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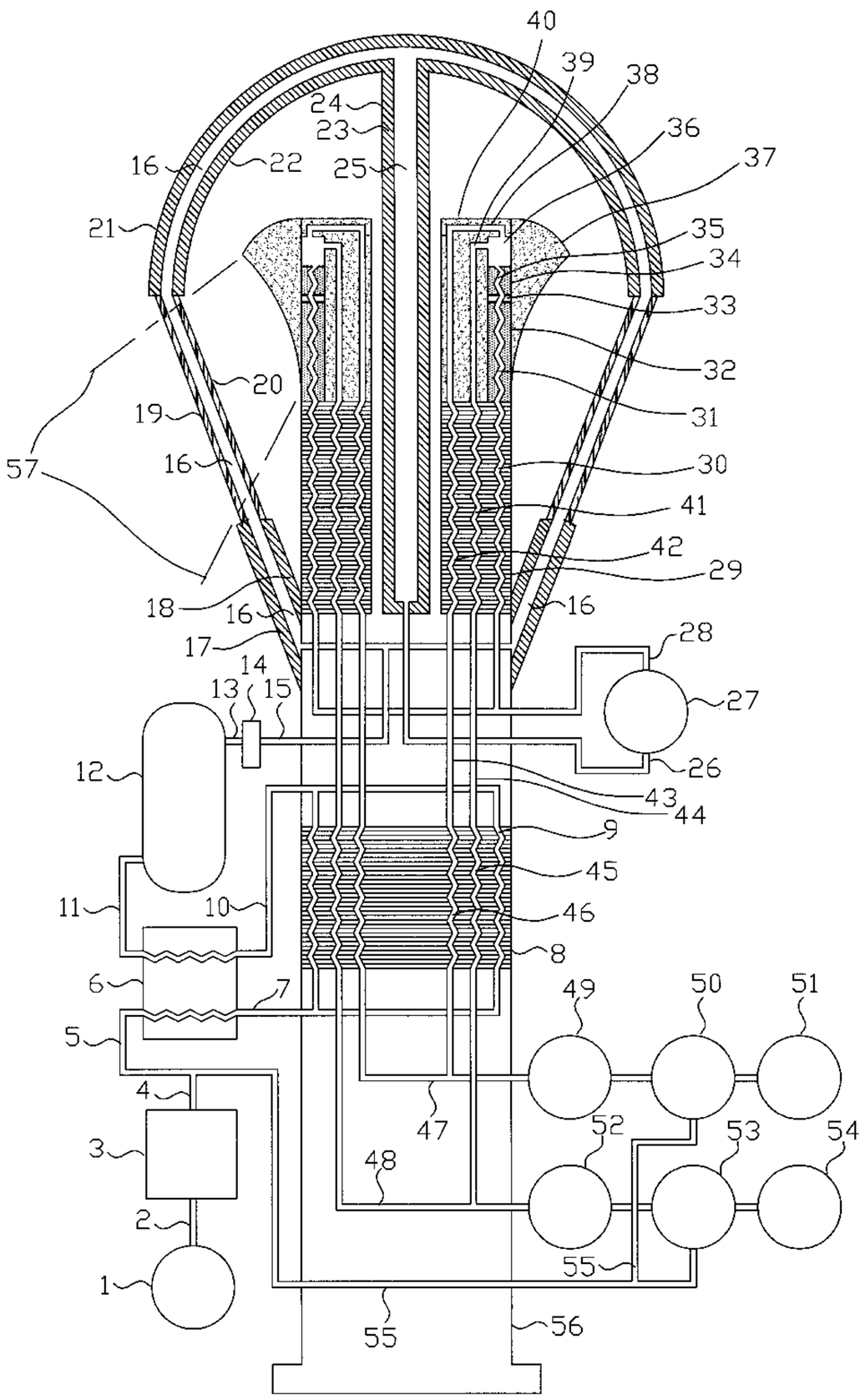
(54) **PROCEDE POUR L'OBTENTION DE L'HYDROGENE PAR DECOMPOSITION SOLAIRE DE L'EAU**

(54) **PROCESS FOR THE PRODUCTION OF HYDROGEN BY SOLAR DECOMPOSITION OF WATER**



(57) The invention provides a process and apparatus for production of hydrogen by thermal decomposition of water. In accordance with the invention, centrifugal forces are applied to water vapour which has been subjected to temperatures sufficient to dissociate oxygen and hydrogen. The dissociated hydrogen thereby separated is preferentially withdrawn from the reactor, driving a further equilibrium shift towards dissociation to improve the efficiency of hydrogen collection. In one embodiment, centrifugal forces may also be used to improve the transfer of heat to the water vapour to facilitate dissociation.

ABSTRACT

The invention provides a process and apparatus for production of hydrogen by thermal decomposition of water. In accordance with the invention, centrifugal forces are applied to water vapour which has been subjected to temperatures sufficient to dissociate oxygen and hydrogen. The dissociated hydrogen thereby separated is preferentially withdrawn from the reactor, driving a further equilibrium shift towards dissociation to improve the efficiency of hydrogen collection. In one embodiment, centrifugal forces may also be used to improve the transfer of heat to the water vapour to facilitate dissociation.

PROCESS FOR THE PRODUCTION OF HYDROGEN BY THERMAL DECOMPOSITION OF WATER

Field of the Invention

The invention is in the field of methods and apparatus for the production of hydrogen by thermal decomposition of water.

Background to the Invention

Hydrogen has long been viewed as an ideal combustible energy source. The product of hydrogen combustion in air is essentially water, although under some conditions traces of oxides of nitrogen may also be produced. An increasingly important advantage is that hydrogen combustion produces no carbon dioxide, a major 'greenhouse' gas which figures prominently in concerns about the deteriorating state of the environment, particularly in urban areas. Recent developments in fuel cell technology, and the high overall energy efficiency of fuel cells, have helped to produce conditions favourable to the adoption and use of hydrogen fuel.

Production of hydrogen is now mainly carried out by reforming hydrocarbons, such as methane, and to a smaller extent, by electrolysis of water. These processes typically involve the use of energy sources that create pollution. As a result, there is a long-felt need for efficient methods to transform water, either

directly or indirectly, into hydrogen, using solar energy.

There are generally three types of solar based production processes for the production of hydrogen from water. Photovoltaic cells are simple in principle but high cost and low efficiencies have been barriers. In the so-called water splitting approach, intermediate chemical agents such as FeO are reacted with water, at low temperature, to produce hydrogen. Regeneration of the resultant ferric oxide complex requires very high temperatures. Despite the plethora of systems, striking a balance between ease of production and ease of regeneration appears elusive.

The final type of process is the direct decomposition of water in solar furnaces at very high temperatures. Temperatures required are in the range of 2200-2500°C to produce small equilibrium amounts of 10-15% hydrogen. The very high temperatures needed gives rise to severe limitations on materials and equipment that might be used to economically carry out this transformation.

A major difficulty in the direct thermal decomposition of water is finding a means to cope with a reaction that is only about 15-20% complete at achievable reactor temperatures of 2500°C (Etievant, Solar Materials, 24(1991)443-440, Elsevier). The major equilibrium reaction products of water at 2500°C include hydrogen, oxygen, steam and hydroxyl species. This equilibrium is established in the primary reactor upon being exposed to the solar beam. Equilibration time at 2500°C is rapid, reportedly of the order of 1/1000th of a second (Etievant).

Much work regarding separations has been carried out with membranes that diffuse oxygen away from the reaction mixture. There have been some claims for a hydrogen diffusion process.

Separation of oxygen and hydrogen produced by dissociation of water using diffusion may require concentration gradients to be established using low pressures and reactors with large surface areas (Etievant, EP 0572 944 A1, FR 2 366 216).

Other means such as quenching the hot exhaust products at a very high speed will prevent the products from recombining to water. This can be achieved with water injection or an inert gas such as argon. The problem with this approach is that efficiencies of only 2 to 3% can be achieved since the energy in the hot products can not be recovered effectively due to the rapid cooling required to prevent recombination of the hydrogen and oxygen into water as these products cool.

Summary of the Invention

In accordance with the present invention, water can be transformed into constituent elements of hydrogen and oxygen, in good yield, by appropriate process design. In particular, a method is presented for taking superheated steam at high vapor velocity, which has been heated in a solar reactor, to cause decomposition of

water to the thermodynamic limits, under operating temperature and pressure of the solar reactor. The high velocity exit steam, consisting of hydrogen, oxygen, hydroxyl's, and steam from the solar reactor is then passed into a final reactor system and subjected to centrifuging or stratification methods such as a vortex tube that enables separation and collection of components through appropriate exit ports with the lighter fraction containing hydrogen and the heavier fraction containing oxygen.

By means of removing one of the reactants within the final reactor, hydrogen, for example, the reaction can be run under upset equilibria conditions and driven further to completion by this well known technique. Additionally, in the case of a dynamic chemical equilibrium, the stratification by a vortex tube of the heavy and light material, oxygen and hydrogen respectively, produces a transition zone containing water and hydroxyl species that has a degree of dynamic instability due to a deficiency of hydrogen and oxygen. By Le Chatelier's principle, water and hydroxyl in this transition zone would decompose to hydrogen and oxygen. This contributes to further production of hydrogen and oxygen. Operating temperatures in the final reactor need to be maintained at levels as close to the primary reactor to maintain rapid kinetics of equilibration.

With inadequate residence time or fall off in temperature of the final reactor, any residual material from the transition zone remaining in the final reactor can be separated at a heavy ends exit port and sent for recycle. With a well insulated system, the oxygen exiting the final reactor can be sent to one or more additional

polishing stratification stages before being heat exchanged with feed water. The same can be done with hydrogen as needed.

Solar energy may be provided to the chemical process section by means of many banks of computer controlled mirrors to produce temperatures of about 2500°C required to partially decompose water into hydrogen and oxygen. The land area required is in the range of 100 Acres or about 1/6th of a square mile. This would provide enough energy for a 100 MW plant that would require 380 liters per minute or about 100 gallons per minuter of feed water.

Feed water for the process of the invention is advantageously purified by filtration by known means, preferably before passing to a first heat exchanger. Preheated water from the first heat exchanger may then be piped to a combination heat exchanger and solar distillation unit, where the water is further purified by distillation. The distilled water may then be cooled in the first heat exchanger, transferring thermal energy to the in-feed water. The water may then be further purified in a third stage, such as reverse osmosis. Purified water may then be sent to the radiant energy capture system which captures a major portion of the energy which would otherwise be lost from thermal radiation. The heated water from this recapture unit is then piped into a third specially designed heat exchanger which heats the water to super heated steam with heat from the final stage of the solar reactor. This steam continues through the first stage solar reactor under pressure of about 10 atmospheres. This piping leads to the orifice within the reactor which allows the pressure to build. This high pressure allows better thermal transfer and

keeps the water from splitting due to its higher pressure.

The output of the orifice leads to a second stage solar reactor. As the steam enters this second stage of the solar reactor, vapor velocity is increased due to the vacuum on the output of the orifice. This in effect lowers the equilibrium temperatures for the water splitting reaction to occur. The solar furnace needs a residence time of about 1/1000 of a second (Lede et al, International Chemical Engineering, 25(2)246, 1985) for operations at 2500C. As the preheated steam enters the solar reactor, it further expands and decomposes to equilibrium concentrations of hydrogen, oxygen and intermediates according to the work of Ihara (Pergamon Press, 1979) and Lede. A catalyst such as platinum or a platinum group element or other catalyst can be introduced in the second stage solar reactor, lowering the equilibrium temperature for the water to split.

In one variation of the design of the solar reactor, steam is introduced into a cylindrical vessel that has an internal helical flight. This sets the steam in helical motion which prevents channeling and ensures a rapid temperature rise due to the steam pressing against the vessel walls caused by centrifugal force. The flight has an open central core. Other arrangements to ensure adequate heat absorption will be evident.

At the exit of the second solar reactor, the hot steam is directed towards the third stage solar reactor which contains one or more vortex tube(s). The vapor

steam is injected perpendicularly and on tangent to the manifold of the vortex tube. This manifold, and its injectors, act to initiate the formation of a vortex. This causes an increase in velocity leading to high gravity of the gas swirl in the vortex tube. Effects of intense gravity cause a mass action equilibrium shift yielding oxygen at outside circumference and hydrogen at the center of the vortex tube. As well, there is a beneficial drop in pressure throughout the system. It is evident that this drop in pressure drives the decomposition favorably towards the products, as indicated by Ihara. The presence of a catalyst such as platinum or a platinum alloy can further decrease equilibrium temperature.

Devices that achieve high centrifugal forces due to gas velocity are: a) Becker/Laval nozzles; b) helical, spiral or cone centrifuges; and c) Ranque-Hilsch vortex tubes. In accordance with the present invention, such devices may be used to achieve stratification of the reaction mixture within the centrifuge system.

As well, in accordance with another aspect of the invention, one of the reaction products, such as hydrogen, can be removed from the centrifuge system shortly after transfer from the solar reactor, to drive the reaction further towards completion. This increases the efficiency of the transformation and reduces the need for costly recycle streams.

This is best seen with a modified Ranque-Hilsch (RH) vortex centrifuge system (J. Phys. Et Rad., 14 (1933)1125) and R. Hilsch (Rev. Sci. Ins.

18(1947)108), a preferred embodiment of the invention. Gas entering a vortex tube at a tangent develops into a vortex. Tube design to rapidly develop a stable vortex may be essential to the optimal operation of RH tubes (Newman Tools, Hartford Conn, USA and Lindstrom-Lange). With conditions of under 100 psi gas inlet pressure, such devices may create a swirl of gas in the range of 1,000,000 rpm (Newman Tools) which translates into angular velocities well into the supersonic range.

In accordance with the invention, exit gases from a primary solar reactor can be directed to one or more RH vortex tubes wherein the hot gas is introduced to a RH tube, in a tangential manner, thereby generating large centrifugal forces due to high gas velocity. After the vortex stabilizes, the heavier oxygen molecules are on the periphery and the lighter hydrogen molecules are at the core of the vortex tube. Because of separation of species, and mass action, water decomposes. Oxygen is drawn off at the periphery at one end of the vortex tube while hydrogen is drawn off from the center core of the tube. With a proper separating radial gas manifold, both gases could be drawn off one end. (Newman Tools).

The fact that hydrogen can be separated from oxygen within the vortex reactor, and drawn out of the vortex reactor, means that it is possible to achieve upset equilibrium conditions that favor further decomposition of water in response to the removal of hydrogen.

Hydrogen can be removed from a point near the stabilization zone of the vortex by a smaller diameter inner draw pipe. This step may be assisted by the use of a comparative vacuum that is not so strong that it disrupts gas dynamics at intermediate and peripheral zones.

Internal tubing in the RH vortex tube may be used to effect gas separation. In one embodiment, inner core diameter may be about 20-30% of vortex tube diameter. An effective single point of removal has been found to be about 25% of the distance down the core from the tangential inflow. The core may be porous or perforated and of extended length in order to promote removal of hydrogen from the vortex tube.

The high centrifugal forces due to gas velocities of 1-2 million rpm, appropriate for this case, cause a radial distribution of mass across the vortex tube. At the center is hydrogen. At the periphery is oxygen. There is a transition zone between these species consisting of water vapor and hydroxyl groups. The transition zone is chemically unstable since it is deficient in oxygen and hydrogen. Separation is favored by larger diameter vortex tubes operating at lower angular gas velocities or rpm's. Under these conditions, effective stratification occurs. The transition zone strives to reach "regional" equilibrium by forming additional hydrogen and oxygen that move to the core and periphery, respectively. Therefore, within the final stage reactor, the system is driven to the products of oxygen and hydrogen. There is a need to maintain temperatures in this system so that the reaction does not become subject to kinetic control. If adequate gas velocities are

not achieved, stratification will not take place and the above phenomena will not occur.

In an alternative embodiment, the vortex tube can be used to strip off the equilibrium concentrations of the gases and several additional stages would be required to allow re-equilibration and gas stripping.

The present invention permits effective dissociation of water at temperatures significantly below that needed for ordinary full dissociation, which is about 3500°C. Additionally, while an operating temperature of 2500°C has been cited as desirable, it will be evident that lower temperatures, such as 2200°C, can be employed provided that sufficient residence time is allowed for equilibration (Etievant). The benefits of lower temperature operation are reduced material demands and the reduction in difficulty of fabricating process equipment for operation at reduced temperatures.

Reactions other than the dissociation of water may be accelerated or catalyzed in accordance with the present invention. For example, ammonia could be made to decompose in a similar manner. Methane reforming may be considered. Other systems are possible if the appropriate mass distribution applies to reactants and products.

The RH vortex tube might be usefully employed in another manner to improve the process of oxygen diffusion investigated by some, (Etievant). Diffusion depends, in part, upon high partial pressures of oxygen on one side of a membrane material and lower partial pressures on the other side. With the vortex tube, oxygen concentration is at a comparatively high level on the periphery.

Other heat sources can be used such as waste heat from thermal electric stations. Although this heat is lower than required for disassociation of water, it would provide a preheat to the process. Later heating stages could use electricity. Candidates for this include fossil fuel and nuclear power plants. Geothermal is another source of heat which would be non-polluting. Again geothermal could be used as a preheat to the process with secondary heating coming from geothermal electric, solar or other.

Brief Description of the Drawings

FIG. 1 shows a schematic view of the preferred embodiment of this invention, for use as a solar hydrogen production process.

FIG. 2 shows a cross sectional pictorial view of the preferred embodiment of this invention which closely follows the **FIG. 1** process.

FIG. 3 shows an outside view of the solar hydrogen tower indicating where

the incident solar radiation bombards the tower.

FIG. 4 shows the side view and general placement of the strut and one way window design for the radiant energy capture system of the solar hydrogen generator.

FIG. 5 shows a top down view detail of the one way window and strut design of the radiant energy capture unit.

FIG. 6 shows the side view detail of the one way window and strut design of the radiant energy capture unit.

FIG. 7 shows the top down view of the solar hydrogen tower with the top dome removed. The center support structure, reactor core, and solar target are visible in the center. Surrounding this reactor assembly is one embodiment of the one way window and strut design based on flat glass components.

FIG. 8 shows the same view as **FIG. 7** but shows another embodiment of the glass structures in which struts are not required and the tapered one way glass cones form the structural members as well as radiant energy capture windows.

FIG. 9 shows the helical channel which represents the path that the water and its products take within the heat exchanger of **FIG. 10.**

FIG. 10 shows preferred embodiment of the construction of the high temperature heat exchanger which has the helical water feed channel feeding up the center path of the exchanger and the counter-flow smaller helixes feeding the products of hydrogen and oxygen down. Also shown is the thermal break preventing a thermal short circuit.

FIG. 10A, 10B, 10C, 10D show other embodiments of the fluid transfer channels with increased surface area for better thermal transfer characteristics.

FIG. 11 shows a detail of another embodiment of the heat exchanger. A section of the helix of **FIG. 10** in which thermal breaks are evident along the path of the helix.

FIG. 12 shows a line path representation of the **FIG. 10** heat exchanger. The wavy lines represent the helixes as shown in **FIG. 10** with the center line being the water in-feed line feeding up and the four lines on each side being the hydrogen and oxygen out-feed lines feeding down.

FIG. 13 shows another embodiment of the heat exchanger of **FIG. 10** in which a double helix out-feeding hydrogen and oxygen, helix around the water in-feed helix, forming a compound helix.

FIG. 14 shows another embodiment of the heat exchanger of **FIG. 10** in which a triple helix exists and this triple helix, helixes around the exchanger, forming a compound helix.

FIG. 15 shows a top down view of another embodiment of the heat exchanger of **FIG. 10** in which the thermal transfer channels are on one flat layer as opposed to being helical.

FIG. 16 shows a side view of **FIG. 15**. Each flat layer is connected to another layer separated by a thermal break layer thus preventing a thermal short circuit.

FIG. 17 shows the helical path within the 1st stage solar reactor shown in **FIG. 18** shows a cutaway view of the 1st stage solar reactor.

FIG. 19 shows the helical path within the 2nd stage solar reactor shown in **FIG. 20**.

FIG. 20 shows a cutaway view of the 2nd stage solar reactor.

FIG. 21 shows the pictorial view of the outside of the vortex tube within the 3rd stage reactor.

FIG. 22 shows a cross sectional side view of the vortex tube within the 3rd stage solar reactor with the in-feed manifold.

FIG. 23 shows the detail of an injector nozzle of the vortex tube within the 3rd stage solar reactor.

FIG. 24 shows the detail view of another embodiment of the vortex tube within the 3rd stage reactor showing more than one injector and showing the in-feed manifold.

FIG. 25 shows the preferred embodiment of the detail construction of the 3rd stage solar reactor which incorporates the vortex tube.

FIG. 25A shows another embodiment of the 3rd stage solar reactor with an additional oxygen draw tube.

Fig. 26 shows a cutaway view of a plurality of vortex tubes assemblies within the 3rd stage solar reactor and mounted on top of the 2nd stage solar reactor.

FIG. 27 shows another embodiment of the 3rd stage solar reactor positioned in relation to the 2nd stage solar reactor helix.

FIG. 28 shows a close up side view of another embodiment of the 3rd stage solar reactor shown in **FIG. 27**.

FIG. 29 shows a top down view of the 3rd stage solar reactor embodiment as described in **FIG. 28**.

FIG. 30 shows another embodiment of the 3rd stage solar reactor.

FIG. 31 shows the side view of a typical solar hydrogen station which would be geographically located in the latitudes not far from the equator, where the sun is high in the sky.

FIG. 32 shows the top down view of **FIG. 31**.

FIG. 33 shows the side view of a typical solar hydrogen station which would be geographically located in the latitudes far from the equator, where the angle of the sun is low on the horizon.

FIG. 34 shows the top down view of **FIG. 33**.

FIG. 35 shows a small scale solar hydrogen station which uses a specially shaped reflective dish and follows the sun directly.

Detailed Description of the Invention

The following description is in reference to **FIG. 1** and **FIG. 2**. **FIG. 1** shows a schematic view of the preferred embodiment of this invention. **FIG. 2** shows a cross sectional pictorial view of the preferred embodiment of this invention which closely follows the **FIG. 1** process.

The water supply and feed pump **1** feed water by supply pipe **2** to a water filter **3**. Water filter **3** removes particulate matter, partially purifying the water. This partially purified water is then fed by pipe **4**, and is combined with recycled water from pipe **55**, and feeds through pipe **5** to an opposing flow or cross flow heat exchanger **6**. Heat exchanger **6** heats the inflow water with heat transferred from another part of the process. The heated water from the heat exchanger **6** then feeds by pipe **7** to combination solar distiller heat exchanger **8**.

Solar distiller heat exchanger **8** uses solar energy to distill the water at the start of the process; however, after the process is running, the hot exhaust gases from pipes **44** and **43** transfer heat by heat exchanger channels **45** and **46** through a cross flow heat transfer method to the distillation section **9** within the exchanger unit **8**. Solar energy therefore is not required once the process is up to operating temperature.

The distilled water from the combination solar distiller heat exchanger **8** is then fed by pipe **10** back to heat exchanger **6** where the heat from the distillation process is recovered and is used to preheat the inflow water feeding from pipe **5**. In this way, most of the energy used for distillation is recovered. The energy of the heat of fusion required to boil water is about 10kcal/mole amounting to about 15% of the energy of the water splitting process. This is a significant amount of energy which would be lost if this heat exchanger **6** was not used.

