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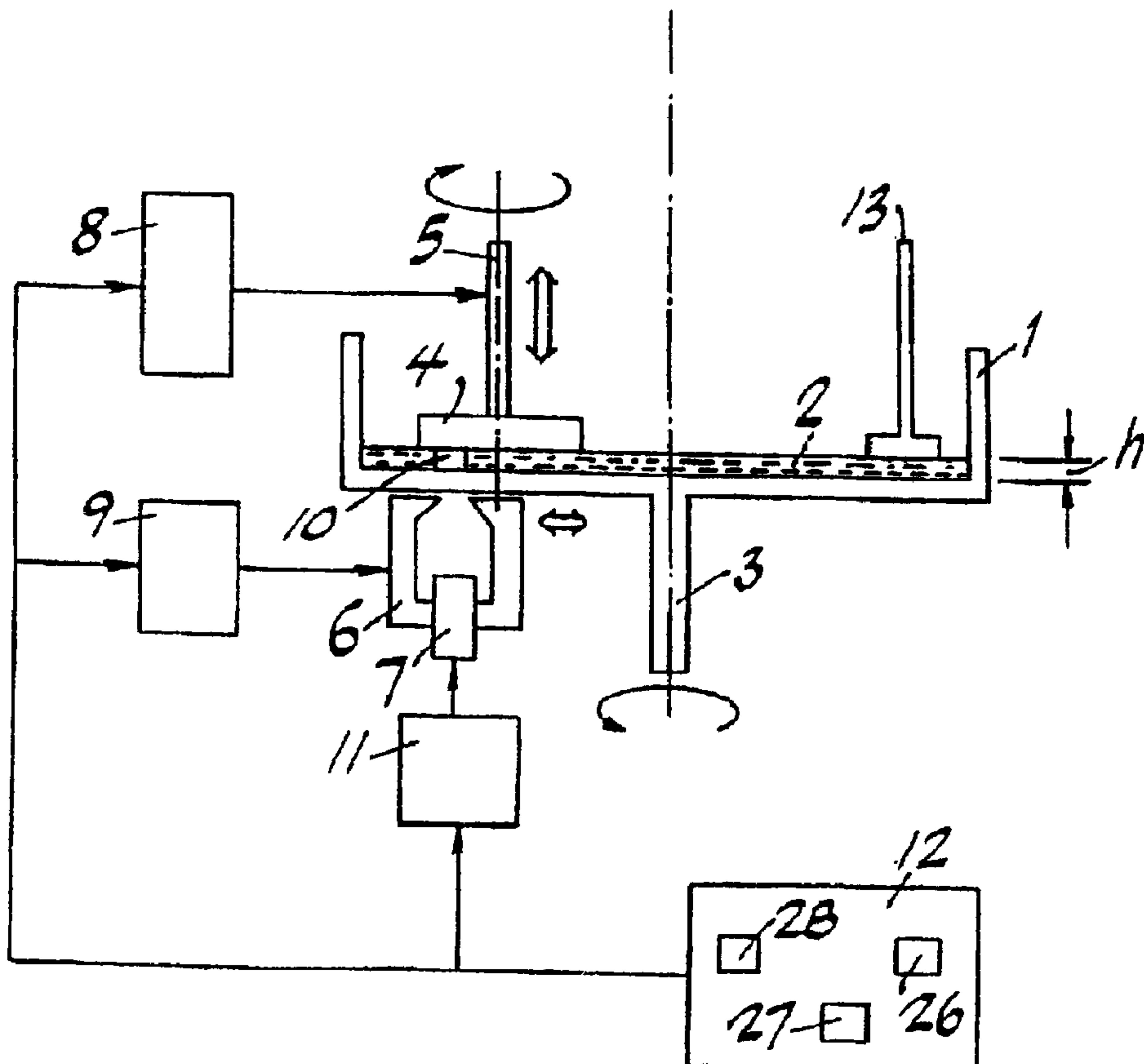
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(54) Titre : METHODES ET DISPOSITIFS DE POLISSAGE MAGNETORHEOLOGIQUES

(54) Title: MAGNETORHEOLOGICAL FLUID



(57) Abrégé/Abstract:

