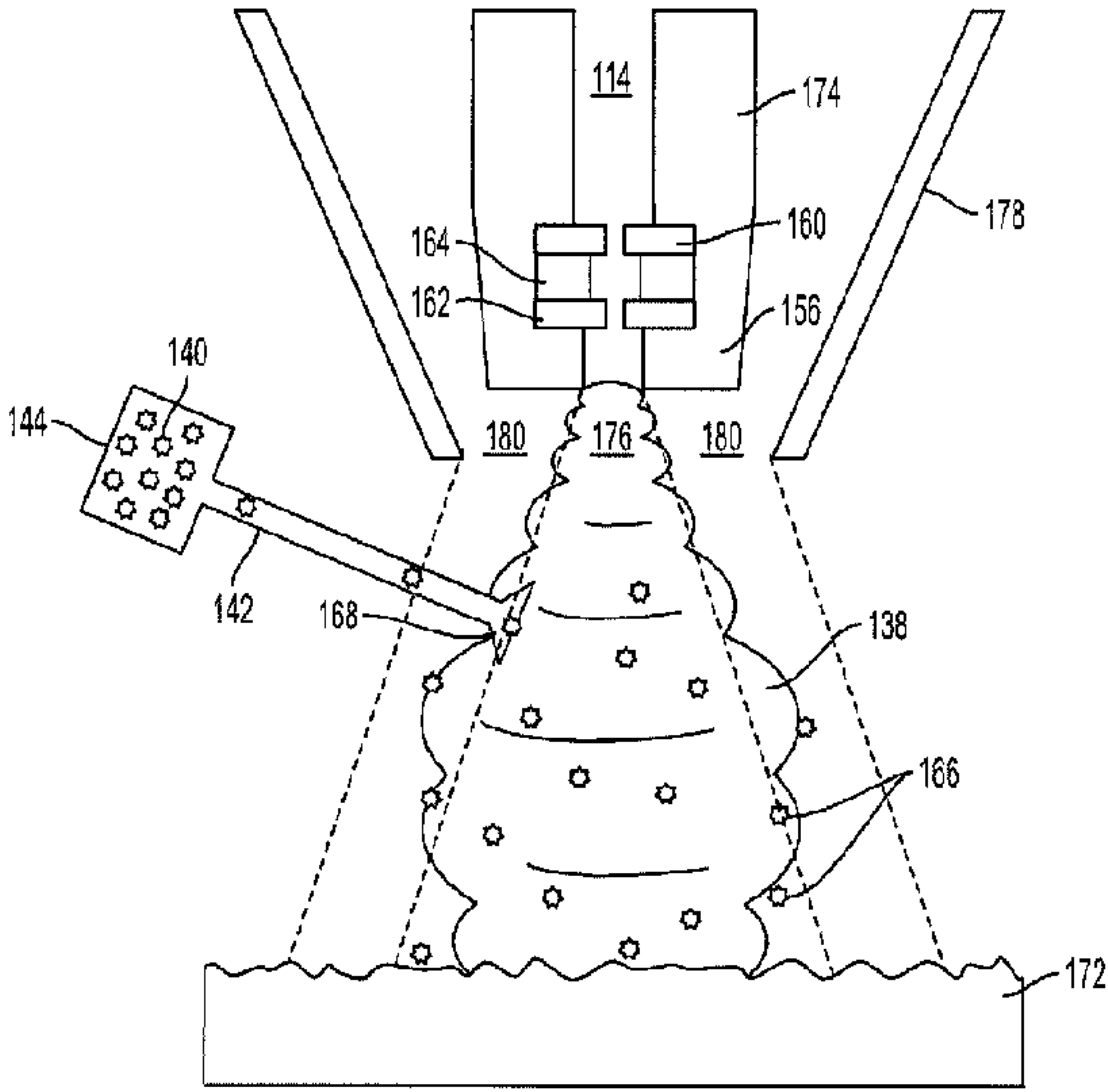
DISCHARGE A FLOW OF FLUID TOWARD A WORKPIECE, IN A FLUID ENVIRONMENT
302
FORM A PLURALITY OF CAVITATION BUBBLES
304
INTRODUCE ABRASIVE MEDIA
306
EXCITE THE ABRASIVE MEDIA WITH THE CAVITATION BUBBLES
308
REMOVE MATERIAL FROM THE WORKPIECE
310

FIG. 9



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