The distilled water from heat exchanger **6** is fed by pipe **11** to a final water purification stage **12**. The final water purification stage **12** can be a reverse osmosis or other high purification method. Reverse osmosis is a low energy process, but normally requires periodic maintenance due to filtration membranes plugging. The pre-distilled water from solar distiller heat exchanger **8** however, removes most of the mineral contaminants, therefore making maintenance low on the reverse osmosis or other high purification method **12**.

The output of the final water purification system **12** is pumped under enough pressure to raise the water to the top of the solar hydrogen tower **56**. This pressurized purified water from water purification and pressurization system **12** is fed by pipe **13** to pressure regulator **14**.

This regulated pressure high purity water is fed by pipe **15** to the radiant energy recovery system **16-25**, **58-67**. Pressure regulator **14** limits the pressure to safe levels so damage is not done due to excessive pressures in the radiant energy recovery system **16-25**, **58-67**. The radiant energy recovery system recaptures most of the energy which would be lost due to radiant heat loss in the reactor section **32**, **33**, **34**, and **36**, and heat exchanger **29**.

The regulated pressure high purity water fed by pipe **15** goes up between outer window support structure **17** and inner window support structure **18**. These support structures can be made of micro polished stainless steel or other highly reflective thermally conductive material. The reflectivity of outer window support structure **17** will reflect any concentrated solar energy **57** which may accidentally fall onto this surface. The reflectivity of inner window support structure **18** will reflect radiant energy from within the structure, back into the structure. Heat absorbed through conduction will be transferred to the water flow **16** between the structures **17** and **18**. This heated water is added to the process preheat.

The water further travels up the radiant energy recovery structure **16-25**, **58-**

67 between outer one way window **19** and the inner one way window **20**. These windows are constructed of quartz glass which is transparent to the ultra violet region of the spectrum. Ordinary glass is not transparent to ultraviolet. These windows **19** and **20** are also one way windows, allowing concentrated solar energy **57** to enter the radiant energy capture unit **16-25**, **58-67** and not allowing radiant energy to escape back out of the unit. Any amount of energy absorbed by these windows **19** and **20** is cooled by the water flow **16** going up between the windows. This absorbed energy in water flow **16** is added to the process thus reducing energy which would otherwise be lost due to thermal radiation and thermal convection.

The water further travels up the structure to the dome which consists of outer hull **21** and inner hull **22**. These domes are constructed of micro polished stainless steel or other highly reflective and thermally conductive material. The reflectivity of outer dome **21** will reflect any concentrated solar energy **57** which may accidentally fall on this surface. The reflectivity of inner dome **22** will reflect radiant energy from within the structure, back into the structure. Heat absorbed through conduction will be transferred to the water flow **16** between the structures **21** and **22**. This heated water is added to the process preheat.

The outer dome **21** and inner dome **22** can be separated by spacers or other various construction methods to hold the domes together and provide a consistent spacing between the domes. The dome shape is not necessary and other shapes can be implemented.

The water is finally drawn down the center **25** of the hollow support structure **23**. The surface of this support structure **24** can be made of micro polished stainless steel or other highly reflective, non-tarnishable and thermally conductive material. Radiant energy from the various components of the reactor core and other components in the energy capture unit **16-25**, **58-67** are reflected back into the energy capture unit **16-25**, **58-67**. Any absorbed energy is added to the process preheat.

Radiant energy which is absorbed by the radiant energy capture unit **16-25**, **58-67** is used to heat the cooling water of the radiant energy capture unit **16-25**, **58-67**. This heated water is fed by pipe **26** to pressurization pump **27**. Pressurization pump **27** raises the pressure of this water to about ten atmospheres. Other pressures are possible and the pressure in not critical. This high pressure water is fed by pipe **28** to the high temperature heat exchanger **29**.

High temperature heat exchanger **29** superheats the water. The water traveling through channel **30** of heat exchanger **29** is heated by thermal conduction of heat transferred from the superheated exhaust gases of adjacent channels **41** and **42**.

This superheated steam is fed directly to the first stage reactor **32**, still under a pressure of about ten atmospheres. This high pressure increases the equilibrium temperature of the thermal splitting of the H_2O steam and keeps the H_2O steam

from disassociating into hydrogen and oxygen. This allows for greater thermal absorption of the solar energy bombarding the first stage reactor **32**.

The concentrated solar energy **57** bombarding the reactor target **37** is thermally conducted to the 1st stage reactor **32** as well as 2nd and 3rd stage reactors **34** and **36** respectively. Reactor target **37** is shaped to provide the best solar energy **57** absorption and minimize reflective losses.

The top, or output of the 1st stage reactor **32**, connects to an orifice **33**. Orifice **33** restricts the flow of gases through it allowing a higher pressure to be built up in the 1st stage reactor **32**. Higher pressures will increase the volume of flow through the reactors **32**, **34**, and **36**, and will increase the amount of product flow through the system as a whole. With higher levels of solar radiation **57** available, higher pressures can be used from pump **27** to increase the rate of hydrogen production from the system.

The output of the orifice **33** feeds directly to the 2nd stage reactor **34**. An immediate pressure drop is realized on this side of the orifice since a partial vacuum is created by process balancing pumps **49** and **52** further along in the process. This lower pressure causes a forced expansion of the superheated steam which would normally tend to cause a temperature drop. This is the principle of operation in which gases while being compressed become hot, and when expanded become cool, absorbing energy. This energy absorption adds to the process of thermally splitting the super heated steam into its constituent components. The lower pressure also

lowers the equilibrium temperature, further aiding in the splitting of the super heated steam. If an appropriate catalyst is also placed within the flow channel **35** of the 2nd stage reactor **34**, then lower temperatures overall can be used to split the water. Channel **35** of the 2nd stage reactor **34** is sufficiently long to allow H_2O splitting to occur to its equilibrium limits.

The output of the 2nd stage reactor **34** is fed into the 3rd stage reactor(s) **36**. One or more 3rd stage reactor(s) **36** can be used in parallel depending on the size of the installation. The 3rd stage reactor **36** is a static gas centrifuge in which the superheated equilibrium mix of H, H_2, O, O_2, hydroxyl's, and H_2O, are rotated in a vortex. The centrifugal force forces the heavier elements of O_2 to the outside of the 3rd stage reactor **36** where it is extracted, while the lighter elements of H and H_2 migrate towards the center where they are extracted. The removal of these elements upsets the equilibrium further causing unsplit H_2O and hydroxyl's to split. This substantially reduces the amount of recycle required and increases overall efficiency of the system because each time a recycle is required, a small percentage of energy is lost since heat exchangers **29**, **8**, and **6** are not 100% efficient. A catalyst can also be used within reactor **36** to reduce the overall temperature required to split H_2O. The catalyst structure in this case must follow the helical flow of the gases in the 3rd stage reactor **36** so not to interfere with the helical flow of the gases.

The hydrogen is exhausted through port **38** while the oxygen is exhausted through port **39** of high temperature piping structure **40** which is part of the entire

reactor structure consisting of **32**, **33**, **34**, **36**, and **37**.

The hot hydrogen and oxygen is fed to the top of the high temperature heat exchanger **29**. The hydrogen feeds through channel **42** and the oxygen through channel **41** of the high temperature heat exchanger **29**. Thermal energy is transferred by thermal conduction and thermal radiation from the exhaust gas channels **42** and **41**, to the steam input channel **30**. This exhaust heat is used to superheat the steam feeding to the 1st stage reactor **32**.

The cooled hydrogen and oxygen is fed from high temperature heat exchanger **29** by connecting pipes **43** and **44** respectively, to the combination solar distiller heat exchanger **8** where the hydrogen feeds through channel **46** and the oxygen feeds through channel **45**. The heat is transferred from these channels to channel **9** where the heat is used to heat the inflow water to distillation temperatures. Sufficient heat still remains after the high temperature heat exchanger **29** to distill water in the combination solar distiller heat exchanger **8**.

The cooled hydrogen is then removed from the combination solar distiller heat exchanger **8** and fed by pipe **47** to the hydrogen vacuum process balancing pump **49**. The output of the hydrogen vacuum process balancing pump **49** is fed to H_2O scrubber **50** where water is removed from the hydrogen gas. Water will exist with the hydrogen gas due to less than 100% effective separation in the 3rd stage reactor **36**. Any oxygen hydrogen mixture from the 3rd stage reactor which exits the

high temperature pipe **38** will recombine to water as the temperature is cooled through the high temperature heat exchanger **29**. After the water is removed by H_2O scrubber **50**, the remaining hydrogen is then sent to hydrogen storage **51**. The water which is removed from H_2O scrubber **50** is recycled through pipe **55**.

The cooled oxygen is likewise removed from the combination solar distiller heat exchanger **8** and fed by pipe **48** to the oxygen vacuum process balancing pump **52**. The output of the oxygen vacuum process balancing pump **52** is fed to H_2O scrubber **53** where water is removed from the oxygen gas. Water will exist with the oxygen gas due to less than 100% effective separation in the 3rd stage reactor **36**. Any oxygen hydrogen mixture from the 3rd stage reactor which exits the high temperature pipe **39** will recombine to water as the temperature is cooled through the high temperature heat exchanger **29**. After the water is removed by H_2O scrubber **53**, the remaining oxygen is then sent to oxygen storage **54**. The water which is removed from H_2O scrubber **53** is recycled through pipe **55**.

The process balancing pumps **49** and **52** are used to create a vacuum for the 2nd and 3rd stage solar reactors **34** and **36** respectively. The pumps must maintain a balanced vacuum in order for the 3rd stage reactor **36** to function properly. Too much vacuum on hydrogen balancing vacuum pump **49** in relation to oxygen process balancing pump **52** would result in excessive oxygen being drawn into the hydrogen exit line. In similar fashion, if there is too much vacuum on oxygen process balancing pump **52** in relation to hydrogen balancing pump **49**, excessive hydrogen would be drawn into the oxygen exit line. This would result in more water forming as the hydrogen and oxygen cool and recombine to water. This extra

water would require recycle. The overall throughput of the system would diminish. The process balancing pumps operate under computer control, following algorithms and tables for all the variable operating conditions the solar hydrogen station will perform under. Optimum production and maximum efficiency can be maintained in this fashion.

FIG. 3 shows an outside view of the solar hydrogen tower. The tower **56** may be constructed using various techniques. Metal or re-enforced concrete are a couple of examples of tower construction techniques. The top of the tower shows the radiant energy capture unit **16-25**, **58-67**. The top outside dome **21**, water cooled struts **58**, outer one way mirrored window **19**, and outer window support structure **17** are visible. The concentrated solar energy **57** enters through the mirrored one way windows **19**. The concentrated solar energy 57 comes from computer steered mirrors **81**, **82**, or **83** as shown in **FIG. 31**, **FIG. 32**, **FIG. 33**, **FIG. 34**, and **FIG. 35**. A portion of this concentrated solar energy **57** is used on the combination solar distiller heat exchanger **8** during process startup at the beginning of the day. After process startup, all of the concentrated solar energy **57** can be focused towards the reactor target **37** of **FIG. 2** within the radiant energy capture unit **16-25**, **58-67**.

FIG. 4 shows a simplified cutaway side view and general placement of the struts and one way window design for the radiant energy capture system **16-25**, **58-67** of the solar hydrogen generator. Purified water **16** passes between the inner and

outer structures **18** and **17** respectively. Structure **18** and **17** can be made of micro polished stainless steel or other highly reflective and non-tarnishable material. The high reflectivity will prevent meltdown of the material in the event of misguided concentrated solar energy **57**, and high temperature radiant energies within the structures. The purified water **16** flowing within the structure will also absorb energy by thermal conduction.

The purified water flows upward between the "one way mirrored glass windows" **19** and **20**. Windows **19** and **20** act as a one way mirror. Concentrated solar energy **57** can pass from the outside into the radiant energy capture system **16-25, 58-67,** however radiant energy within this structure is reflected back into the structure. The material used in the windows **19** and **20** is quartz glass. Ordinary window glass is a very effective blocker of ultra violet radiation, whereas quartz glass is much more transparent to ultraviolet radiation. A great deal of energy exists in the ultra violet spectrum and is therefore desirable to be captured. The purified water **16** also flows upward between the outer and inner windows **19** and **20** respectively. This water keeps the glass cool while absorbing energy from thermal conduction, thermal radiation, and even a very small percentage of the energy absorbed from the concentrated solar energy **57**. Even if 1% of the concentrated solar radiation is absorbed by the windows **19** and **20**, and by the purified water **16**, that would represent one million watts of energy on a one hundred mega watt station. This amount of energy would melt structures, however the water flow **16** within the structure absorbs this energy and utilizes it to add energy to the process instead of simply wasting it. **FIG. 4** also shows the

construction struts consisting of inner strut **59**, outer strut **58**, and center strut **60** which are detailed in **FIG. 5** and **FIG. 6.** These construction struts form part of the radiant energy capture unit **16-25**, **58-67** structure and act to hold and join the one way mirrored glass pains **19** and **20** together.

FIG. 5 shows a top down view detail of the one way window and strut design of the radiant energy capture unit. The flat quartz glass one way mirrored glass pains **19** and **20** are joined with silicon rubber seals **61**. These seals may be made of any material which can form a water tight seal, withstand hot water temperatures, and afford some pliability so small movements may occur due to thermal expansion and contraction. Center strut **60** is a spacer strut which holds the outer glass pain **19** and inner glass pain **20** apart. Strut **60** remains cool since water is present on both sides of the strut.

Outer strut **58** is shaped so that incident concentrated solar energy hitting it is reflected into the radiant energy capture unit **16-25**, **58-67** and onto target **37**. The struts shape is long and pointy so that incident angles of the concentrated solar energy **57** is reflected at a low reflective angle and therefore enters the radiant energy capture unit **16-25**, **58-67**. A shorter strut with less angle would result is the concentrated solar energy **57** being reflected away from the radiant energy capture unit **16-25**, **58-67**. This strut may be constructed of micro polished stainless steel or other material which is highly reflective and a thermal conductor. Chrome plating of the strut would make it highly reflective. Inner cooling channel **63** within the

strut **58** allows water to pass through it to keep it cool. Water moves from the bottom of the strut to the top of the strut by thermal convection. The hotter the strut becomes, the more water passes through it. The inner cooling channel **63** within strut **58** may be of any shape and may even contour to the general outside shape of the strut. This contouring could provide better cooling to the strut.

Inner strut **59** is shaped so that radiant energy from the target **37** is reflected back to target **37** within the radiant energy capture unit **16-25**, **58-67**. This strut may be constructed of micro polished stainless steel or other material which is highly reflective and a thermal conductor. Chrome plating of the strut would make it highly reflective. Inner cooling channel **66** within the strut **59** allows water to pass through it to keep it cool. Water moves from the bottom of the strut to the top of the strut by thermal convection. The hotter the strut becomes, the more water passes through it. The inner cooling channel **66** within strut **59** may be of any shape and may even contour to the general outside shape of the strut. This contouring could provide better cooling to the strut.

FIG. 6 shows the side view detail of the one way window and strut design of the radiant energy capture unit **16-25**, **58-67**. The flat quartz glass one way mirrored glass pains **19** and **20** are sandwiched between outer strut **58**, middle strut **60**, and inner strut **59**. Center strut **60** is a spacer strut which holds the outer glass pain **19** and inner glass pain **20** apart. Strut **60** remains cool since water is present on both sides of the strut.

The water cooling channel **63** can be seen on outer strut **58**. Water is drawn by thermal convection through port **62**, is then moved up channel **63** within strut **58** by thermal convection, and finally exit at port **64**. In like manner, cooling water is pulled into the inner strut **59** through port **65**. The water then moves up channel **66** within inner strut **59** by thermal convection and finally exits port **67**.

FIG. 7 shows the top down view of the solar hydrogen tower with the top dome removed. The center support structure **23**, reactor core section **40**, and solar target **37** are visible in the center. Surrounding this reactor assembly is one embodiment of the one way window and strut design based on flat glass components. Outer "one way quartz glass mirrors" **19** surrounds the outer perimeter of the radiant energy capture unit **16-25**, **58-67**. Inner "one way quartz glass mirrors" **20** are also visible. The outer struts **58**, inner struts **59**, and center struts **60** are also visible. The number of these struts may vary depending on the design and size of the radiant energy capture unit **16-25**, **58-67**. Concentrated solar energy **57** comes in from all sides to heat the reactor core target **37** evenly on all sides.

FIG. 8 shows the same view as **FIG. 7**, but shows another embodiment of the glass structures in which struts are not required and the tapered one way mirrored glass cones **19** and **20** form the structural members as well as the radiant energy capture windows. This embodiment simplifies the complexity by not requiring the unique strut design as shown in **FIG. 7**. The outer tapered one way

mirrored quartz glass cone **19** allows concentrated solar energy **57** to enter. The concentrated solar energy **57** then passes through the cooling water stream **16** and then through the inner tapered one way mirrored quartz glass cone **20**. The water stream **16** sandwiched between outer cone **19** and inner cone **20**, keeps the outer cone **19** and inner cone **20** cool. Any energy absorbed by the outer cone **19**, or inner cone **20**, or water stream **16**, is added to the process in the form of preheating the water for further downstream processing.

FIG. 9 shows the helical channel **30** which represents the path that the water and its products take within the heat exchanger of **FIG. 10**. The helix is basically the shape of a spring. **FIG. 9** shows a rectangular or square structure to the helix; however, any cross sectional shape is possible such as circular, elliptical or other.

FIG. 10 shows the preferred embodiment of the high temperature heat exchanger **29** which has the helical water feed channel **30** helixing up the heat exchanger **29** multiple helix structure. The helix results in a large thermal transfer area in a small volume of space. The helix also causes centrifugal force, forcing the water and steam to press against the outer walls of in-feed helix **30**. The force of the water and steam pressing against the inside of in-feed helix **30** greatly increases the thermal transfer of heat from the thermally conductive material **68** which forms the helix material. Traditional methods of thermally transferring heat to steam was with a thermal hotplate. This however is an ineffective means of thermally transferring heat in that it relies primarily on molecular motion of the water or

steam to effect heat transfer.

The out-flow smaller helixes **41** and **42** feeds the products of oxygen and hydrogen down the helixes in an opposite direction to the in-flow water and steam of helical cannel **30**. These out-flow helixes **41** and **42** are adjacent and effectively parallel to the in-feed helix **30**. Four oxygen out-flow helixes **41** and four hydrogen out-flow helixes **42** are shown in **FIG. 10**. These helixes are in parallel to each other. The number of out-flow helixes is not critical; however, a larger number would be preferable to effectively act as thermal transfer conduits of the higher volume of exhaust gases of oxygen in out-flow helix **41** and hydrogen in the out-flow helix **42**. The larger number of out-flow helixes **41** and **42**, the better the thermal transfer. The inside surfaces of the in-flow helix **30**, and outflow helixes **41** and **42** do not necessarily have to have be square, circular, or rectangular shapes. The cross sectional shapes of in-flow helix **30** and out-flow helixes **41** and **42** can be such that the surface area is significantly increased as is shown in **FIG. 10A**, **10B**, **10C**, and **10D**. This increased surface area results in more effective thermal transfer to the thermally conductive material **68**. The opposing flows of helix **30** to helixes **41** and **42** results in close to 100% thermal energy transfer.

Material **68** can be any thermally conductive material which can withstand the high temperatures required in heat exchanger **29**. Typical materials can include thermally conductive ceramics such as oxides of zirconia and many others. The material **69** shown in **FIG. 10** is a thermally insulative material which is able to

withstand the high temperatures required for the high temperature heat exchanger **29**. Typical insulating material may include oxides of aluminum, or any other material suitable for this application. The thermal insulating material **69** prevents thermal short circuits of the adjacent coils of the thermally conductive material **68** of the helix structure. An analogy to this is an electric motor in which the coils of wire within the motor have a layer of insulation on it. If this insulation did not exist, then there would be electrical short circuits between the various coils of wire within the motor. In similar fashion, material **69** forms a thermal insulating barrier to prevent thermal short circuits in helix material **68**.

One means of manufacturing the high temperature heat exchanger **29** is by a process called investment casting. The internal hollow shapes of high temperature heat exchanger **29** are constructed of machinable wax. The materials for constructing the high temperature heat exchanger **29** are poured around these wax shapes. The ceramic material can be available as a powder which mixes with a liquid binder material forming a slurry with the consistency of wet concrete. The material is layered together to form alternate layers of conductive material **68** and insulating material **69**. Since the machinable wax material could not support its own weight for the entire length of the helix, it would be constructed in stages. It is however, necessary to assemble the unit **29** quickly enough so that the ceramics are still in the green state. This is required so that the material **68** and **69** will fuse together when later sintered. After the entire structure is assembled which would not only include the high temperature heat exchanger **29**, but all the other components of the reactor as well, then the ceramic material would be allowed to

harden. After hardening, the structure would be heated to allow the internal wax shapes to melt out. The design of the entire shape would be such that the wax would flow out without any pockets of wax pooling in any of the structure. Once the wax is melted out, then the entire structure would be sintered.

An alternative method of manufacturing is to use "light cured liquid polymers" in which a three dimensional (3D) model of the entire structure is in a computer. The computer program would slice the 3D model layer by layer, and using a LASER, trace the pattern of that layer within the polymer. The LASER light would cause that layer of polymer to harden. Layer upon layer of hardened polymer would build the shape of the total internal hollow structures within the entire ceramic structure. The ceramics would then be poured in the appropriate layers around the entire hardened polymer structure. Once the ceramics hardened, then the polymer would be melted out of the structure, and the remaining ceramics would be sintered.

Another alternative method of manufacturing would be to machine solid blocks of the ceramic material. Specialized machining tools would be required. One tool for example would consist of a miniature machining robot which would cut out the helixes. This robot would grind away the ceramics and grab the sides of the hollowed out structure to provide a means of support while it steered its way along the helix. In this way various sections of the entire ceramic structure would be built in sections. The sections would later be adhered together with a high temperature cement to form the entire structure.

FIG. 10A, **10B**, **10C** and **10D** show various alternative shapes of the internal structures of helixes **30**, **41** and **42** of **FIG. 10**. These shapes are a way to effectively increase the surface area of the internal structures and therefore increase thermal transfer to and from the fluids flowing through these structures. The tooth shaped protrusions are wider near the walls of the fluid flow channel such as helical channel **30** in **FIG. 10B** and narrows as it protrudes towards the center of the channel. The wider base provides more thermal transfer material in a similar way that heat sinks are designed for cooling electronic equipment. These protrusions may have further protrusions on them to further increase its surface area as is detailed in **FIG. 10D**.

These various alternative shapes of the structures for helixes can be used in the helixes **30**, **41** and **42** of the high temperature heat exchanger in **FIG. 10.** These shapes can also be used in helix **31** of the 1st stage solar reactor of **FIG. 18**, and helix **35** of the 2nd stage solar reactor of **FIG. 20**.

FIG. 11 shows a detail of another embodiment of the high temperature heat exchanger **29** in **FIG. 10**. A section of the helix of **FIG. 10** is shown in **FIG. 11** in which thermal breaks are evident along the path of the helix. These thermal breaks consist of thermally insulating materials **70** which could be the same material **69** of **FIG. 10**.

FIG. 12 shows a line path representation of the preferred embodiment of the

FIG. 10 high temperature heat exchanger **29**. The wavy lines represent the helixes as shown in high temperature heat exchanger **29**, with the center line being the water in-feed channel **30** feeding up, and the four lines on each side being the hydrogen channel **42** and oxygen channel **41** feeding down. This arrangement is a parallel helix arrangement. This line path representation of the parallel helix is to provide a reference when discussing other embodiments in **FIG. 13** and **FIG. 14**, of the high temperature heat exchanger **29** of **FIG. 10**.