A method of polishing an object is disclosed. In one embodiment, as shown in the figure, the method comprises the steps of creating a polishing zone (10) within a magnetorheological fluid (2); determining the characteristics of the contact between the

**(57) Abrégé(suite)/Abstract(continued):**

object and the polishing zone necessary to polish the object (4); controlling the consistency of the fluid (2) in the polishing zone (10); bringing the object (4) into contact with the polishing zone (10) of the fluid (2); and moving at least one of said object (4) and said fluid (2) with respect to the other. Also disclosed is a polishing device (1). In one embodiment, the device comprises a magnetorheological fluid (2), a means (6) for inducing a magnetic field, and a means for displacing the object (4) to be polished or the means (6) for inducing a magnetic field relative to one another.

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**Abstract**

A method of polishing an object is disclosed. In one embodiment, as shown in the figure, the method comprises the steps of creating a polishing zone (10) within a 5 magnetorheological fluid (2); determining the characteristics of the contact between the object and the polishing zone necessary to polish the object (4); controlling the consistency of the fluid (2) in the polishing zone (10); bringing the object (4) into contact with the polishing zone 10 (10) of the fluid (2); and moving at least one of said object (4) and said fluid (2) with respect to the other. Also disclosed is a polishing device (1). In one embodiment, the device comprises a magnetorheological fluid (2), a means (6) for inducing a magnetic field, and a means for displacing the 15 object (4) to be polished or the means (6) for inducing a magnetic field relative to one another.

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**MAGNETORHEOLOGICAL FLUID**

This application is a divisional of Canadian Patent Application Serial No. 2,163,671 filed June 3, 1994.

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**FIELD OF THE INVENTION**

This invention relates to methods of polishing surfaces using magnetorheological fluids.

**BACKGROUND OF THE INVENTION**

Workpieces such as glass optical lenses, 10 semiconductors, tubes, and ceramics have been polished in the art using one-piece polishing tools made of resin, rubber, polyurethane or other solid materials. The working surface of the polishing tool should conform to the workpiece surface. This makes polishing complex surfaces 15 complicated, and difficult to adapt to large-scale production. Additionally, heat transfer from such a solid polishing tool is generally poor, and can result in superheated and deformed workpieces and polishing tools, thus causing damage to the geometry of the workpiece surface 20 and/or the tool.

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SUMMARY OF THE INVENTION

Improved devices and methods for polishing objects in a magnetorheological polishing fluid (MP-fluid) are provided. More particularly, a highly accurate method of 5 polishing objects, in a magnetorheological fluid, which may be automatically controlled is provided, as are improved polishing devices. The method comprises the steps of creating a polishing zone within a magnetorheological fluid; bringing an object to be polished into contact with the 10 polishing zone of the fluid; determining the rate of removal of material from the surface of the object to be polished; calculating the operating parameters, such as magnetic field intensity, dwell time, and spindle velocity, for optimal polishing efficiency; and moving at least one of said object 15 and said fluid with respect to the other according to the operating parameters.

The polishing device comprises an object to be polished, a magnetorheological fluid, which may or may not be contained within a vessel, a means for inducing a 20 magnetic field, and a means for moving at least one of these components with respect to one or more of the other components. The object to be polished is brought into contact with the magnetorheological fluid and the magnetorheological fluid, the means for inducing a magnetic 25 field, and/or the object to be polished are put into motion, thereby allowing all facets of the object to be exposed to the magnetorheological fluid.

In the method and devices, the magnetorheological fluid is acted upon by a magnetic field in the region where 30 the fluid contacts the object to be polished. The magnetic field causes the MP-fluid to acquire the characteristics of a plasticized solid whose yield point depends on the magnetic field intensity and the viscosity. The yield point

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of the fluid is high enough that it forms an effective polishing surface, yet still permits movement of abrasive particles. The effective viscosity and elasticity of the magnetorheological fluid when acted upon by the magnetic field provides resistance to the abrasive particles such that the particles have sufficient force to abrade the workpiece.

One broad aspect of the present invention may be summarized as a magnetorheological fluid for finishing workpiece surfaces, comprising: soft magnetic particles; abrasive particles; a stabilizer; and a carrying fluid, wherein the soft magnetic particles are coated with an oxidation inhibiting polymer and wherein the carrying fluid comprises water.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a cross-sectional side view of a polishing device of an embodiment of the invention.