FIG. 13 shows another embodiment of the high temperature heat exchanger of **FIG. 10** in which a double helix consisting of out-feed hydrogen channel **42** and out-feed oxygen channel **41**, helix around the water in-feed helix **30**, forming a compound helix. In this embodiment the volume of out-flow gases of hydrogen and oxygen is larger than the in-flow water and steam, without having to parallel channels as is done in **FIG. 12**.

FIG. 14 shows another embodiment of the high temperature heat exchanger of **FIG. 10** in which a triple helix exists. This triple helix, helixes around the exchanger, forming a compound helix. Another variation of these is to have non-compounded triple helix arrangements in parallel to each other, which are similar in arrangement to the 3rd stage solar reactors **36** of **FIG. 26**. These smaller helixes would result in more centrifugal force. Smaller helixes could also be used in other embodiments of the high temperature heat exchanger **29** of **FIG. 10**, the 1st stage solar reactor **32** of **FIG. 18**, and the 2nd stage solar reactor **34** of **FIG. 20**.

Other embodiments may be possible.

FIG. 15 shows a top down view of another embodiment of the high temperature heat exchanger **29** of **FIG. 10** in which the thermal transfer channels are on one flat layer as opposed to being helical. The primary advantage of this embodiment is in manufacturing ease if machining the channels in solid ceramic material, since the machining is done on a flat surface instead of complex internal 3D shapes. In this embodiment of the high temperature heat exchanger, thermally conductive material **68** forms a disk in which the fluid channels are machined. A thermal break **70** which can consist of thermally insulating material, or an air gap, prevents a thermal short circuit within the high temperature heat exchanger disk. Water and steam in-feed channel **30** is placed between oxygen out-feed channel **41** and hydrogen out-feed channel **42**. The water and steam in channel **30** flows in the opposite direction of the oxygen and hydrogen in channels **41** and **42**. This opposing flow causes nearly 100% heat exchange. A number of these high temperature heat exchange disks are connected in series as shown in the side view of **FIG. 16**.

FIG. 16 shows a side view of **FIG. 15** which is another embodiment of the high temperature heat exchanger **29** of **FIG. 10**. Each heat exchange layer consisting of thermally conductive material **68** is connected to another layer by the same high temperature material in channel **30**, **41** and **42**. Each layer is separated by a thermal break layer consisting of thermally insulating material **69** thus

preventing a thermal short circuit.

FIG. 17 shows the helical channel **31** within the 1st stage solar reactor shown in **FIG. 18**. This helical channel is similar to the helical channel **30** of the high temperature heat exchanger **29** of **FIG. 10**. Variations of this helical channel **31** can have the same variations as shown in **FIG. 10A**, **10B**, **10C**, and **10D**.

FIG. 18 shows a cutaway view of the 1st stage solar reactor **32**. The entire structure is made of the same thermally conductive material because thermal short circuits are not a concern. The superheated steam from the high temperature heat exchanger **29** of **FIG. 10** enters the bottom of the 1st stage solar reactor **32**. The steam helixes up channel **31**. The centrifugal force of the helical motion of the steam causes it to press against the outer walls of channel **31**, and therefore increases the thermal transfer efficiency of heat from the thermally conductive material of which the 1st stage reactor is made. This could be the same material as the thermally conductive material **68** of high temperature heat exchanger **29** of **FIG. 10**. The steam is also under pressure to further increase its thermal transfer efficiency. This pressure is maintained by the orifice **33** of **FIG. 1** and **FIG. 2**, and pressurization pump **27** of **FIG. 1** and **FIG. 2**. High temperature gas exit channels **38** and **39** of **FIG. 18** are for the out-flow gases of hydrogen and oxygen respectively from further along in the process.

FIG. 19 shows the helical path **35** within the 2nd stage solar reactor shown in

FIG. 20. This helical channel is similar to the helical channel **31** of **FIG. 18**, and the helical channel **30** of the high temperature heat exchanger **29** of **FIG. 10**. Variations of this helical channel **35** can have the same variations as shown in **FIG. 10A**, **10B**, **10C**, and **10D**. In another embodiment of the 2nd stage reactor **34**, the helical channel **35** can also have a catalyst material placed within the steam flow channel **35**. This catalyst will have the effect of causing the steam to disassociate at lower temperatures. Platinum, platinum group or other catalyst alloys are possible.

FIG. 20 shows a cutaway view of the 2nd stage solar reactor. Helical channel **35** can be seen going up near the outside edge of the thermally conductive reactor material. Since the concentrated solar energy **57** of **FIG. 2** bombards the outer edge of the reactor cores **32**, **34** and **36** of **FIG. 2**, it is desirable to have the helix near the outer edge as can be seen in 1st stage reactor of **FIG. 18** and the 2nd stage reactor of **FIG. 20**.

The superheated steam from the 1st stage solar reactor **32** of **FIG. 18** enters the bottom of the 2nd stage solar reactor **34** after passing through orifice **33** of **FIG. 1** and **FIG. 2**. The steam helixes up channel **35** of the 2nd stage solar reactor. The centrifugal force of the helical motion of the steam causes it to press against the outer walls of channel **35** and therefore increases the thermal transfer efficiency of heat from the thermally conductive material of which the 2nd stage reactor is made of. This could be the same material as the thermally conductive material **68** of high temperature heat exchanger **29** of **FIG. 10**. The steam is also under partial vacuum

which lowers the equilibrium temperatures and causes rapid thermal absorption due to active pressure reduction, similar to a refrigerators evaporator coil. This partial vacuum is maintained by the orifice **33** of **FIG. 1** and **FIG. 2** and process balancing pumps **49** and **52** of **FIG. 1** and **FIG. 2**. The introduction of catalyst material within channel **35** of the 2nd stage solar reactor **34** of **FIG. 20** further lowers the equilibrium temperature.

High temperature gas exit channels **38** and **39** of **FIG. 20** are for the out-flow gases of hydrogen and oxygen respectively from further along in the process.

FIG. 21 shows the pictorial view of the outside of the vortex tube **71** of the 3rd stage solar reactor **36**. Also visible from this outside view are the vortex spin nozzle **72** and oxygen spill gate **76**. **FIG. 22**, **FIG. 23**, and **FIG. 24** show cross sectional views of this vortex tube.

FIG. 22 shows a cross sectional side view of the vortex tube **71** within the 3rd stage solar reactor **36** with the in-feed manifold **74**. The equilibrium mixture of partially disassociated steam from the 2nd stage solar reactor channel **35** of **FIG. 20**, enters the manifold **74**. The manifold directs the equilibrium mixture, primarily consisting of steam (but also with hydrogen, oxygen and hydroxyl's), to vortex spin nozzle **72** in which injector paths **73** injects the steam on a tangent into the vortex tube **71**. This steam **75** vortexes or helixes around the inside of vortex tube **71** and exits at the oxygen spill gate **76**. Further details of the processes within the vortex

tube will be explained in **FIG. 25**.

FIG. 23 shows the end view detail of one embodiment of an injector nozzle of the vortex tube's 3rd stage solar reactor. **FIG. 23** shows injector nozzle **72** with one injector port **73**. In this particular drawing, the steam entering through injector port **73**, spins around the inside of the vortex tube **72** in a counter clockwise direction. It is possible to modify the design for a clockwise direction spin. The direction of rotation is not a factor in the overall embodiment of the invention. The steam migrates down the inside **75** of the vortex tube **71** of **FIG. 22**.

FIG. 24 shows the detailed view of another embodiment of the vortex tube 3rd stage reactor showing more than one injector **73** and showing the in-feed manifold **74**. Experimental testing has shown that the number of injectors does not affect the operation of the vortex tube except to increase the amount of steam which can pass through the tube. Vortex tube designs have been tested and verified experimentally from 1 to 8 injectors. The amount of steam flow is increased nearly proportionately to the number of injectors.

FIG. 25 shows the preferred embodiment of the detailed construction of the 3rd stage solar reactor **36** of **FIG. 2** which incorporates the vortex tube. The materials used in the 3rd stage solar reactor of **FIG. 25** are all the same materials consisting of high temperature thermally conductive ceramics or other materials capable of handling high temperatures. These are the same materials as are used in

other sections of the invention such as the 1st and 2nd stage solar reactors of **FIG. 18** and **FIG. 20** respectively and portions of the high temperature heat exchanger **29** as shown in **FIG. 10**.

Different shading is shown in **FIG. 25** to make visibly apparent, the vortex tube and its components within the 3rd stage solar reactor, even though the same material is used throughout.

The equilibrium mixture of partially disassociated steam from the 2nd stage solar reactor channel **35** of **FIG. 20** enters the manifold **74** of **FIG. 25**. The manifold directs the equilibrium mixture, primarily consisting of steam (but also with hydrogen, oxygen and hydroxyl's), to the vortex spin nozzle **72** in which injector paths **73** injects the steam on a tangent into the vortex tube **71**. This steam **75** vortexes or helixes around the vortex tube **71** and exits at the oxygen spill gate **76**. While this steam is propagating from the injector nozzles **73** to the oxygen spill gate **76**, it does so in a helical or vortex fashion. This vortex action causes centrifugal force on the equilibrium mixture **75**. This centrifugal force causes the equilibrium mixture to stratify with the heavier components of oxygen migrating to the outside circumference of the vortex tube **71**, while the lighter products of hydrogen migrate towards the center of the vortex tube **71**.

Hollow draw tube **77** draws off the hydrogen through small holes throughout its length except for section **79** of the draw tube. The hydrogen is then drawn out

through high temperature pipe **38**. Section **79** of draw tube **77** prevents the oxygen concentration near the oxygen spill gate **76** from being drawn into the draw tube **77**. The removal of hydrogen causes the equilibrium mixture to upset, forcing more steam and hydroxyl's to disassociate into more hydrogen and oxygen in order to maintain an equilibrium balance at temperature. Concentrated solar energy **57** of **FIG. 2** is thermally conducted and radiated from the target **37** to the 3rd stage solar reactor **36**. The outside surface of the 3rd stage solar reactor **36** surrounds the vortex tube **71** as can be seen in **FIG. 25**. A continual supply of thermal energy is required in the 3rd stage solar reactor of **FIG. 25** because the continuous disassociation of steam into hydrogen and oxygen requires a continuous supply of energy. Although much of the energy is provided in the 1st and 2nd stage solar hydrogen reactors, a further boost is provided in the 3rd stage solar reactor.

This equilibrium upset in the 3rd stage solar reactor causes a much higher percentage of disassociation than would otherwise be achievable and therefore reduces the amount of recycle and therefore reduces the amount of lost energy in the system. This also increases the throughput of the system as a result of less recycle.

The oxygen concentration which is left in the vortex tube **71** of **FIG. 25** spills over the oxygen spill gate **76**. The angle of the spill gate exit is such that it follows the natural flow which the exit gases want to take. The exit angle of the oxygen spill gate is accurately shown in **FIG. 25** as has been experimentally determined. Other angles will work as well. The oxygen which is spilled over the

oxygen spill gate **76** is drawn into chamber **80**. Chamber **80** is shaped so not to interfere with the transitional flow of the oxygen from the oxygen spill gate **76** to the high temperature oxygen exit pipe **39**. Chamber **80** prevents flow disruption which would otherwise impede the vortex within the vortex tube **71**.

In another embodiment of the vortex tube **71**, a catalyst material **78** can be placed within the equilibrium mixture **75** flow which would cause lower temperature disassociation of the steam. In this particular case the airflow must not be disturbed by the catalyst structure **78** otherwise the stratification would be disrupted and separation impeded. In this embodiment the catalyst material is deposited on a ceramic structure which helixes in the same path as the steam flow **75** through the vortex tube **71**. In this way the steam flow is unaffected and stratification remains unimpeded.

The partial vacuums created by the process balancing pumps **49** and **52** of **FIG. 1** and **FIG. 2** result in lower temperatures being required to obtain the same level of equilibrium concentrations of steam, hydrogen, oxygen and hydroxyl's. Any un-reacted hydroxyl's later recombine with oxygen or hydrogen to form water during the cooling process in the high temperature heat exchanger of **FIG. 10**.

FIG. 25A shows another embodiment of the 3rd stage solar reactor in which an oxygen draw tube **85** is placed in the vortex tube **71**. Oxygen is removed from the periphery of the vortex tube **71**. Upset equilibrium can occur with the removal

of either or both of hydrogen and oxygen.

FIG. 26 shows a cutaway view of a plurality of vortex tube assemblies within the 3rd stage solar reactor **36** and mounted on top of the 2nd stage solar reactor **34**. **FIG. 26** illustrates eight 3rd stage solar reactors mounted within the cylindrical shape on top of the 2nd stage solar reactor. The relatively small inside diameter of the vortex tubes within the 3rd stage solar reactors **36** produce significantly high centrifugal force to stratify the equilibrium mixture (steam). It has been found with laboratory testing that the smaller diameter vortex tubes generate significantly higher centrifugal force for the same volume of product steam compared to larger diameter vortex tubes; however, it has also been found that stratification is very poor with small diameter vortex tubes. A skin effect resulting from air friction drag along the surface of the tube introduces turbulence and mixing therefore impeding stratification. It has been found in the lab that larger diameter vortex tubes offer superior stratification. It has also been found in the lab that angular velocities of the steam in the vortex tube can be far less than molecular velocity of the steam when used in larger diameter vortex tubes. Effective stratification still occurs because even though the molecular velocities are higher, the molecules are bouncing into each other and do not have a free flight path over the distance of the radius of the vortex tube.

FIG. 27, 28, 29 shows another embodiment of the 3rd stage solar reactor **36** positioned in relation to the 2nd stage solar reactor helix **35**. In this embodiment a much smaller diameter helix causes a significantly higher centrifugal force. The

equilibrium mixture of steam, hydrogen, oxygen, and hydroxyl's (steam) stratify as the steam propagates along the helix. As the steam mixture nears the end of the first helix, a set of knives cuts the flow, removing the hydrogen concentration from the inside radius through exit port **38**, while the oxygen concentration is removed from the outer radius through exit port **39** as can be seen in **FIG. 29** which is the top view of this embodiment.

The intermediate products of steam continue to the next stage as can be seen in **FIG. 27** and closeup view **FIG. 28** of the 3rd stage solar reactor. Three stages are shown in this embodiment; however, more or less can be implemented. **FIG. 28** shows that each stage is of lesser diameter than the stage before it. This is because there is less steam and to maintain the velocities within the helix for effective separation, a smaller radius is required.

FIG. 28 shows a close up side view of another embodiment of the 3rd stage solar reactor shown in **FIG. 27**.

FIG. 29 shows a top down view of the embodiment as described in **FIG. 28**.

FIG. 30 shows another embodiment of the 3rd stage solar reactor. In this embodiment, the more effective vortex tube is used. As the equilibrium mixture of steam, hydrogen, oxygen, and hydroxyl's migrate down the vortex tube **71** of the 3rd

stage reactor **36**, from the vortex nozzle **72** toward the hydrogen exit port **38** and oxygen exit port **39**, stratification occurs. Circular knives within the vortex flow cut the product of hydrogen from the inside diameter of the flow and exit it through hydrogen exit **38**, while the heavier oxygen which has stratified to the outside of the vortex tube is cut and exits through the oxygen exit port **39**. The intermediate products of steam and hydroxyl's migrate to the second stage vortex tube which is of smaller diameter since less steam is present and sufficient centrifugal force is required to stratify the steam as it further disassociates into its constituent components. Any number of stages can be used.

FIG. 31 shows the side view of a typical solar hydrogen station which would be geographically located in the latitudes not far from the equator, where the sun is high in the sky. The mirrors **81** track the sun and focus the solar radiation **57** towards the solar reactor dome at the top of tower **56**.

FIG. 32 shows the top down view of **FIG 31.** Computer steered mirrors **81** track the sun to focus solar radiation to the top of tower **56**. The mirrors are placed all around the tower.

FIG. 33 shows the side view of a typical solar hydrogen station which would be geographically located in the latitudes far from the equator, where the angle of the sun is low on the horizon. The computer steered mirrors would be north of the tower in northern latitudes and south of the tower in southern latitudes. Some of the solar radiation **57** from the mirrors **81** are steered towards mirror **82**. Mirror **82**

reflects the solar radiation **57** to the part of the tower **56** which would otherwise not receive solar radiation **57**. Mirror **82** is shaped to focus the light into the top of tower **56**. The amount of solar radiation reflecting off of mirror **82** would be very concentrated. For this reason mirror **82** would be water cooled. The heated water from cooling mirror **82** would be used as a preheat to the process.

FIG. 34 shows the top down view of **FIG. 33** and shows the special curvature required on mirror **82** to reflect the concentrated solar energy **57** to the dark side of the tower **56**.

FIG. 35 shows a small scale solar hydrogen station which uses a specially shaped reflective dish and tracks the sun directly. In this scenario, the size of the shadow cast by the tower **56** dome is significant in relation to the size of the collection area mirror **83**. A mirrored cone reflector **84** is placed at the top of the dome of tower **56**. Cone reflector **84** reflects solar energy **57** so it does not hit the dome, but is reflected to the specially contoured edge of mirror **83**. The edge contours of mirror **83** reflect this solar energy **57** into the dome at the top of the tower **56**.

Although the application shown in this invention are for the use of solar energy to disassociate water into hydrogen and oxygen, other sources of heat may be used. These include waste heat from power stations. In this case the level of heat is relatively low, but can be used as a heat boost in which further heat is added

to the process. In the case of nuclear energy, or fossil fuel, the waste heat from cooling towers or condensers would preheat the water to a certain temperature. Further heat could be applied electrically. Geothermal would be non-polluting source of heat which could be used. The benefit of solar energy is that there is an abundance of it. About 18,000 times more energy bombards the planet than mankind currently uses.

The radiant energy capture unit also has application in solar distillation processes, and solar heated boiler systems used to generate steam for heating and for turbine use, especially in solar turbine electric systems.

What is claimed is:

1. A process for dissociating water into oxygen and hydrogen comprising:

heating water vapor to a temperature of between about 1800°C and about 3000°C to form a dissociated water reaction mixture comprising hydrogen gas and oxygen gas;

subjected the dissociated water reaction mixture to a high gravity field due to high swirl velocity in a vortex tube reactor such that there is stratification of the hydrogen gas and the oxygen gas in the dissociated water reaction mixture; and,

preferentially extracting hydrogen gas from the vortex tube reactor.

2. The process of claim 1 wherein the water vapour is heated in a reactor having heated walls wherein the water vapour is subjected to a high gravity field due to high swirl velocity in the reactor so that centrifugal force urges the water vapour into contact with the heated walls.

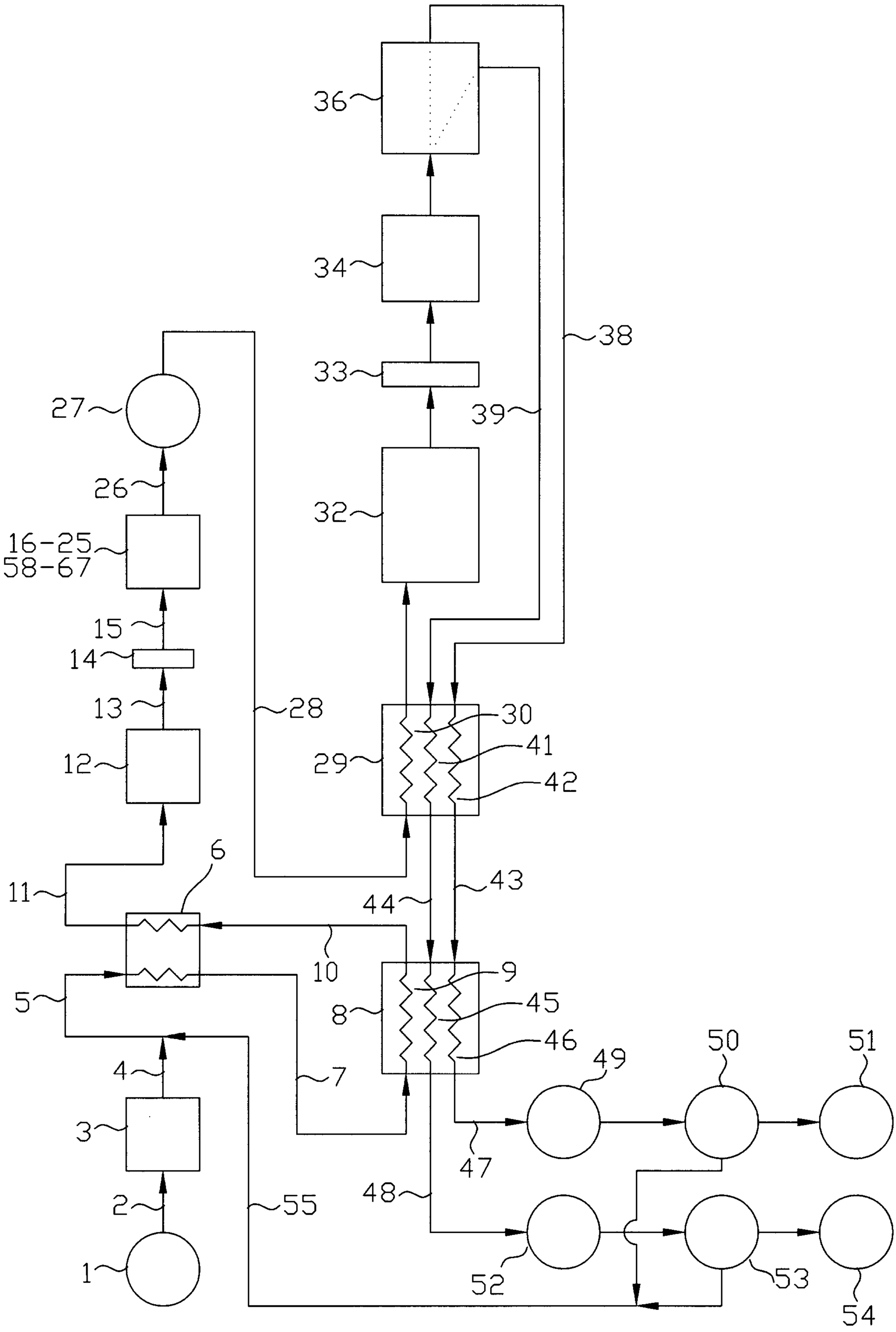

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Fig. 1

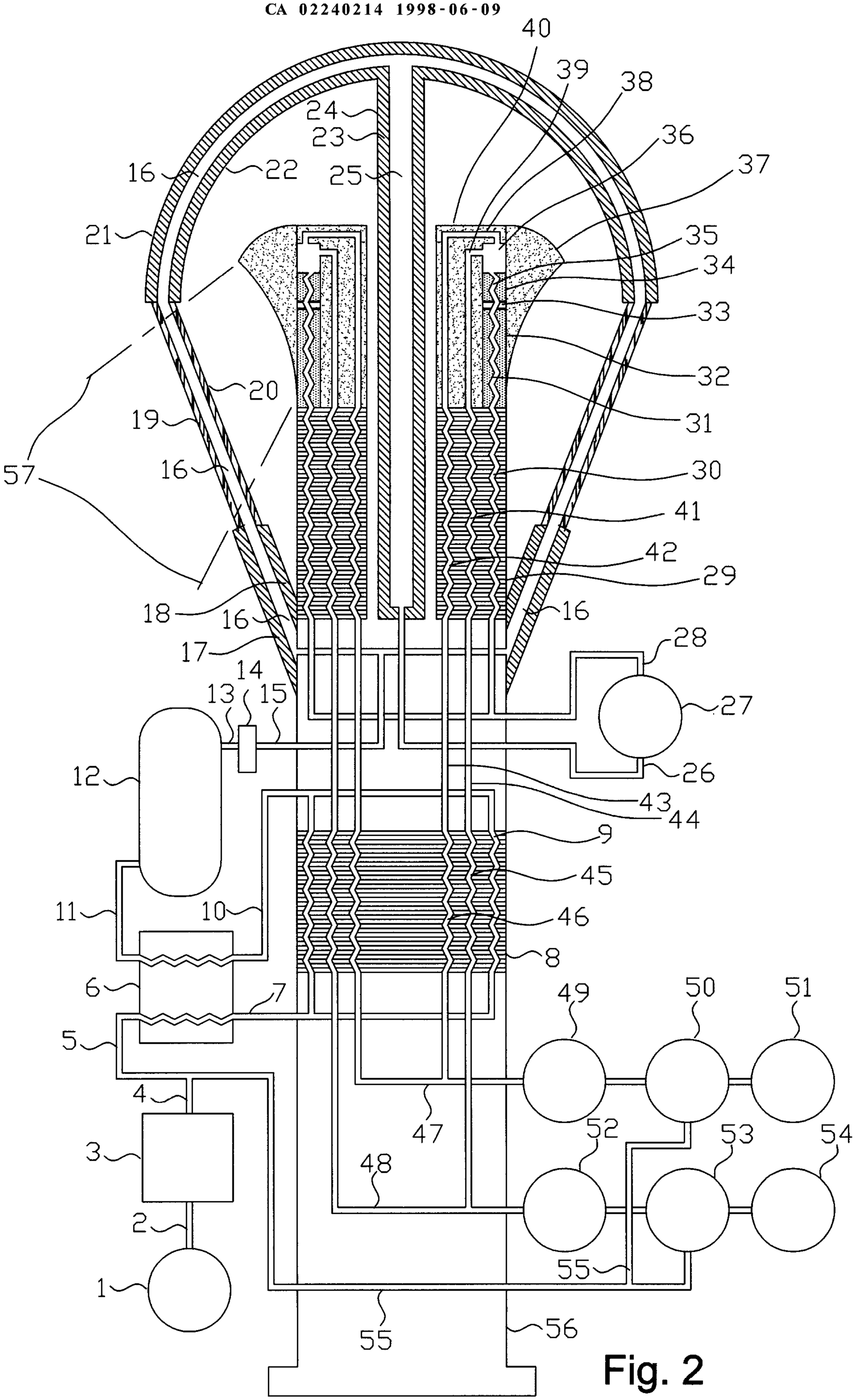
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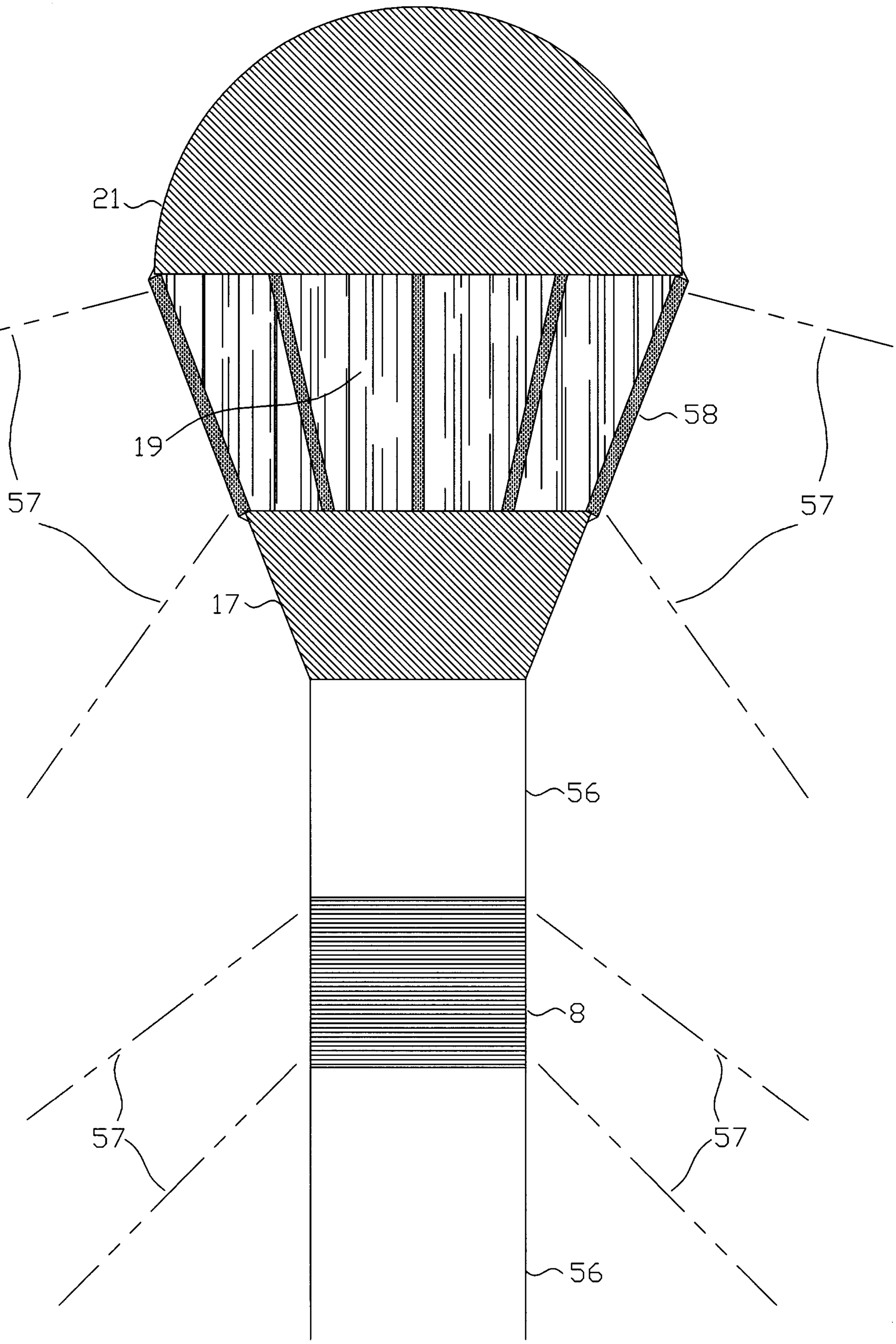
Fig. 2



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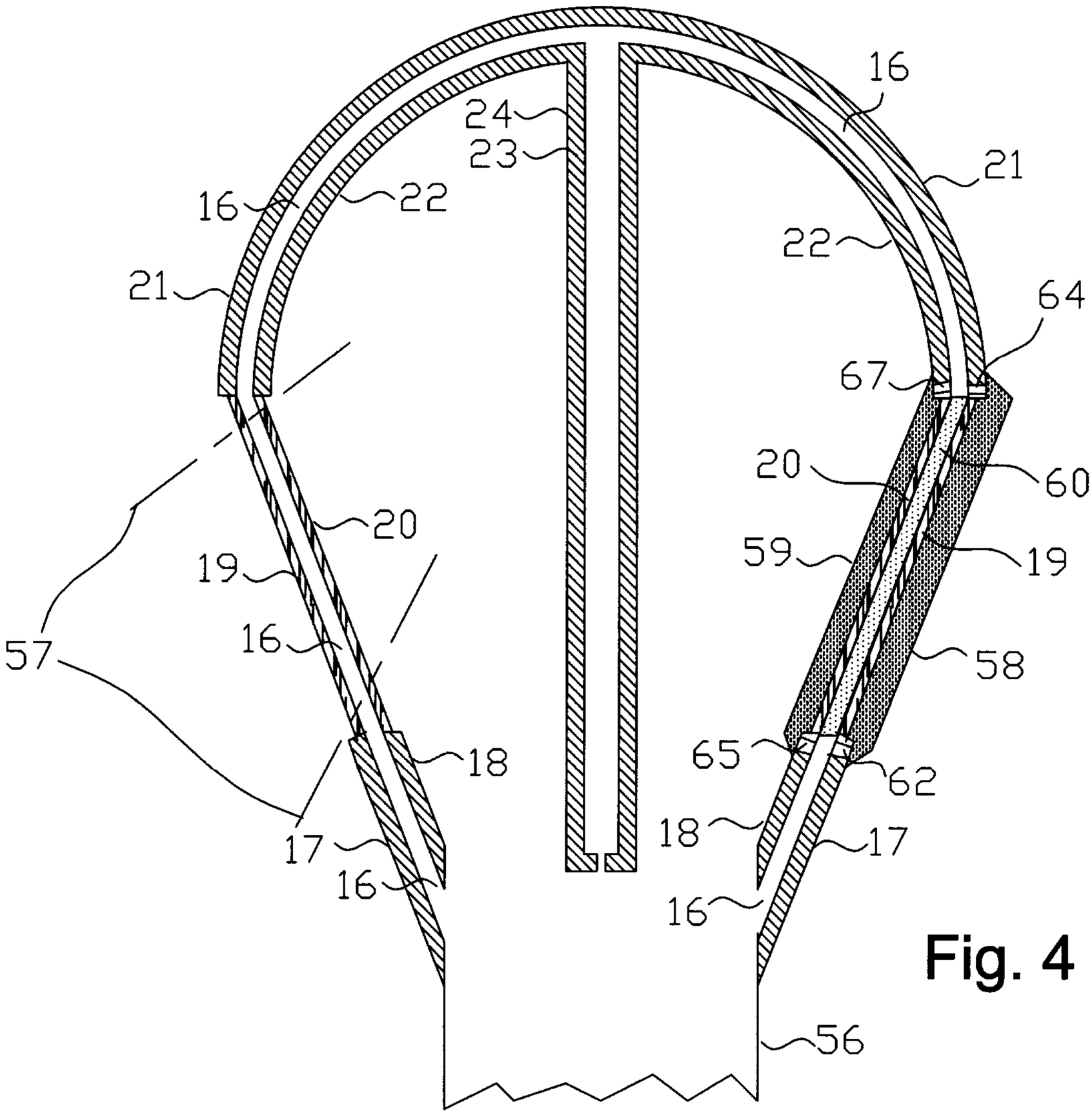

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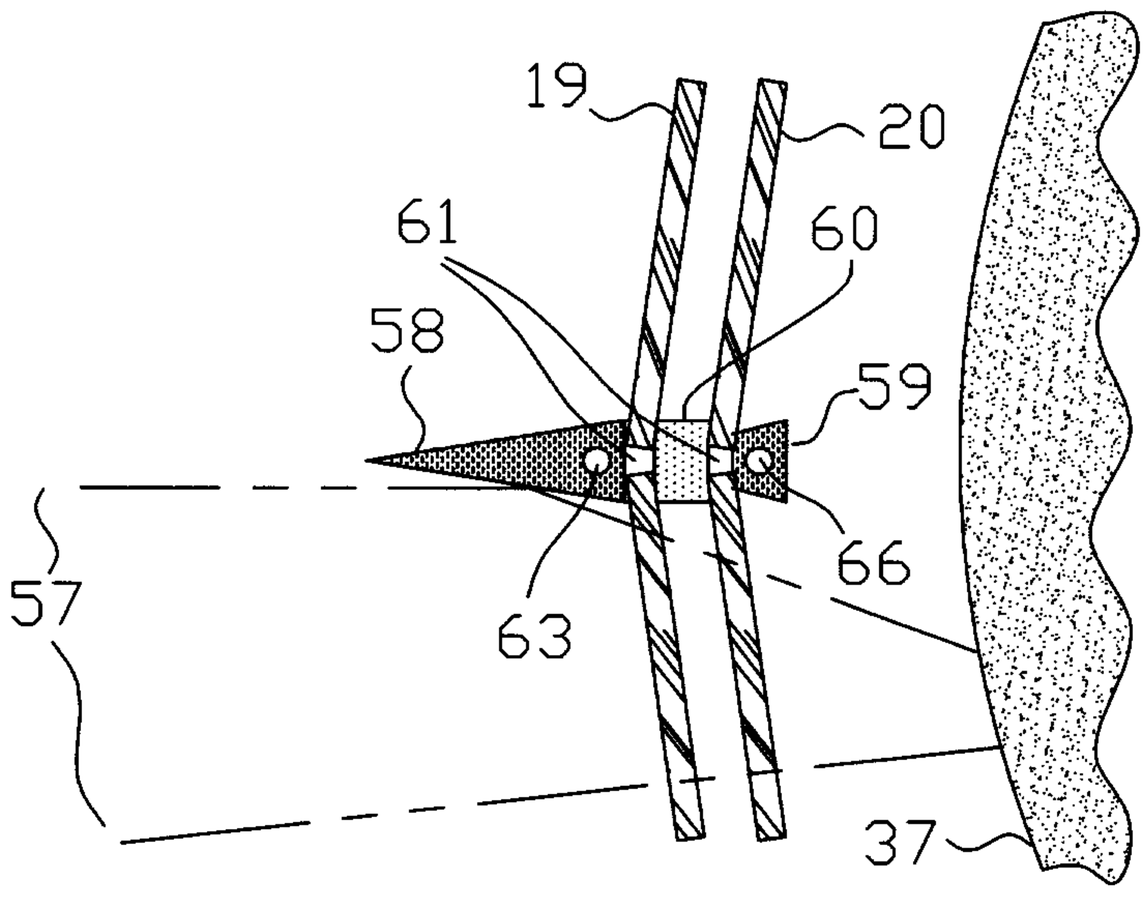

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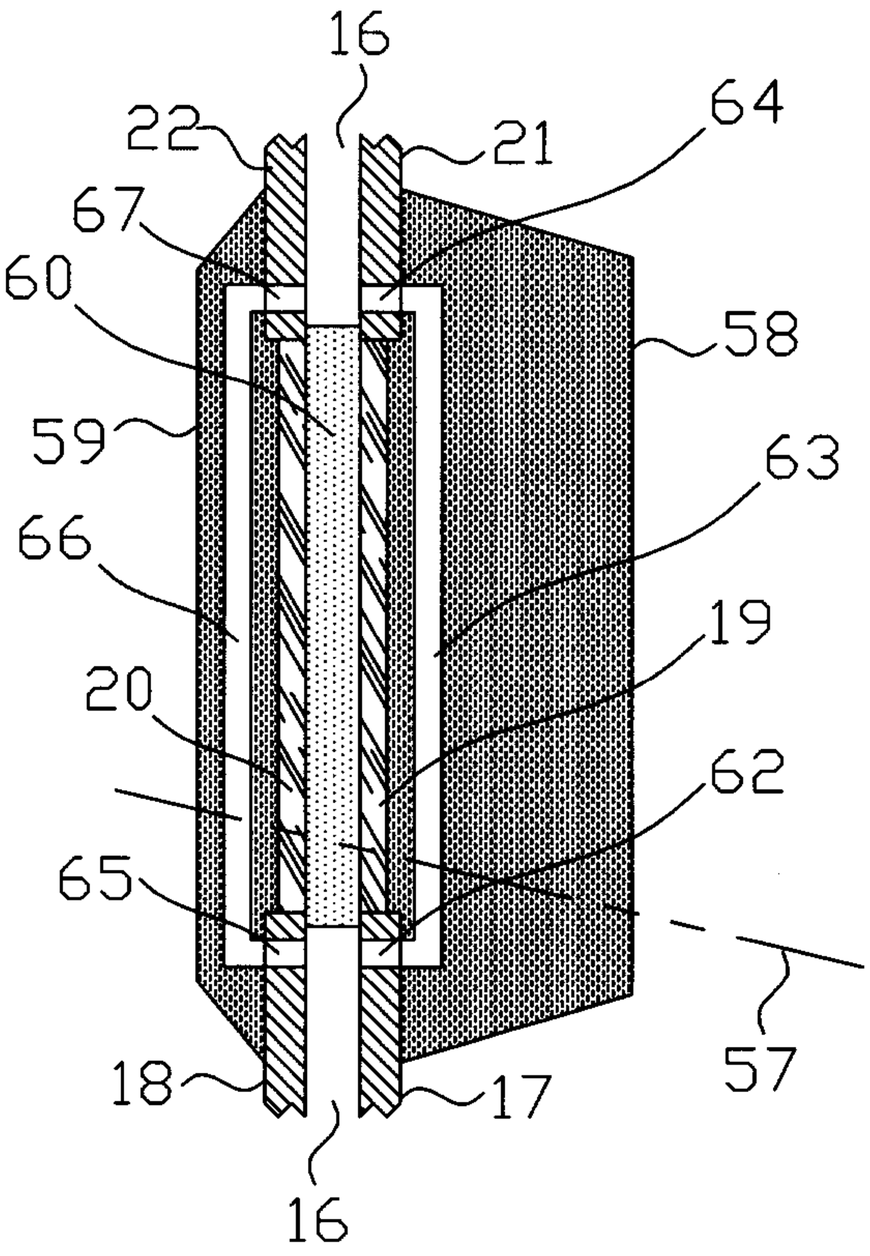

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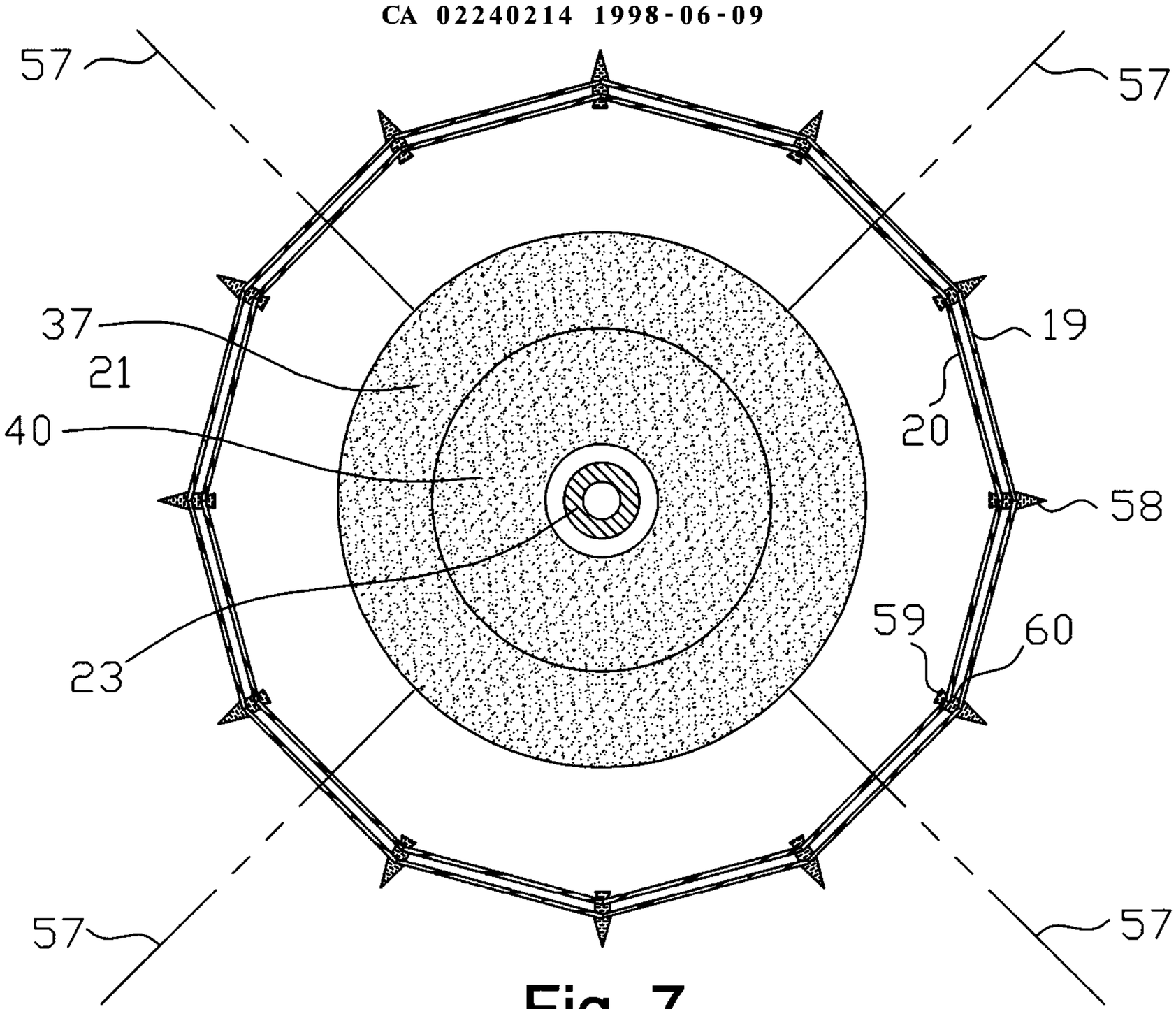

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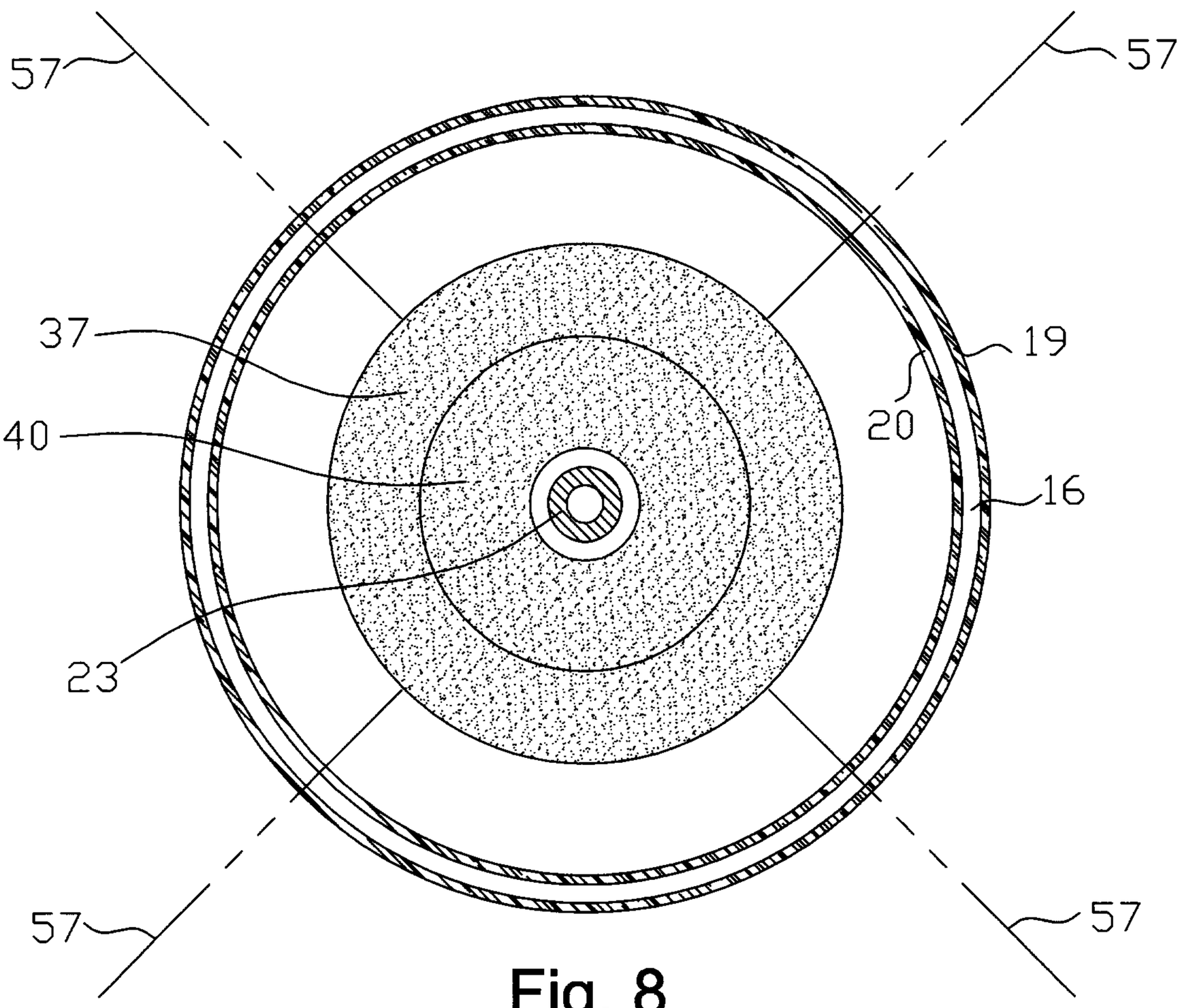