Figure 2 is a cross-sectional side view of another embodiment of the invention.

Figure 3 is a cross-sectional side view of another embodiment of the invention.

Figure 4 is a graph showing the amount of material removed, as a function of distance from the center of the workpiece, for an exemplary workpiece.

Figure 5, appearing on drawing sheet 16 together with Figure 22, is a schematic diagram illustrating the parameters used in the method of an embodiment of the invention to control polishing for a flat workpiece.

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Figure 6 is a schematic diagram illustrating the parameters used in the method of the invention to control polishing for a curved workpiece.

Figure 7 is a graph showing the relationship between the rate of material removal during polishing and the magnetic field intensity.

Figure 8 is a graph showing the relationship between the rate of material removal during polishing and the clearance between a workpiece and the bottom of a vessel in which the workpiece is polished.

Figure 9 is a cross-sectional side view of another embodiment of the invention.

Figure 10 is a cross-sectional side view of another embodiment of the invention.

Figure 11 is a cross-sectional side view of another embodiment of the invention.

Figure 12 is a cross-sectional side view of another embodiment of the invention.

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Figure 13 is a cross-sectional side view of another embodiment of the invention.

Figure 14 is a cross-sectional side view of another embodiment of the invention.

5 Figure 15 is a cross-sectional side view of another embodiment of the invention.

Figure 16 is a cross-sectional side view of another embodiment of the invention.

10 Figure 17 is a cross-sectional side view of another embodiment of the invention.

Figure 18 is a cross-sectional side view of another embodiment of the invention.

Figure 19 is a cross-sectional side view of another embodiment of the invention.

15 Figure 20 is a cross-sectional side view of another embodiment of the invention.

Figure 21 is a cross-sectional side view of another embodiment of the invention.

20 Figure 22 is a cross-sectional side view of another embodiment of the invention.

Figure 23 is a cross-sectional side view of another embodiment of the invention.

Figure 24 is a cross-sectional side view of another embodiment of the invention.

25 Figure 25 is a cross-sectional side view of another embodiment of the invention.

Figure 26 is a cross-sectional side view of another embodiment of the invention.

30 Figure 27 is a cross-sectional side view of another embodiment of the invention.

Figure 28 is a cross-sectional side view of another embodiment of the invention.

Figure 29 is a cross-sectional side view of another embodiment of the invention.

35 Figure 30 is a cross-sectional side view of another embodiment of the invention.

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DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a schematic of a polishing device which may be operated according to the method of the 5 present invention. In Fig. 1, a cylindrical vessel 1 contains magnetorheological polishing fluid (MP-fluid) 2. In a preferred embodiment, the MP-fluid 2 contains an abrasive. Vessel 1 is preferably constructed of a non-magnetic material which is inert to the MP-fluid 2. In 10 Figure 1, vessel 1 is semi-cylindrically shaped in cross-section and has a flat bottom. However, the particular shape of vessel 1 may be modified to suit the workpiece to be polished, as will be described in greater detail.

An instrument 13, such as a blade, is mounted 15 into vessel 1 to provide continuous stirring of the MP-fluid 2 during polishing. A workpiece 4 to be polished is connected to a rotatable workpiece spindle 5. Workpiece spindle 5 is preferably made from a non-magnetic material. Workpiece spindle 5 is mounted on a 20 spindle slide 8, and can be moved in the vertical direction. Spindle slide 8 may be driven by a conventional servomotor which operates according to electrical signals from a programmable control system 12.

Rotation of vessel 1 is controlled by vessel 25 spindle 3, which is preferably positioned in a central location below vessel 1. Vessel spindle 3 can be driven by conventional motor or other power source.

An electromagnet 6 is positioned adjacent to vessel 1 so as to be capable of influencing the MP-fluid 30 2 in a region containing the workpiece 4. Electromagnet 6 should be capable of inducing a magnetic field sufficient to carry out the polishing operation, and preferably will induce a magnetic field of at least about 100 kA/m. Electromagnet 6 is activated by winding 7 from power supply unit 11 which is connected to control system 35 12. Winding 7 can be any conventional magnetic winding. Electromagnet 6 is set up on an electromagnet slide 9 and

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can be moved in a horizontal direction, preferably along the radius of vessel 1. Electromagnet slide 9 may be driven by a conventional servomotor which operates according to electrical signals from the programmable control system 12.

5                   Winding 7 is activated by power supply unit 11 during polishing to induce a magnetic field and influence the MP-fluid 2. Preferably, MP-fluid 2 is acted on by a none-uniform magnetic field in a region adjacent to the workpiece 4. In this preferred embodiment, equal-intensity  
10 lines of the field are normal, or perpendicular, to the gradient of said field, and the force of the magnetic field is a gradient directed toward the vessel bottom normal to the surface of workpiece 4. Application of the magnetic field from electromagnet 6 causes the MP-fluid 2 to change  
15 its viscosity and plasticity in a limited polishing zone 10 adjacent to the surface being polished. The size of the polishing zone 10 is defined by the gap between the pole-pieces of the electromagnet 6 and the shape of the tips of the electromagnet 6. Abrasive particles in the MP-fluid are  
20 preferably acted upon by the MP-fluid substantially only in polishing zone 10, and the pressure of MP-fluid against the surface of workpiece 4 is largest in the polishing zone 10.

                  The composition of the MP-fluid 2 used in the method and devices discussed herein may take different  
25 forms. In a preferred embodiment, an MP-fluid comprising a plurality of magnetic particles, a stabilizer, and a carrying fluid selected from the group consisting of water and glycerin, is used. In a further preferred embodiment, the magnetic particles (preferably

carbonyl iron particles) are coated with a protective layer of a polymer material which inhibits their oxidation. The protective layer is preferably resistant to mechanical stresses, and as thin as practicable. In a 5 preferred embodiment, the coating material is Teflon™. The particles may be coated by the usual process of microcapsulation.

The polishing machine shown in Figure 1 can operate as follows. Workpiece 4 is coupled to workpiece 10 spindle 5, and positioned by spindle slide 8 at a clearance,  $h$ , with respect to the bottom of vessel 1 so that preferably a portion of the workpiece 4 to be polished is immersed in the MP-fluid 2. Said clearance  $h$  may be any suitable clearance which will permit polishing 15 of the workpiece. The clearance  $h$  will affect the material removal rate  $V$  for the workpiece 4, as illustrated in Figure 8, and will also affect the size of a contact spot  $R_c$  at which the polishing zone 10 contacts the workpiece 4. The clearance  $h$  is preferably chosen so 20 that the surface area of the contact spot  $R_c$  is less than one third of the surface area of the workpiece 4. The clearance  $h$  may be changed during the polishing process.

In a preferred embodiment, both workpiece 4 and vessel 1 are rotated, preferably counter to each other. 25 Vessel spindle 3 is put into rotating motion, thereby rotating vessel 1. Vessel spindle 3 rotates about a central axis and preferably rotates vessel 1 at a speed sufficient to effect polishing but insufficient to generate a centrifugal force sufficient to substantially 30 eject or spray MP-fluid 2 out of vessel 1. In a preferred embodiment, the vessel is rotated at a constant velocity. The motion of vessel 1 provides continuous delivery of a fresh portion of MP-fluid 2 to the region where workpiece 4 is located, and provides continuous 35 motion of the MP-fluid 2 in contact with the surface of the workpiece being polished in the polishing zone 10. In a preferred embodiment additional carrying fluid,

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preferably water or glycerin, is added during polishing to replenish carrying fluid that has vaporized, and thus maintain the properties of the fluid.

5 Workpiece spindle 5 is also rotated, about a central axis, to provide rotating movement to workpiece 4. In a preferred embodiment, workpiece spindle 5 operates at speeds of up to 2000 rpm, with about 500 rpm particularly preferred. The motion of workpiece spindle 5 continuously brings a fresh part of the surface of the 10 workpiece 4 into contact with the polishing zone 10, so that material removal along the circumference of the surface being polished will be substantially uniform.

15 As abrasive particles in the MP-fluid 2 contact the workpiece 4, a ring-shaped area having a width of the polishing zone is gradually polished on to the surface of the workpiece 4. Polishing is accomplished in one or more cycles, with an incremental amount of material removed from the workpiece in each cycle. Polishing of the whole surface of the workpiece 4 is achieved by 20 radial displacement of the electromagnet 6 using electromagnet slide 9, which causes the polishing zone 10 to move relative to the workpiece surface.