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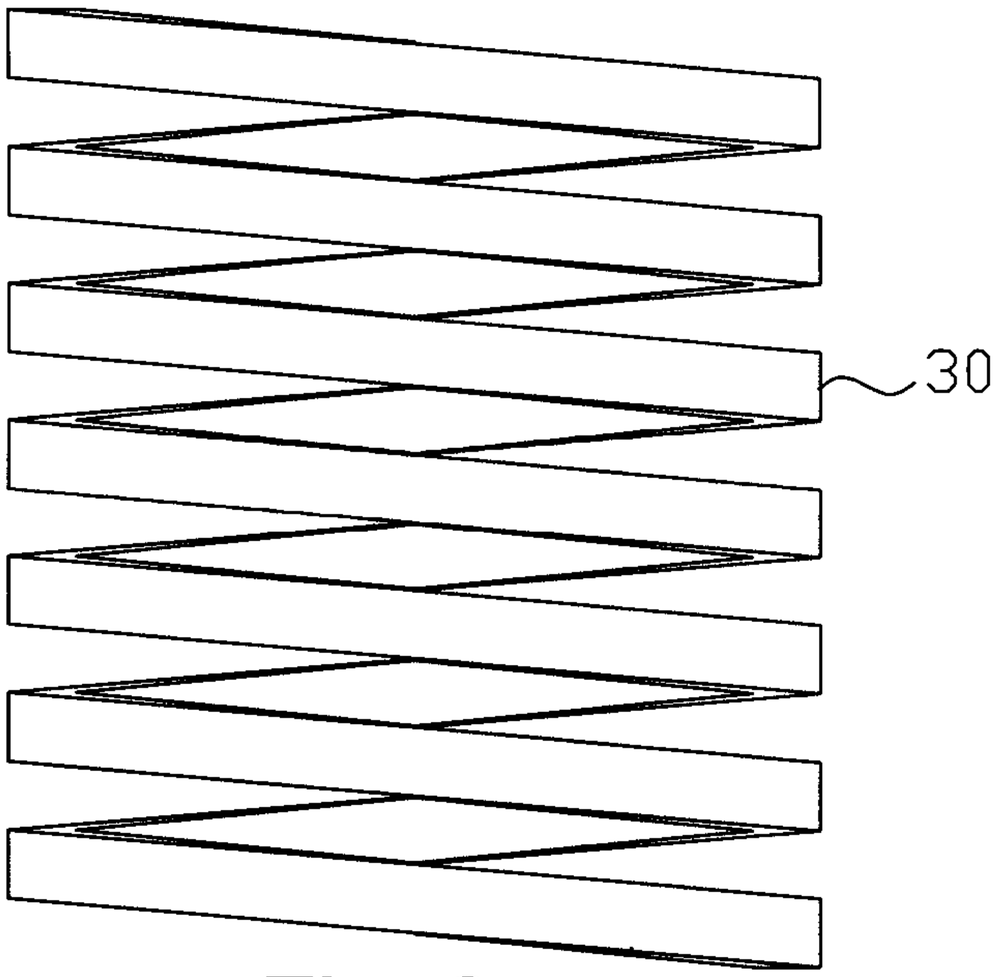

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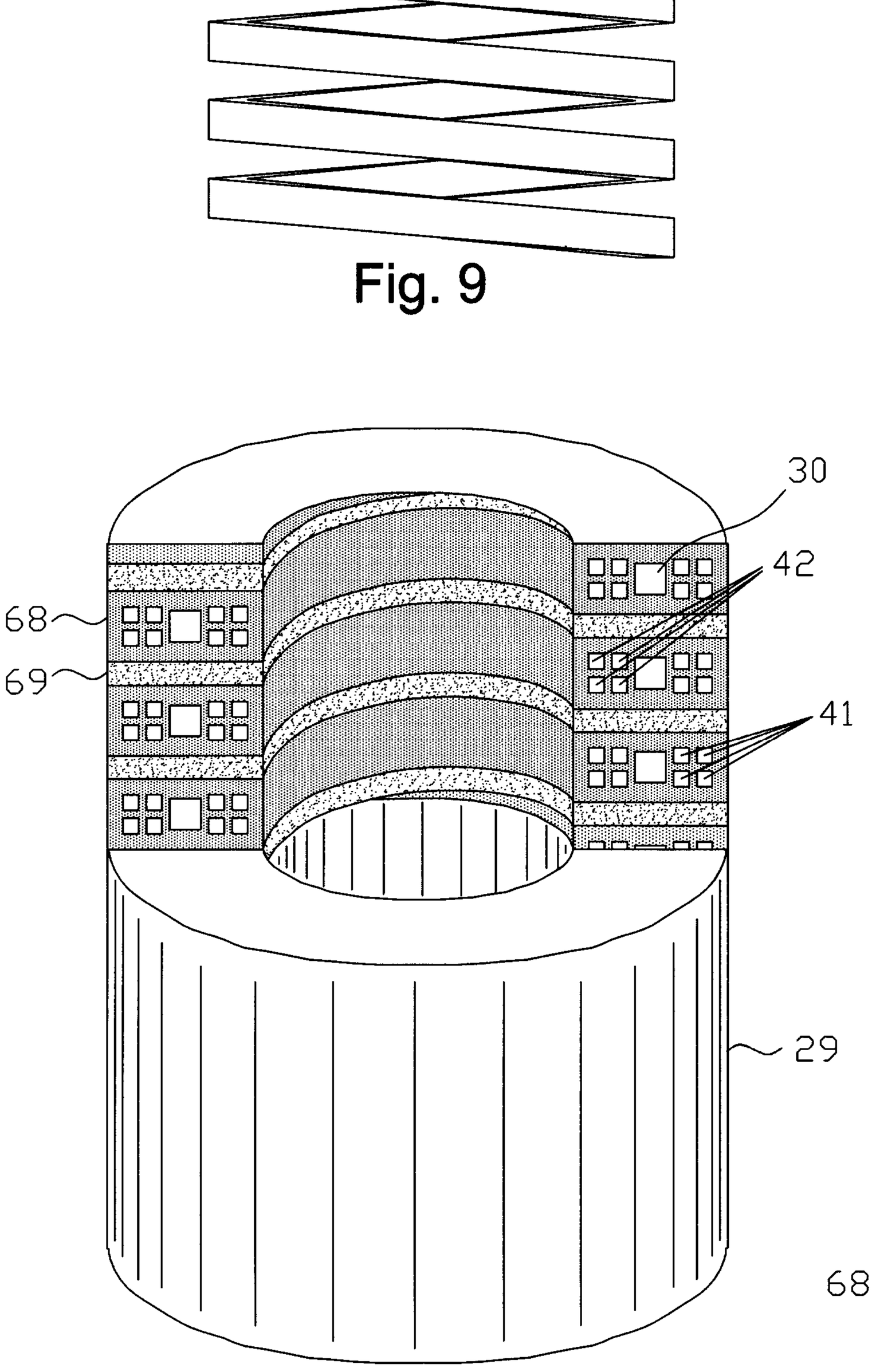


Fig. 10

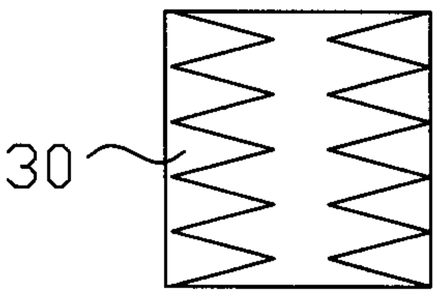


Fig. 10A

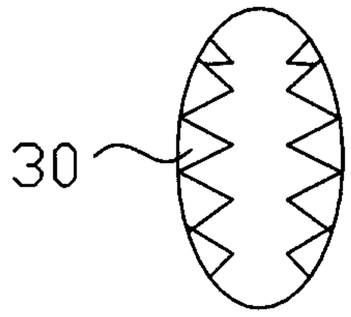
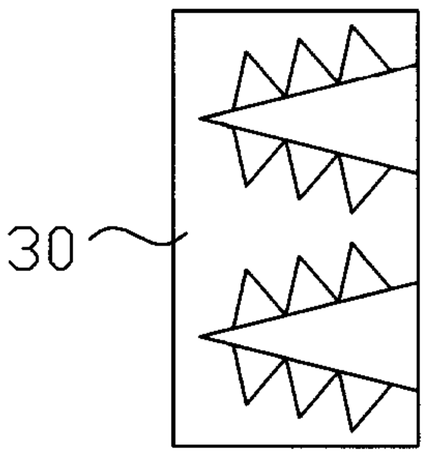


Fig. 10B

Fig. 10C



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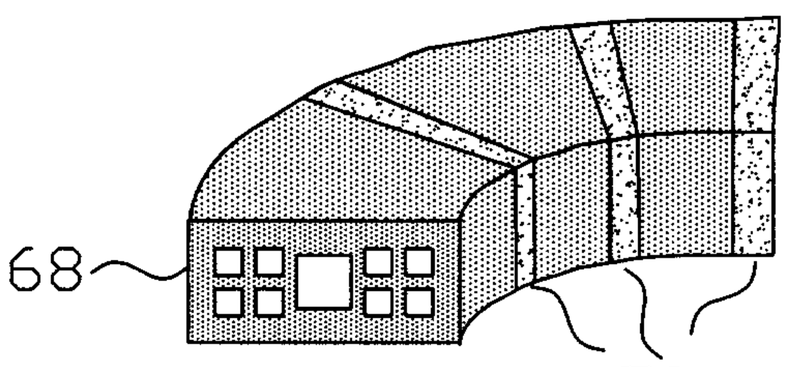

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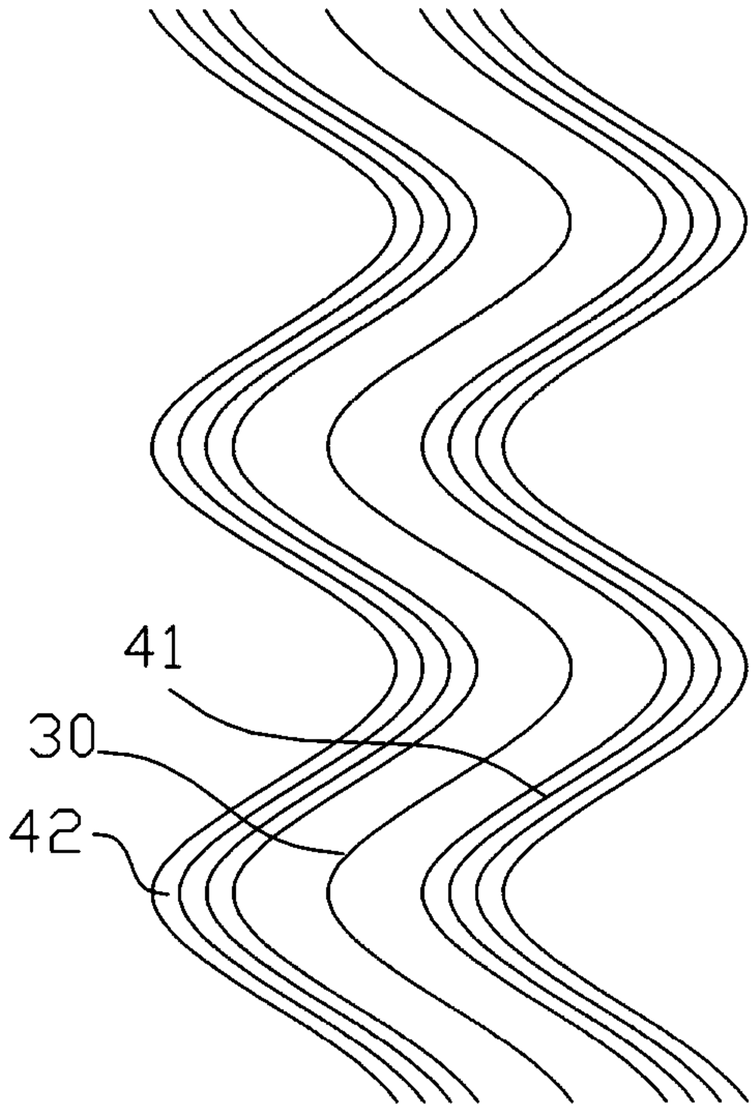

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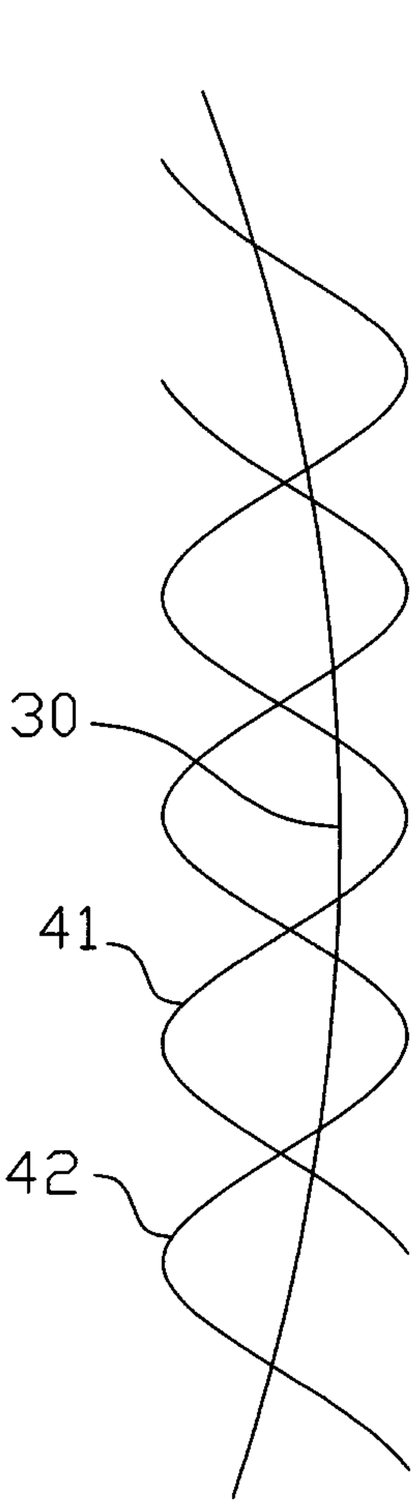

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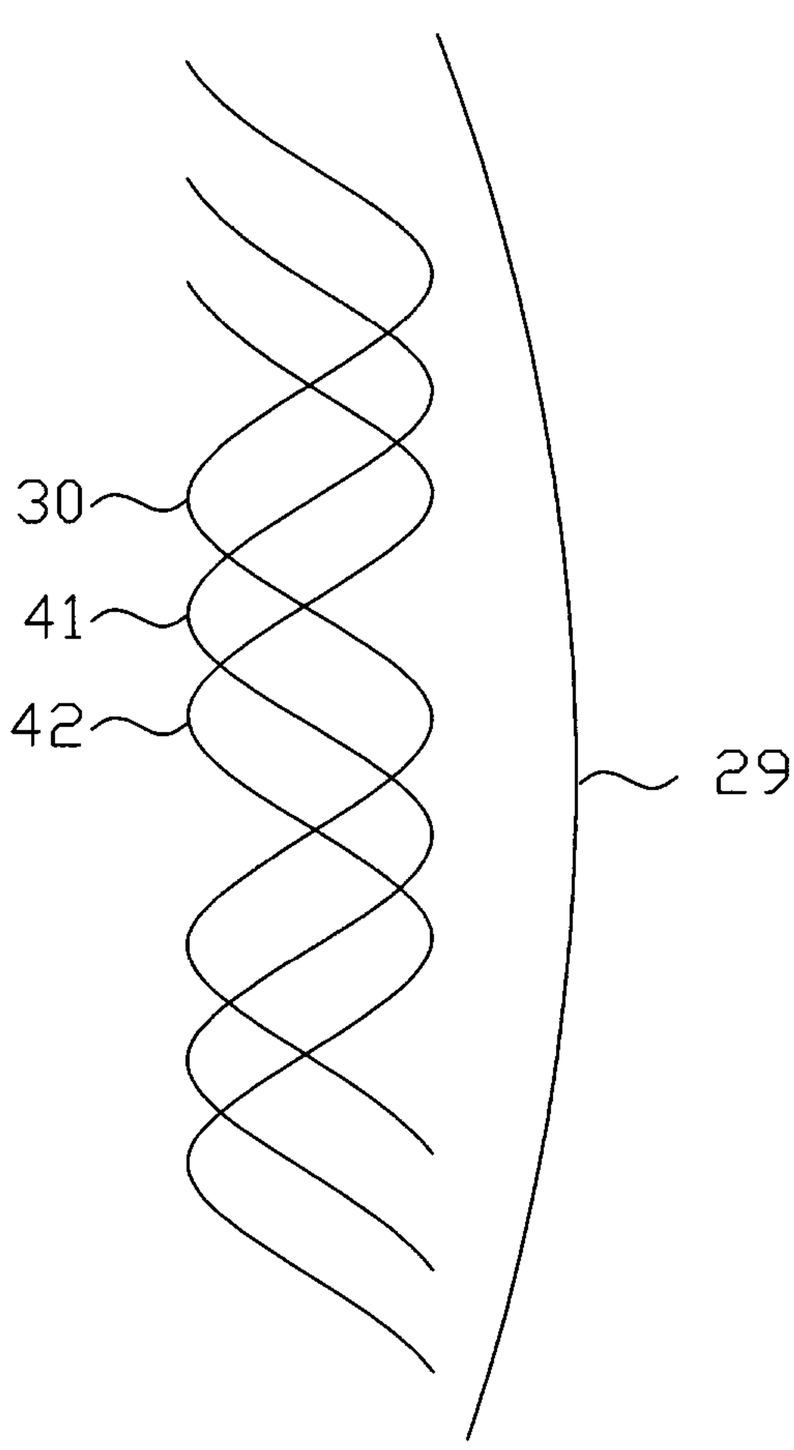

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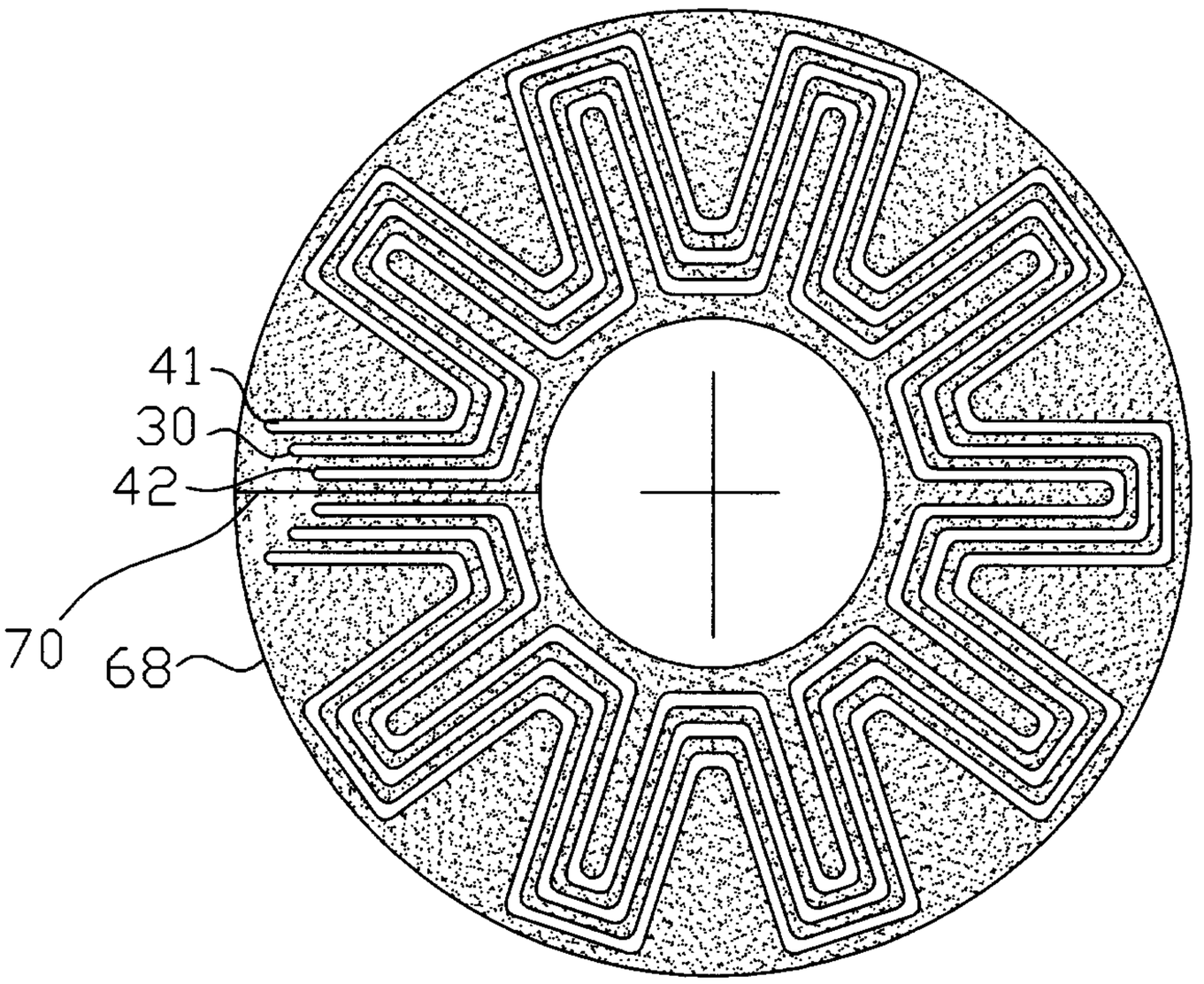