25 The radial motion of the electromagnet 6 may be continuous, or in discrete steps. If the movement of the electromagnet 6 is continuous, the optimal velocity  $U_z$  of electromagnet 6 for each point of the trajectory of motion is calculated. The velocity of the electromagnet,  $U_z$ , can be calculated according to the following formulae:

$$(I) \quad U_z = 2R_z/t$$

30 or

$$(II) \quad U_z \leq 2R_zV/k,$$

35 wherein  $R_z$  is the radius of the contact spot, in mm, in the polishing zone 10 which contacts the workpiece 4,  $t$  is the time, in seconds, for which the contact spot  $R_z$  is polished during one cycle,  $V$  is the material removal rate, in  $\mu\text{m}/\text{min}$ , and  $k$ , is the thickness, in  $\mu\text{m}$ , of the workpiece material layer to be removed during one cycle

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of polishing.

$R_z$  is a function of the clearance  $h$ , as described above. The material removal rate,  $V$ , can be empirically determined given the clearance  $h$  and the 5 velocity at which the vessel 1 is rotated. The material removal rate  $V$  may be determined by measuring the amount of material removed from a given spot in a given time. The thickness of the workpiece material layer to be removed during one polishing cycle,  $k_3$ , is a function of 10 the accuracy required for the finished workpiece;  $k_3$  may be selected to minimize local error accumulation. For example, when optical glass is polished, the value of  $k_3$  is determined by the required fit to shape in waves. The amount of time for which the contact spot  $R_z$  should be 15 polished during one cycle,  $t$ , is calculated according to the formula:

$$t \leq k_3/V$$

When  $k_3$  and the velocity of the magnet,  $U_z$ , have been determined, the number of cycles required and the 20 time required for polishing may be determined. To calculate the total number of cycles,  $N$ , to polish the workpiece 4, the thickness of the layer of material to be removed during polishing,  $K$ , is calculated according to the formula:

$$25 \quad K = k_1 + k_2$$

where  $k_1$  is the initial surface roughness in  $\mu\text{m}$ , and  $k_2$  is the thickness of the subsurface damage layer in  $\mu\text{m}$ . The number of cycles required,  $N$ , may then be determined using the formula:

$$30 \quad N = K/k_3$$

The amount of time required for one cycle,  $t_c$ , may be calculated using the following formula:

$$t_c = R_w/U_z$$

where  $R_w$  is the radius of the workpiece. Figure 5 shows 35 the relationship of the radius of the workpiece  $R_w$ , the contact spot  $R_z$ , the clearance  $h$ , and the velocity of the magnet  $U_z$  for a flat workpiece such as is shown in

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## Figure 1.

The total time  $T$  required for polishing may be calculated using the formula:

$$T = NR_w/U_z$$

5 where  $N$  is the number of cycles required,  $R_w$  is the radius of the workpiece, and  $U_z$  is the velocity of the electromagnet 6.

If the electromagnet 6 is moved in discrete steps, the dwell time at each step must be determined. 10 In a preferred embodiment, the overall material removal is maintained constant at each step. To remove a constant amount of material during stepwise polishing, it is necessary to take into account material removal due to overlapping of the contact spots  $R_z$  at successive steps.

15 The coefficient of overlapping,  $I$ , is determined by the formula:

$$I = r/2R_z$$

where  $r$  is the displacement of the workpiece in a single step, in mm, and  $R_z$  is the radius of the contact spot.

20 The displacement in a single step,  $r$ , may be determined empirically using results from preliminary trials, such as those detailed in the example given below.

The dwell time for each step in a given cycle,  $t_d$ , may be determined according to the formula:

$$25 t_d = k_3 I/V$$

where  $k_3$  is the thickness of the workpiece material layer to be removed during one polishing cycle,  $I$  is the coefficient of overlapping, and  $V$  is the material removal rate for the workpiece at a given clearance  $h$  and a given velocity of the vessel 1.

The number of steps in one cycle,  $n_s$ , for stepwise polishing may be determined using the formula:

$$n_s = R_w/r$$

35 where  $R_w$  is the radius of the workpiece, and  $r$  is the displacement of the workpiece in a single step. The total number of cycles,  $N$ , required to polish the workpiece may be calculated using the formula used with

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continuous polishing, that is:

$$N = K/k,$$

where  $K$  is the thickness of the layer of material to be removed during polishing, and  $k$ , is the thickness of the workpiece material layer to be removed during one polishing cycle. The total time required for stepwise polishing,  $T$ , may be calculated using the formula:

$$T = t_d n N$$

where  $t_d$  is the dwell time for each step,  $n$ , is the number of steps in one cycle, and  $N$  is the total number of cycles.

In a preferred embodiment of the invention, a computer program for control unit 12 may be prepared on the basis of these calculations, for either continuous or stepwise polishing. The whole process of polishing a workpiece 4 may then be conducted under automatic control. As shown in Figure 1, the control unit 12 preferably includes an input device 26, a processing unit 27, and a signal generator 28.

In an alternate embodiment of the invention, the accuracy of figure generation, or correspondence of the finished workpiece to the desired shape and tolerances, may be improved by conducting tests to determine the spatial distribution of the removal rate of the material as a function of  $R_z$ ,  $V[R_z]$ , in the contact spot  $R_z$ . The spatial distribution of the removal rate may be determined by the method of successive approximation, as detailed in the example given below and in Figure 4. The spatial distribution of the removal rate may then be used to more accurately determine the parameters of the polishing program, such as the dwell time,  $t_d$ , using the formulas previously discussed. In this case, the dwell time can be determined using the formula:

$$t_d = k_z I / V[R_z]$$

Referring to Figure 2, there is shown an alternate embodiment of the invention. This embodiment achieves highly efficient polishing of convex workpieces

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204, such as spherical and nonspherical optical lenses. In Figure 2, the vessel 201 is a circular trough, and the radius of curvature of the internal wall, adjacent to polishing zone 210, is larger than the largest radius of curvature of workpiece 204. During polishing, it is desirable to minimize the movement of the fluid 202 relative to the vessel 201. To minimize this movement, or slippage, of the MP-fluid 202, the internal wall of the vessel 201 may be covered with a layer of a nap, or porous, material 215 to provide reliable mechanical adhesion between the MP-fluid 202 and the wall of the vessel 201.

Workpiece spindle 205 is connected with spindle slide 208, which is connected with a rotatable table 216. The rotatable table 216 is connected to a table slide 217. Spindle slide 208, rotatable table 216, and table slide 217 may be driven by conventional servomotors which operate according to electrical signals from programmable control system 212. Rotatable table 216 permits workpiece spindle 205 to be continuously rocked about its horizontal axis 214, or permits its positioning at an angle  $\alpha$  with the initial vertical axis 218 of spindle 205. Axis 214 preferably is located at the center of curvature of the polished surface at the initial vertical position of the workpiece spindle. Spindle slide 208 permits vertical displacement  $\delta$  of the center of polished surface curvature relative to axis 214. Table slide 217 moves the rotatable table 216 with spindle slide 208 and workpiece spindle 205 to obtain, and maintain, the desired clearance  $h$  between the polished surface of workpiece 204 and the bottom of vessel 201. In this embodiment, an electromagnet 206 is stationary, and is positioned below the vessel 201 such that its magnetic gap is symmetric about the workpiece spindle axis 218 when this axis is perpendicular to the plane of polishing zone 210. The device illustrated in Figure 2 is the same as the device shown in Figure 1 in all other respects.

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The polishing machine operates as follows. To polish workpiece 204, workpiece spindle 205 with attached workpiece 204 is positioned so that the center of the radius of curvature of workpiece 204 is brought into coincidence with the pivot point (axis of rotation 214) of the rotatable table 216. The removal rate for the workpiece to be polished is then determined experimentally, using a test workpiece similar to the workpiece to be polished. Polishing of work piece 204 may then be conducted automatically by moving its surface relative to polishing zone 210 using rotatable table 216, which rocks workpiece spindle 205 and changes the angle  $\alpha$  according to calculated regimes of treatment.