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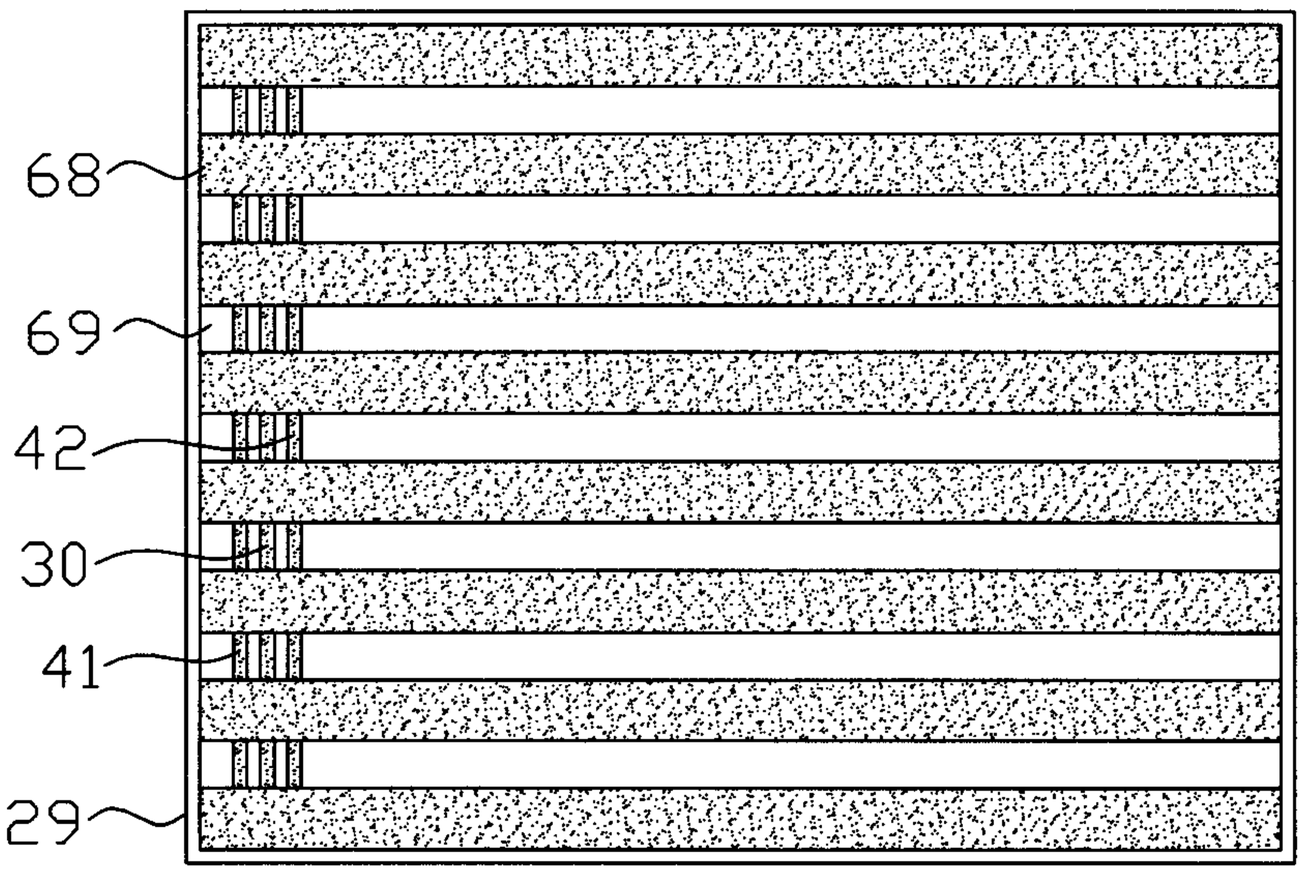

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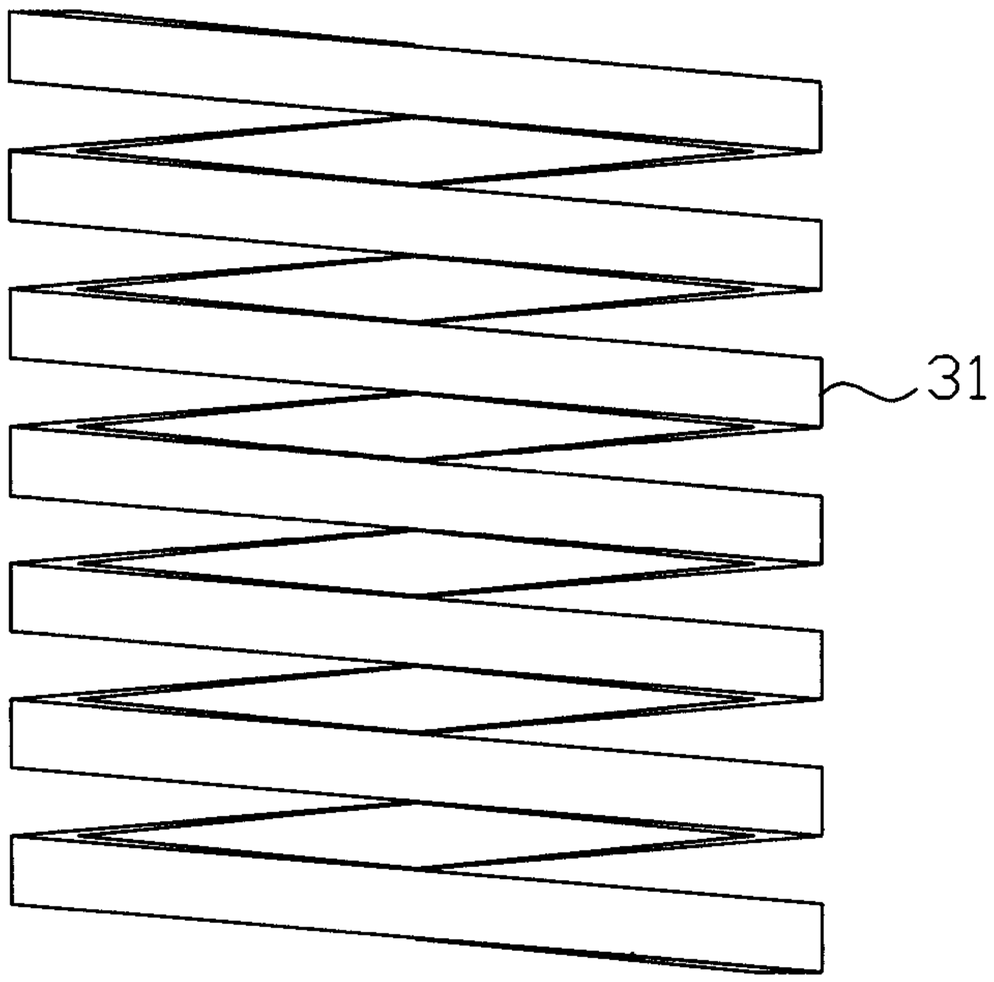

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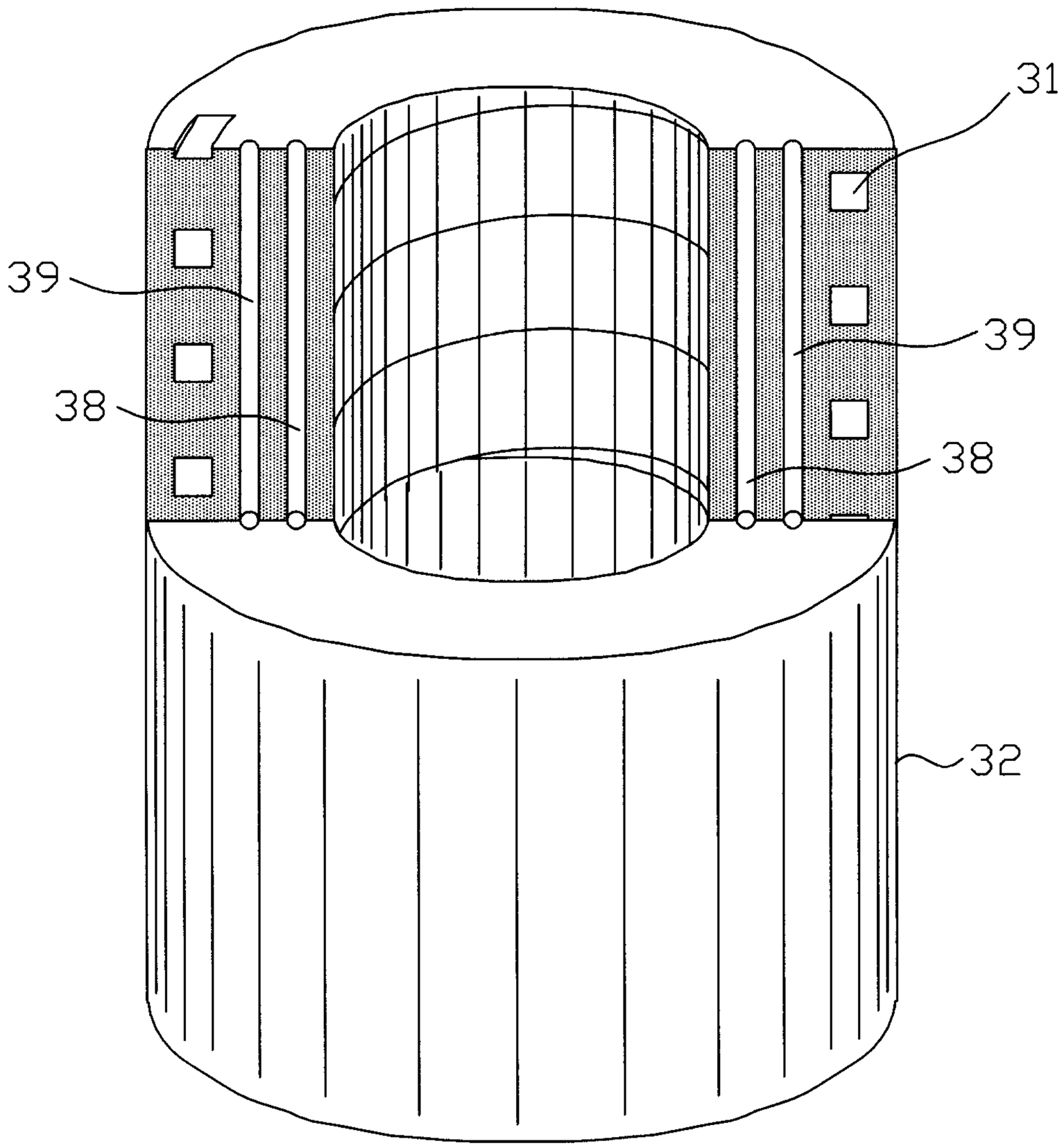

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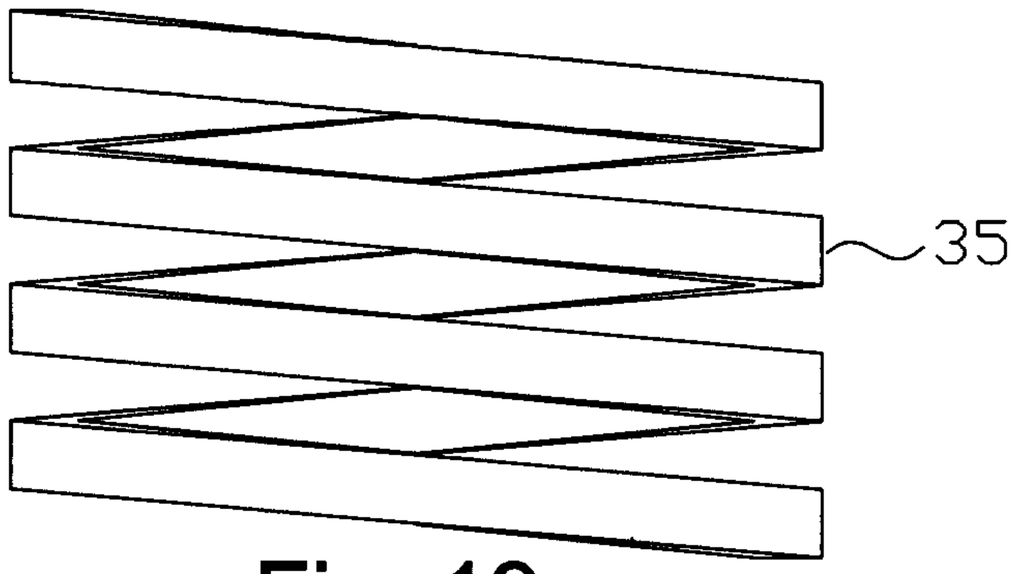

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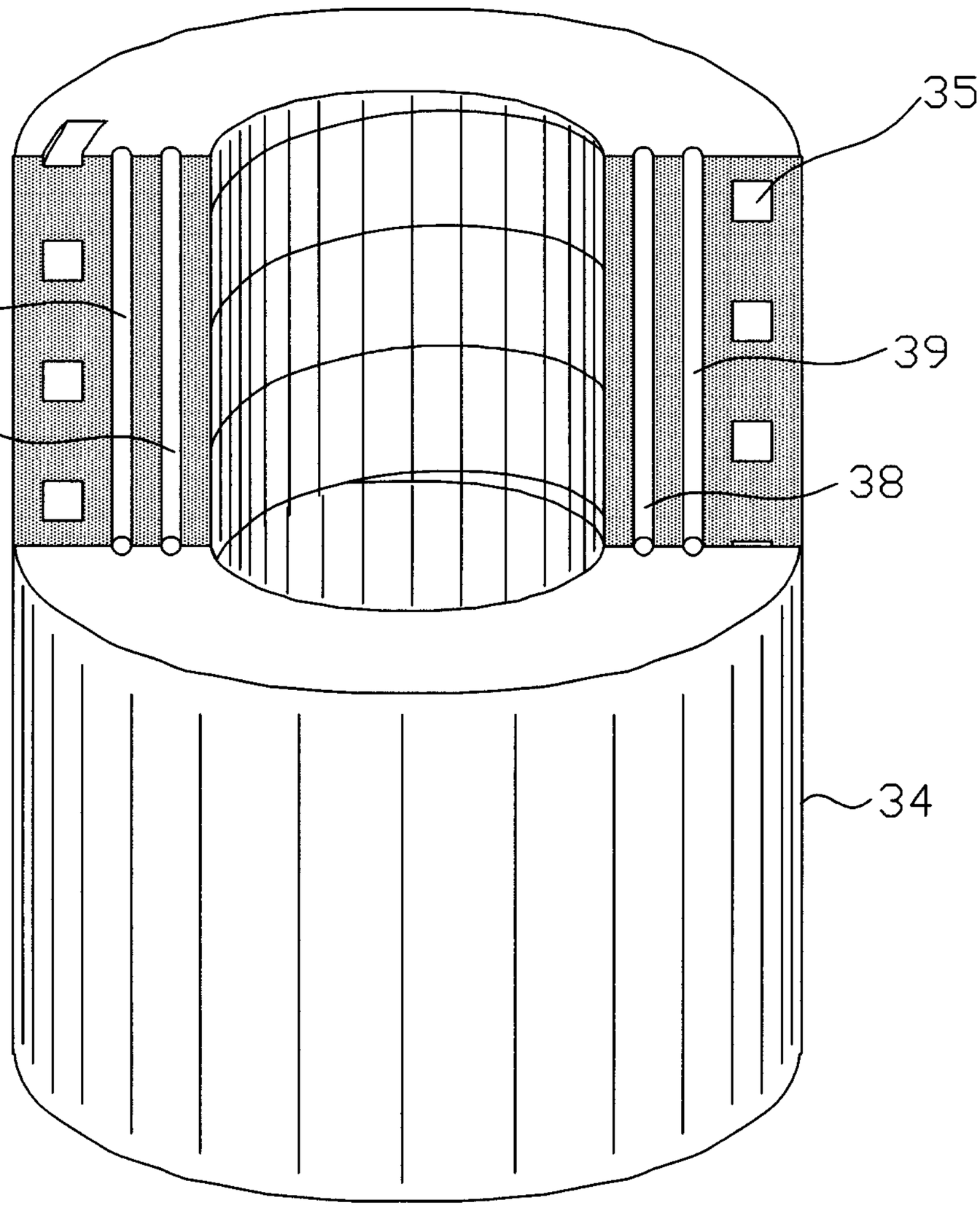

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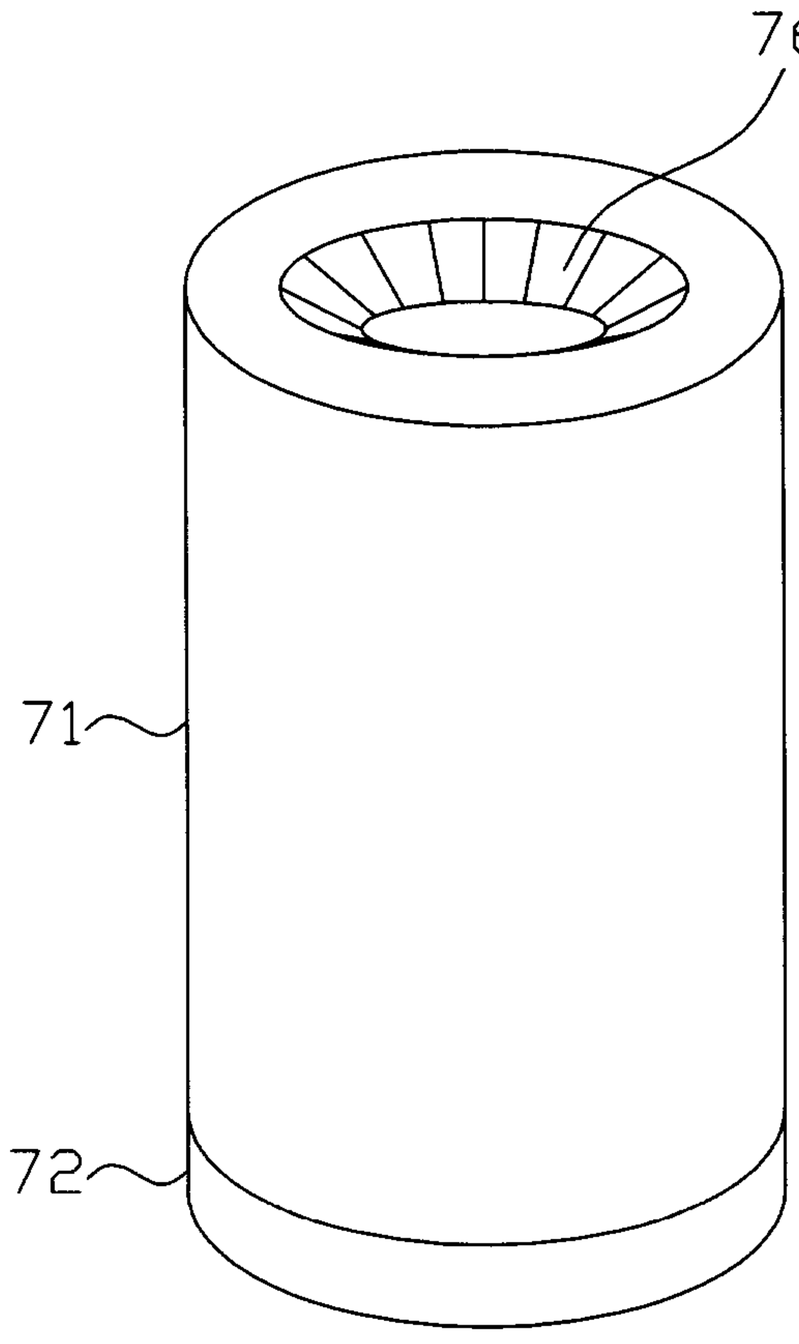

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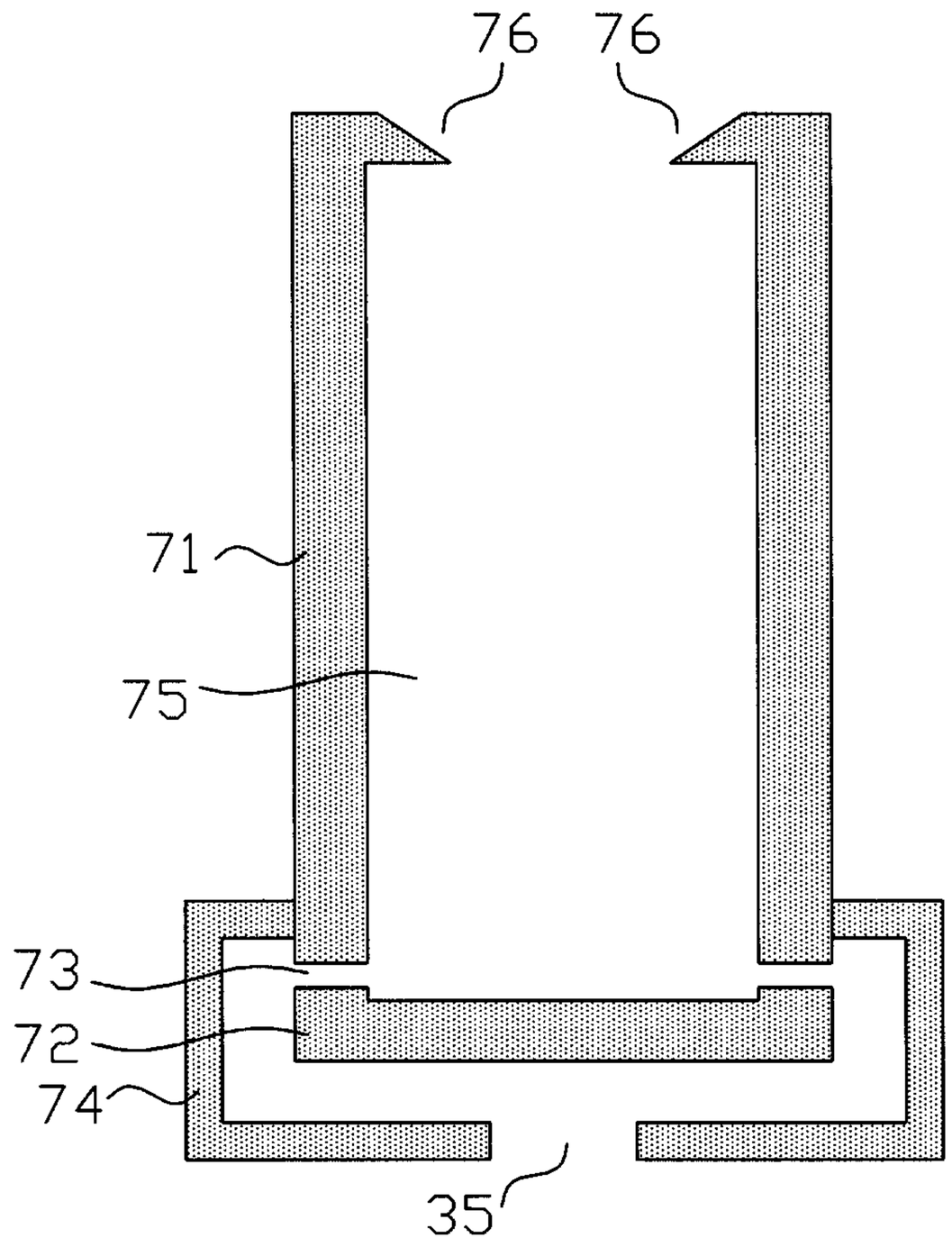

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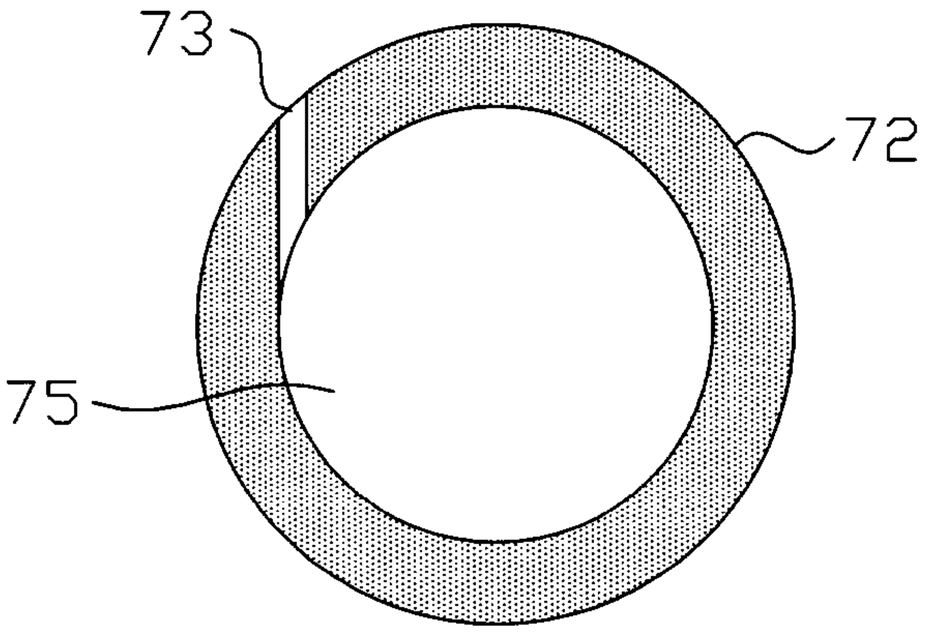

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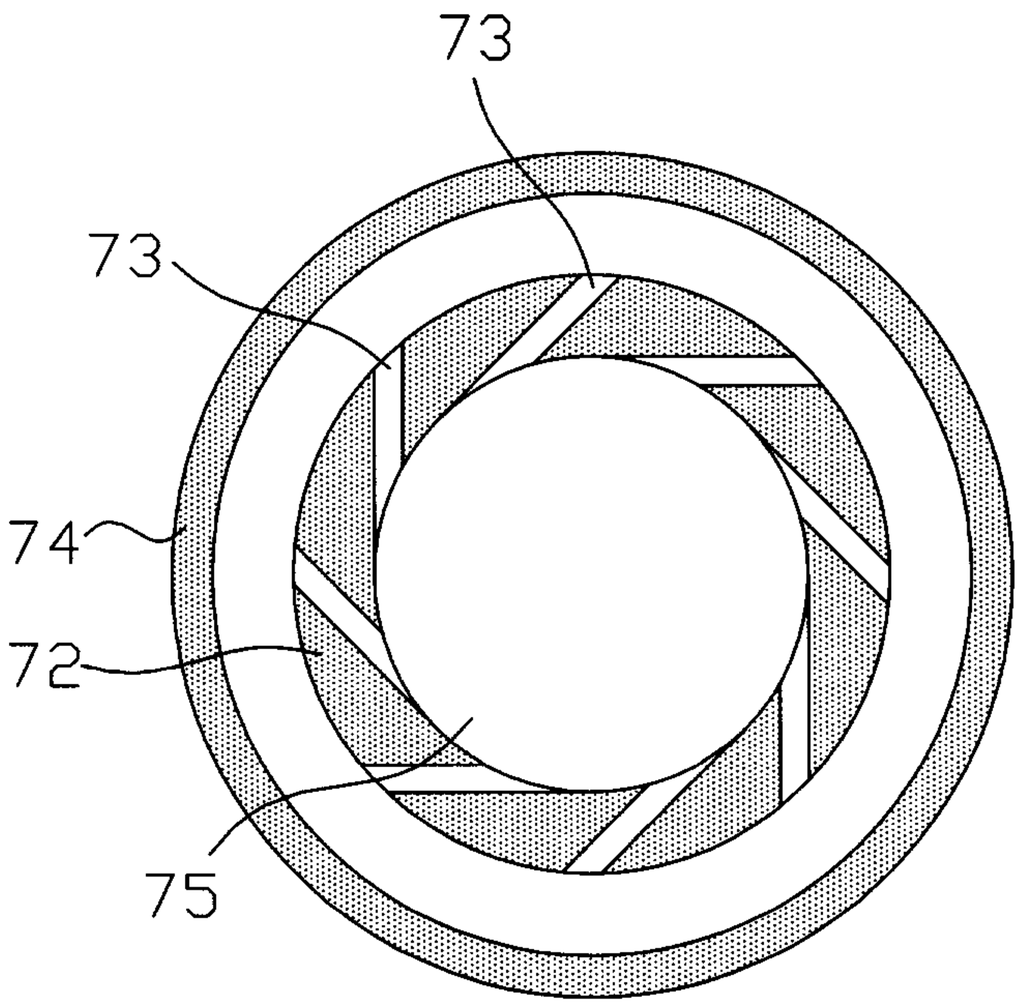
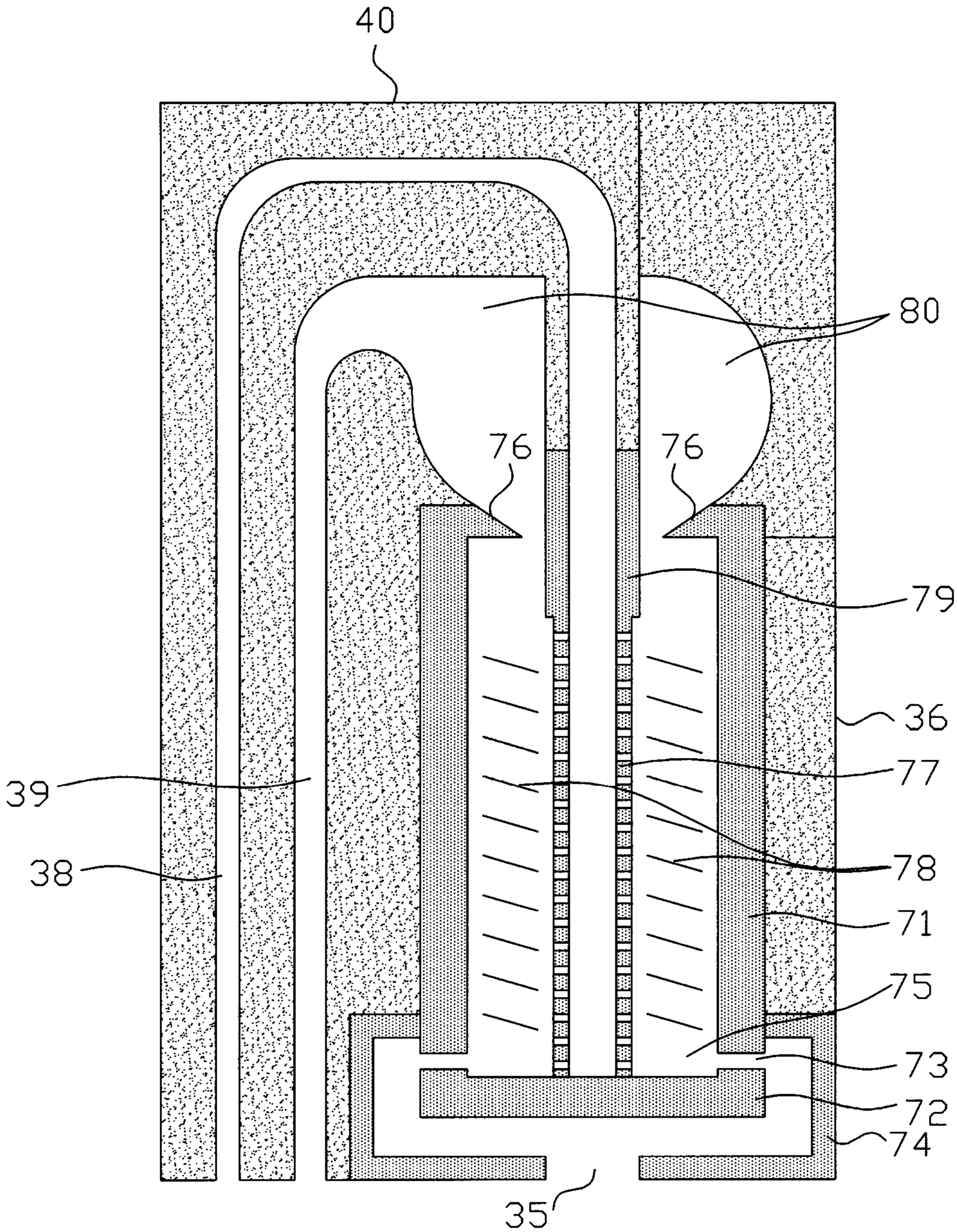


Fig. 24



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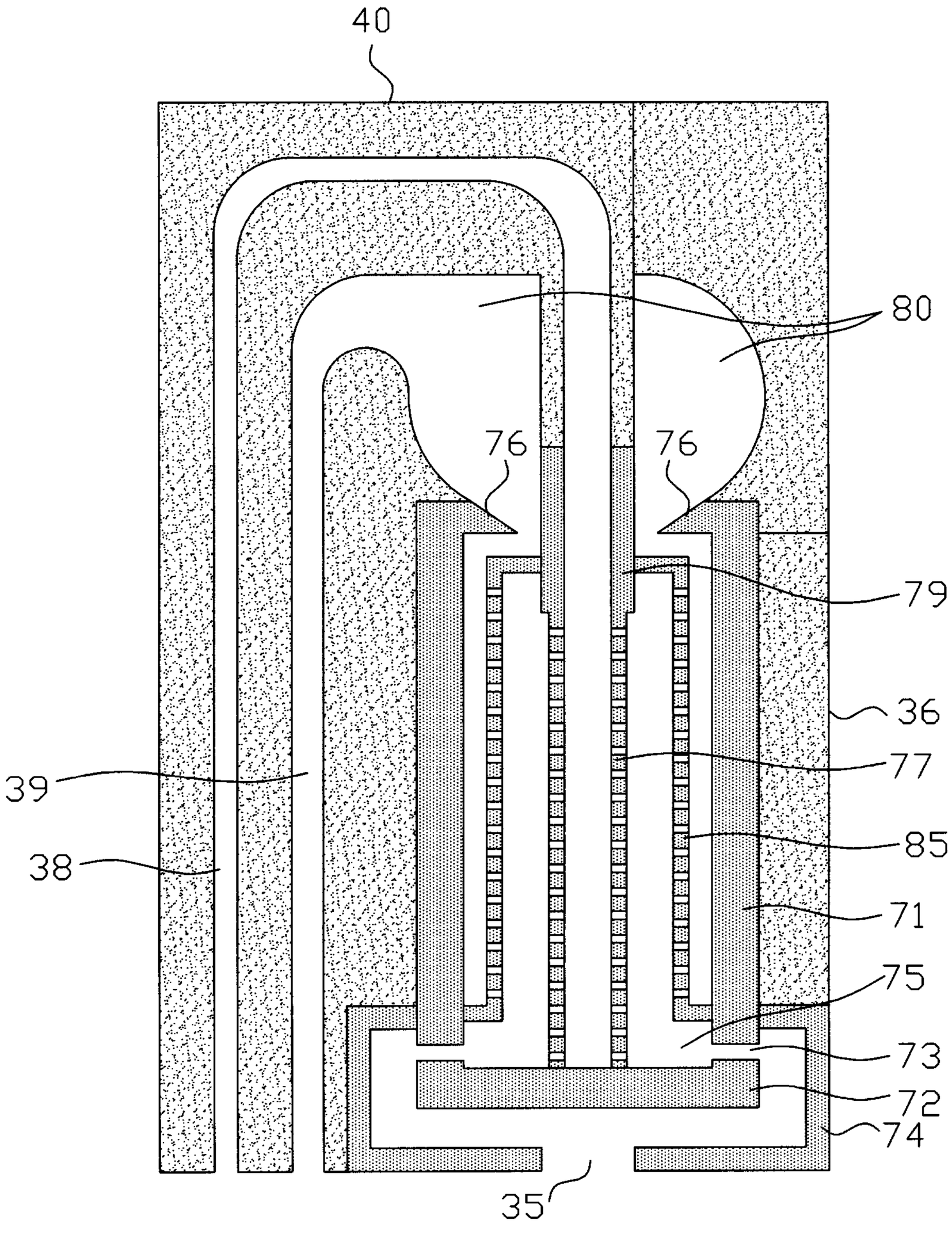


Fig. 25A

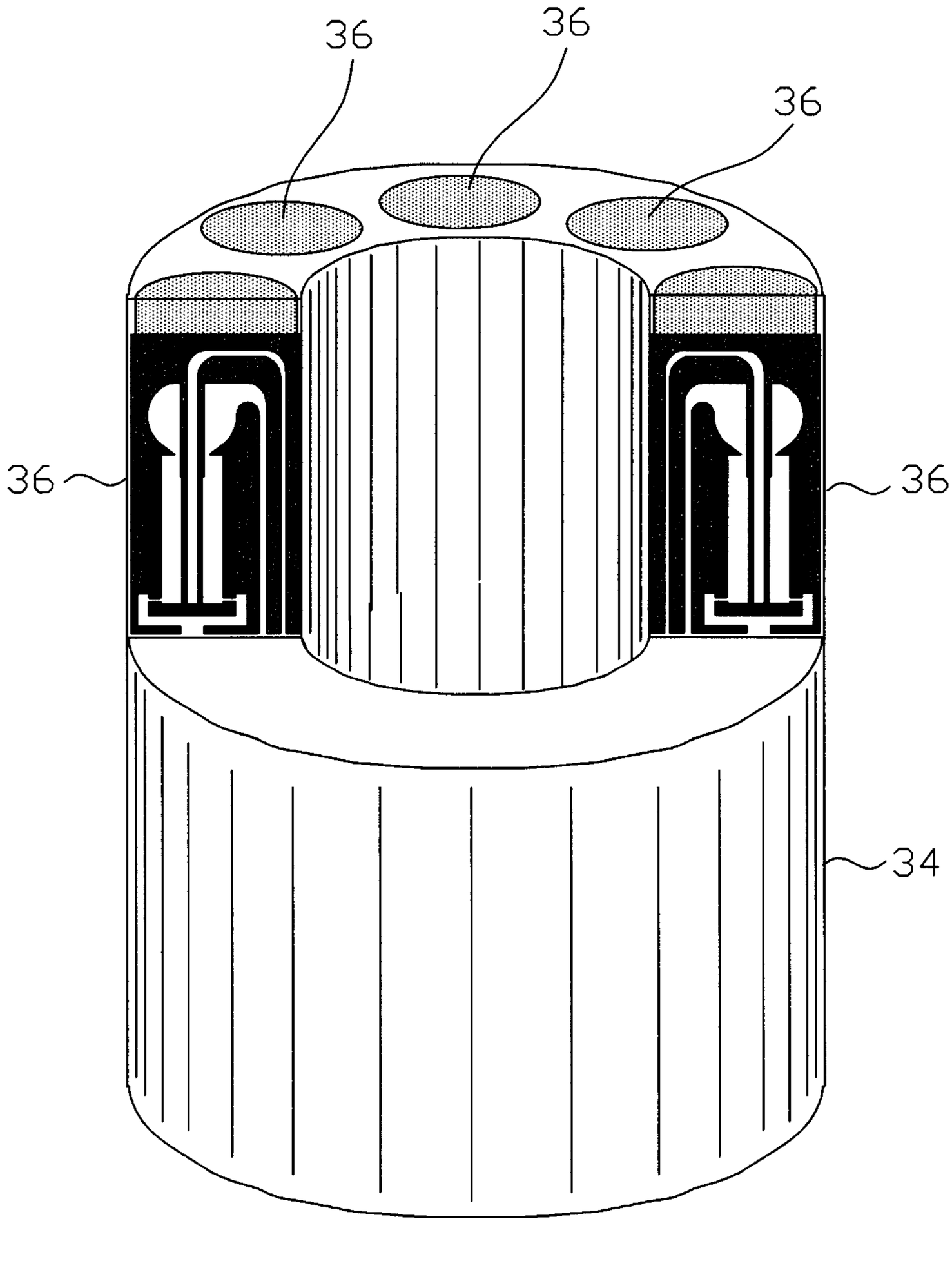
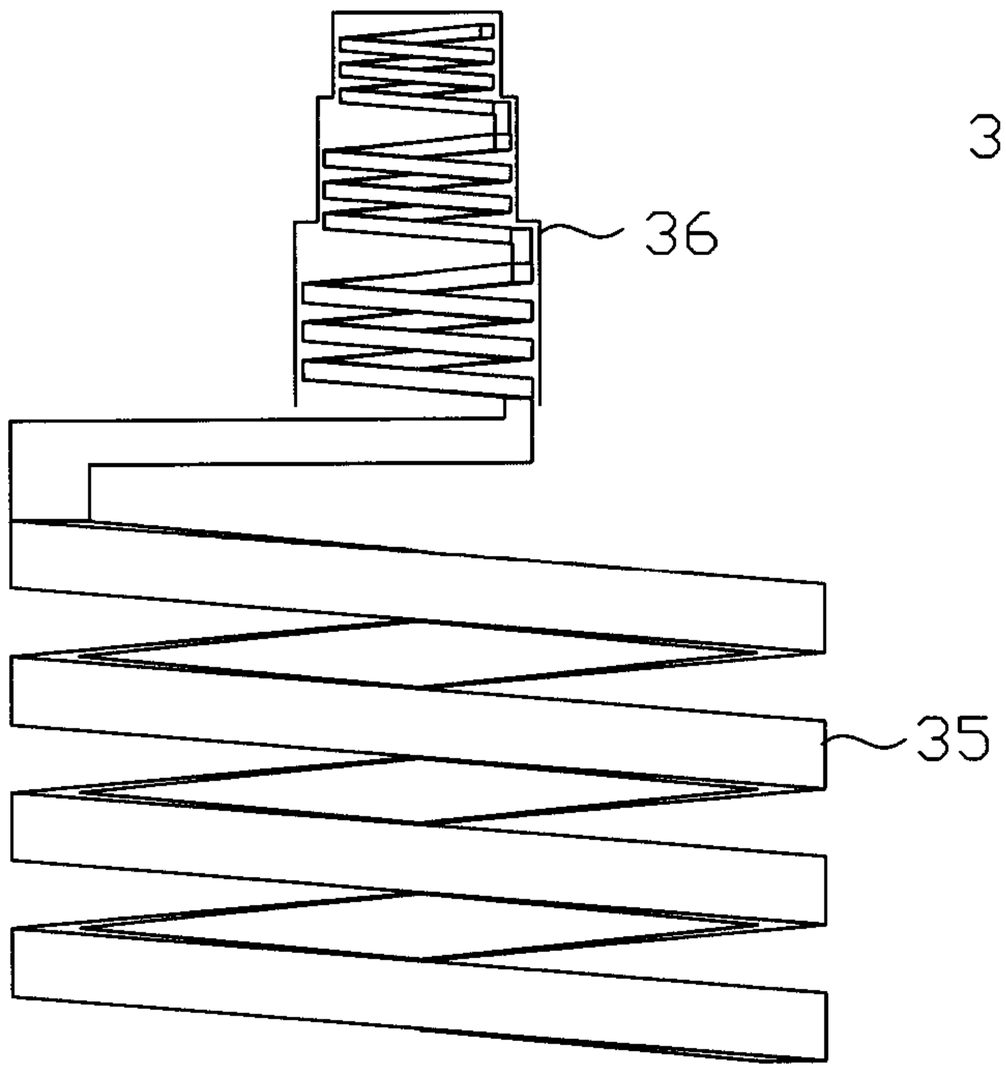


Fig. 26



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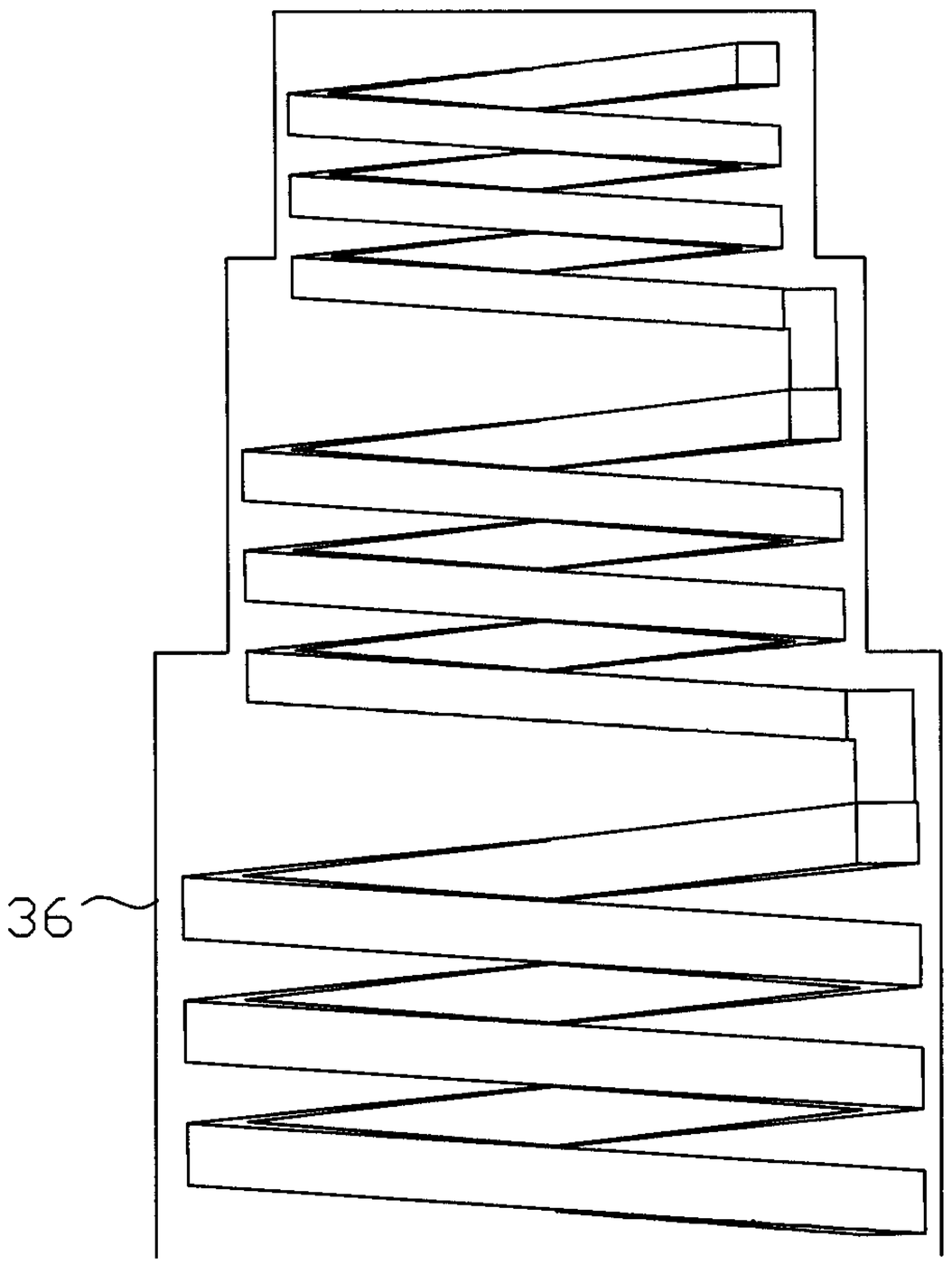
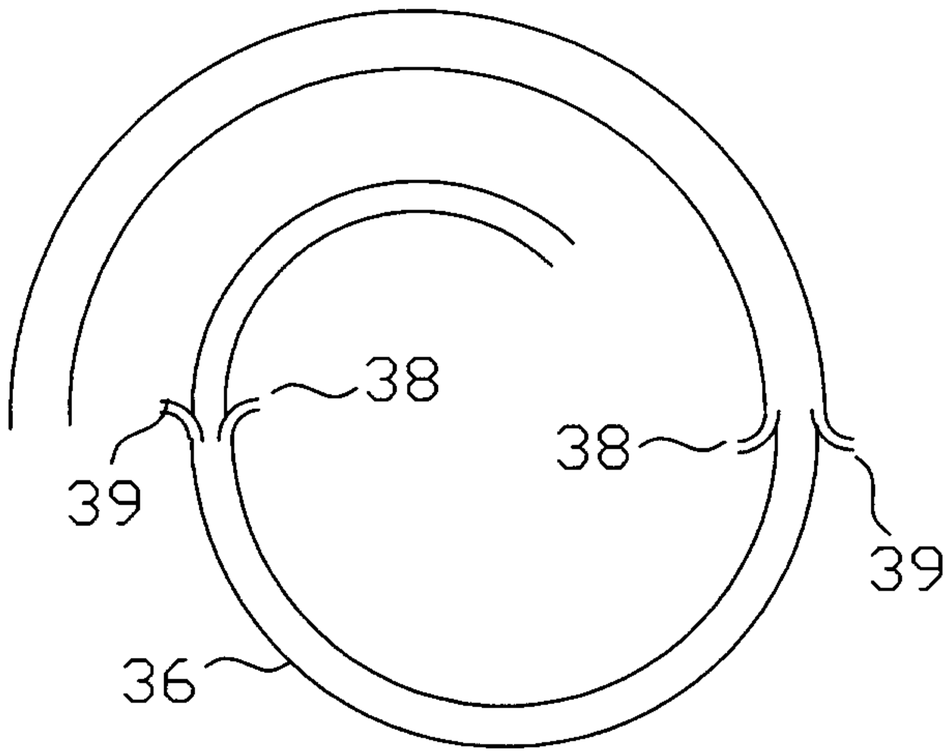


Fig. 28



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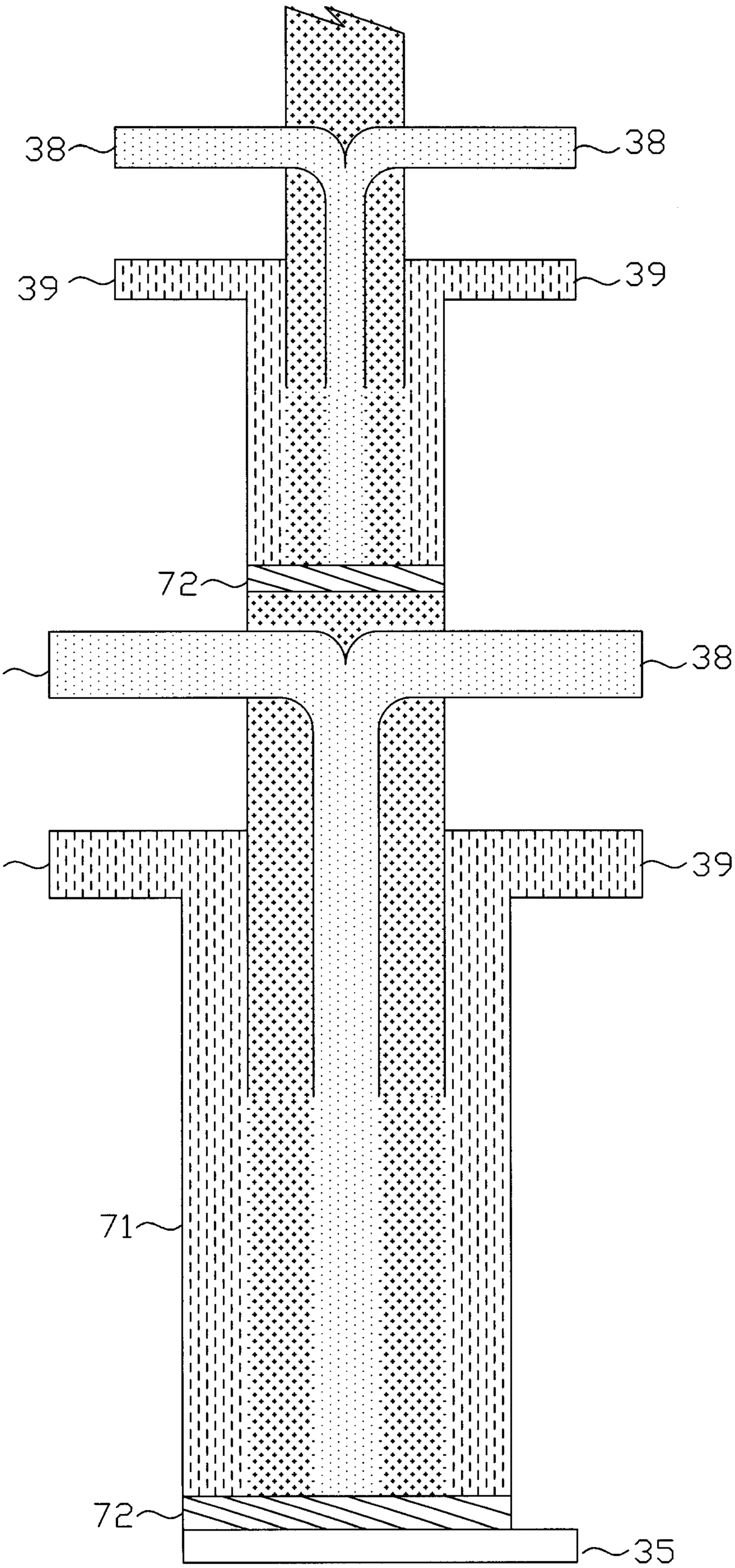

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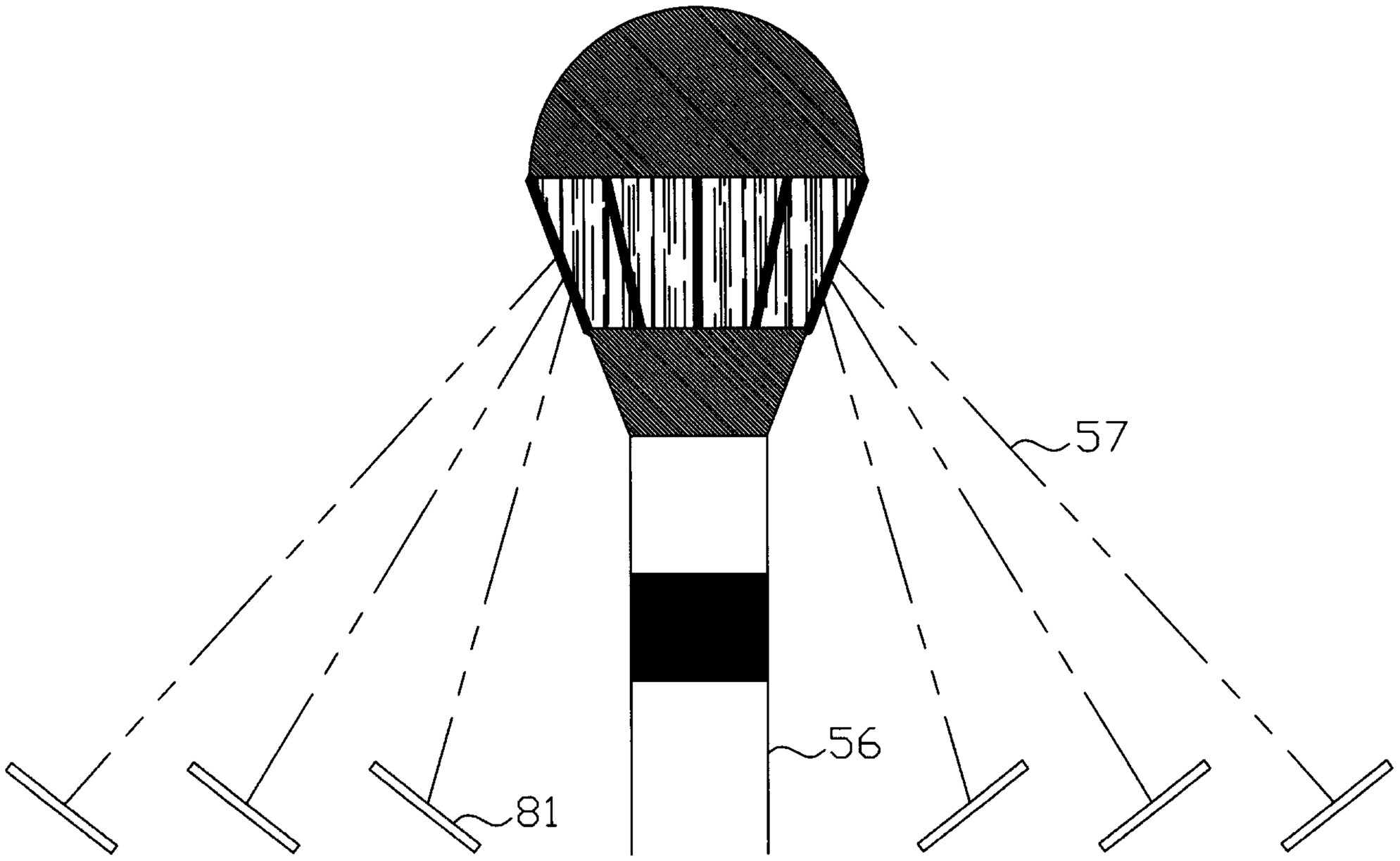

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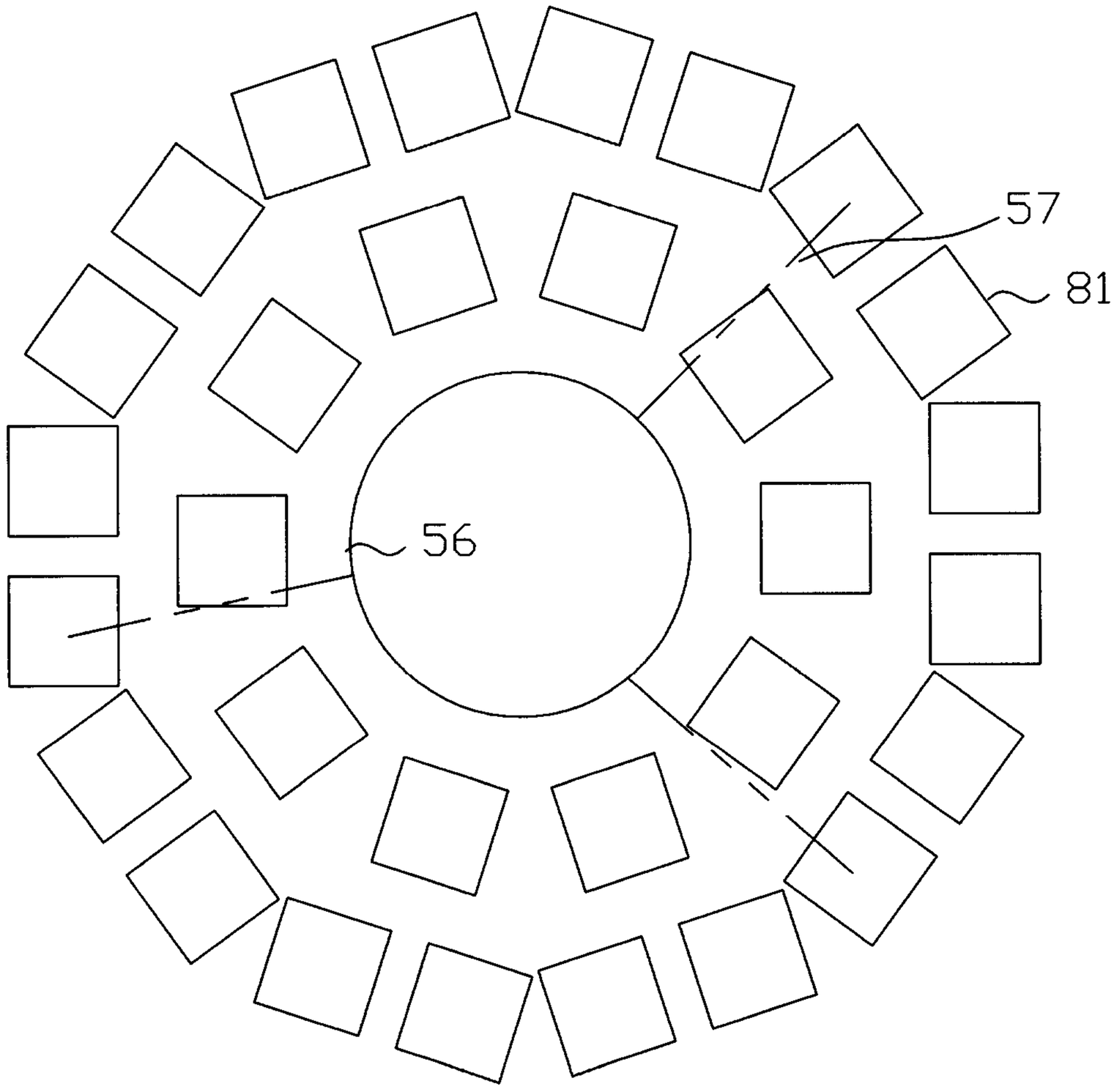

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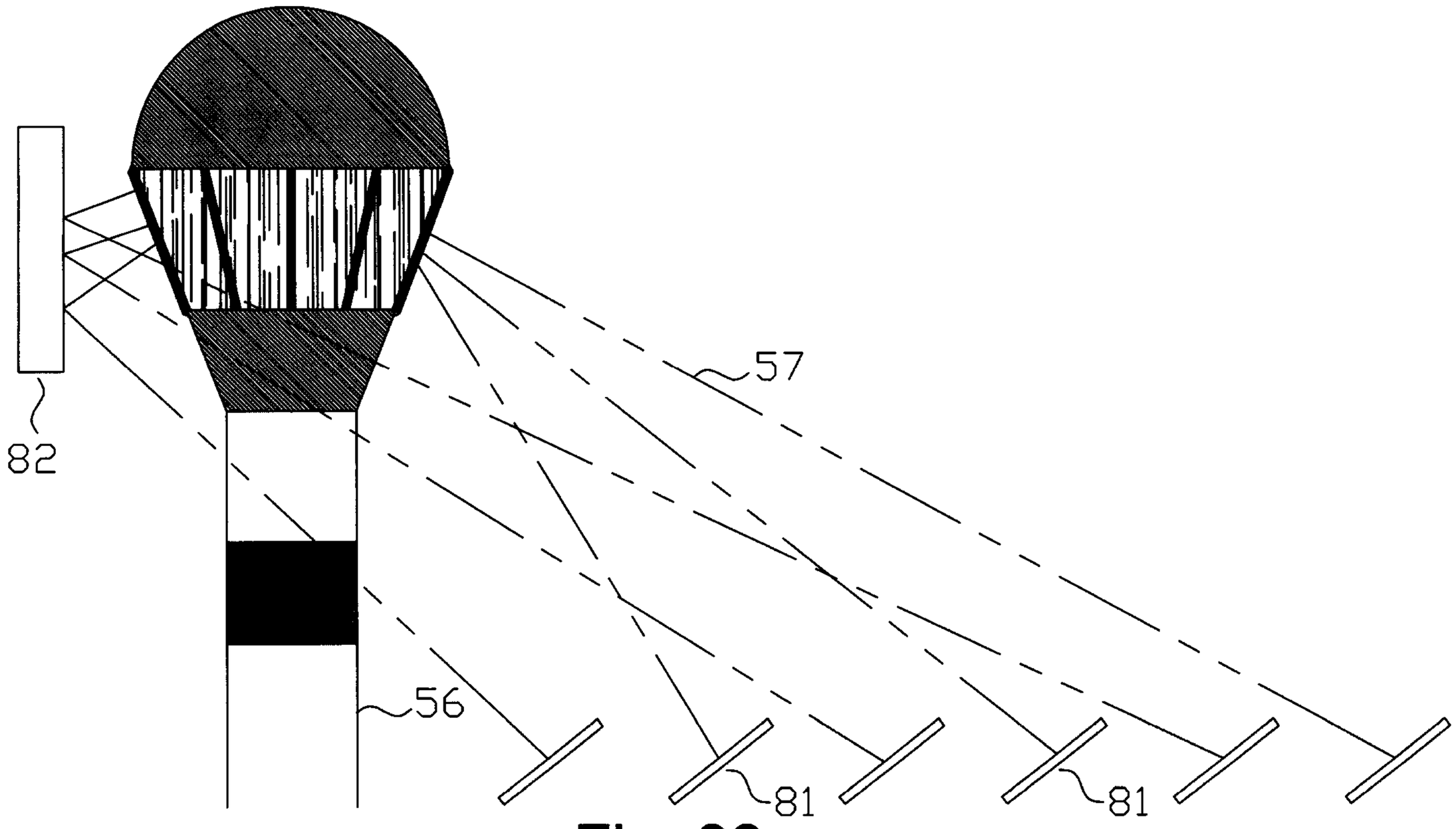

Fig. 33

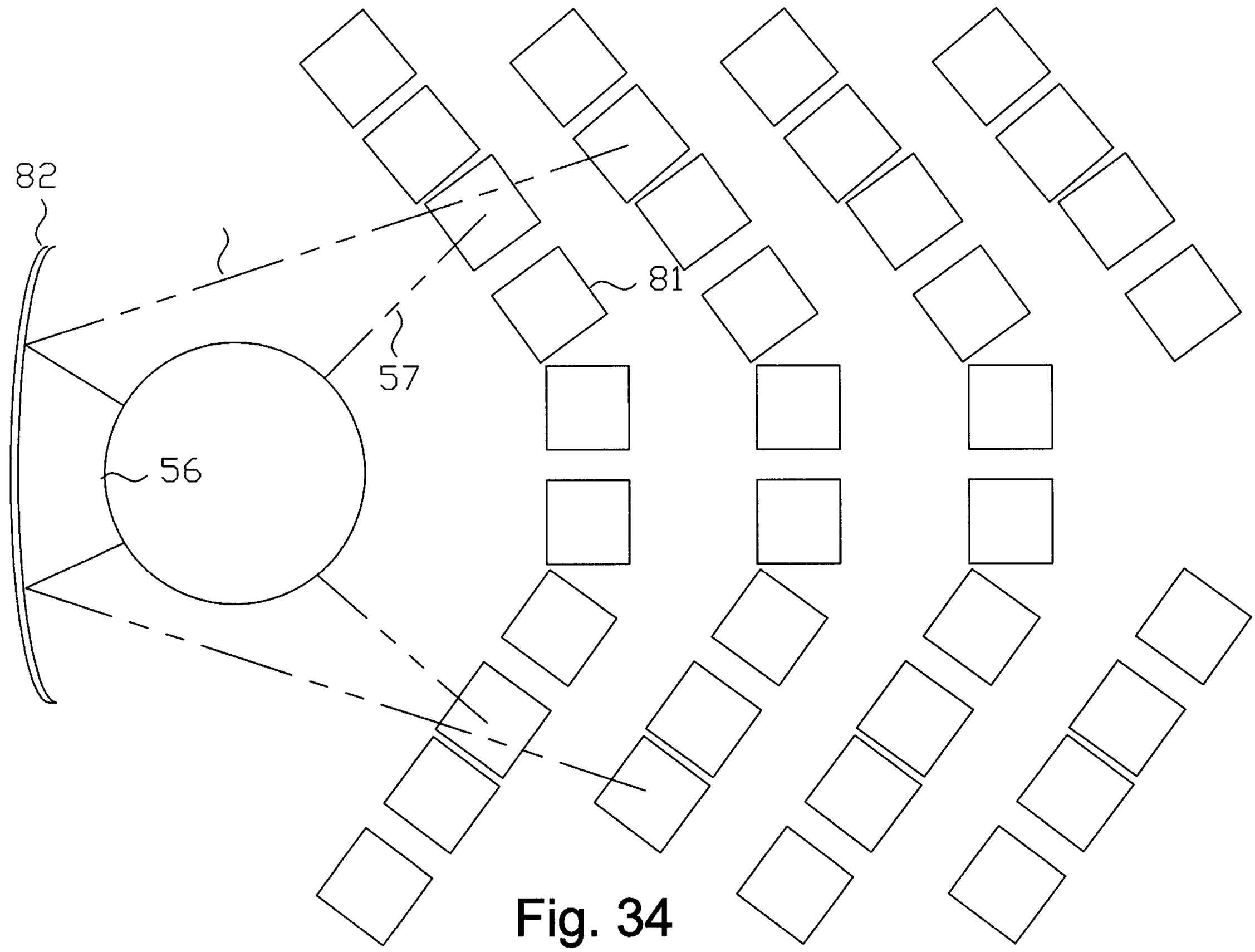

Fig. 34

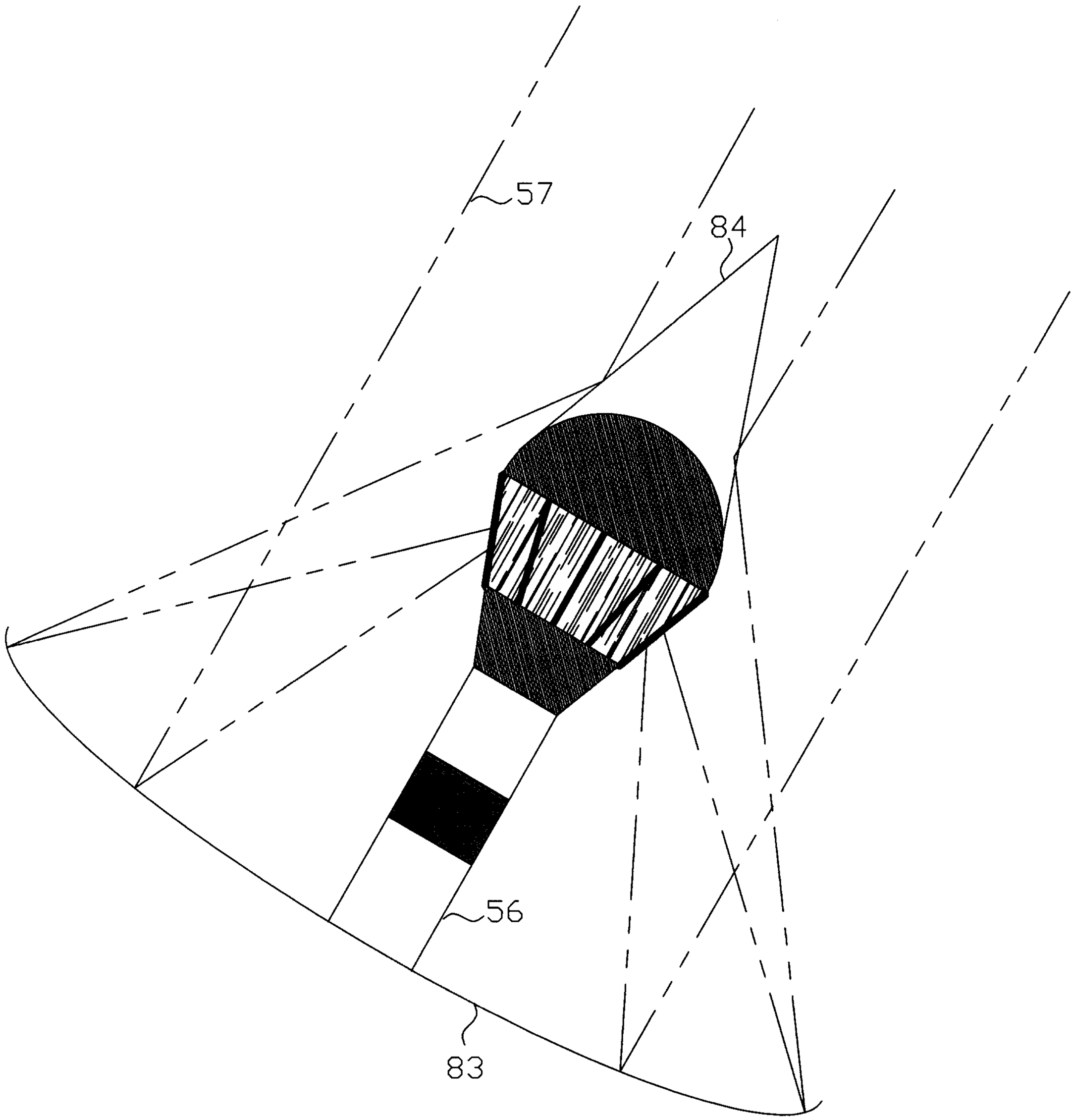

Fig. 35