The maximal angle  $\alpha$  to which the spindle 205 may be rocked is determined using the formula:

$$\cos \alpha_{\max} = (R_{sf} - L) / R_{sf}$$

where  $R_{sf}$  is the radius of the total sphere. As shown in Figure 6,  $R_{sf}$  represents what the radius of the workpiece would be if it were spherical, based upon the radius of curvature of the actual workpiece 204.  $L$  represents the thickness of the workpiece 204, as indicated on Figure 6, and it may be calculated using the formula:

$$L = R_{sf} - R_{sf}^2 - R_w^2$$

The angle dimension of the contact spot,  $\beta$ , also indicated on Figure 6, may be determined using the formula:

$$\cos \beta = (R_{sf} - h_0) / R_{sf}$$

where  $R_{sf}$  is the radius of the total sphere and  $h_0$  is the clearance between the bottom of the vessel 201 and the edge of the contact spot  $R_z$  for a curved workpiece, as shown in Figure 6. The height of the contact spot,  $h_0$ , may be determined using the formula:

$$h_0 = R_{sf} - R_{sf}^2 - R_z^2$$

where  $R_{sf}$  is the radius of the total sphere and  $R_z$  is the width of the contact spot.

Rocking of workpiece spindle 205 may be continuous or stepwise. If the workpiece spindle 205 is

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continuously rocked, the angular velocity  $\omega_z$  of this motion is determined by the formula:

$$\omega_z \approx \beta V/k_3$$

5 where  $\beta$  is the angle dimension of the contact spot,  $V$  is the material removal rate, and  $k_3$  is the thickness of the workpiece material layer to be removed during one cycle of polishing. The duration of one cycle,  $t_c$ , may then be calculated using the formula

$$t_c = \alpha_{\max}/\omega_z$$

10 where  $\alpha_{\max}$  is the maximal angle  $\alpha$  to which the spindle 205 may be rocked, and  $\omega_z$  is the angular velocity of the rocking motion.

15 To calculate the total number of cycles,  $N$ , to polish the workpiece 204, the thickness of the layer of material to be removed during polishing,  $K$ , is calculated according to the formula

$$K = k_1 + k_2$$

20 where  $k_1$  is the initial surface roughness in  $\mu\text{m}$ , and  $k_2$  is the thickness of the subsurface damage layer in  $\mu\text{m}$ . The number of cycles required,  $N$ , may then be determined using the formula

$$N = K/k_3$$

where  $k_3$  is the thickness of the workpiece material layer to be removed during one cycle of polishing.

25 The total time  $T$  required to polish the workpiece may then be calculated using the formula

$$T = t_c N$$

where  $t_c$  is the duration of one cycle, and  $N$  is the number of cycles required.

30 If the workpiece spindle 205 is rocked in discrete steps, the dwell time for each step must be calculated. In calculating the dwell time for each step, it is necessary to take the coefficient of overlapping  $I$  into account. The coefficient of overlapping  $I$  is determined by the formula

$$I = \alpha_s/\beta$$

where  $\beta$  is the angle dimension of the contact spot, and  $\alpha_s$

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is the angle displacement for one step. The angle displacement for one step,  $\alpha_s$ , may be calculated by the formula:

$$\alpha_s = \alpha_{\max}/n_s$$

5 where  $\alpha_{\max}$  is the maximal angle  $\alpha$  to which the spindle 205 may be rocked, and  $n_s$  is the number of steps in one cycle. The number of steps per cycle,  $n_s$ , may be calculated using the formula

$$n_s = \alpha_{\max}/\beta$$

10 where  $\alpha_{\max}$  is the maximal angle  $\alpha$  to which the spindle 205 may be rocked, and  $\beta$  is the angle dimension of the contact spot. The current angle  $\alpha$  during polishing may be calculated using the formula:

$$\alpha = \alpha_s N_s$$

15 where  $\alpha_s$  is the angle displacement for one step, and  $N_s$  is the number of the current step.

To calculate the total number of cycles,  $N$ , to polish the workpiece 204, the thickness of the layer of material to be removed during polishing,  $K$ , is calculated 20 according to the formula:

$$K = k_1 + k_2$$

where  $k_1$  is the initial surface roughness in  $\mu\text{m}$ , and  $k_2$  is the thickness of the subsurface damage layer in  $\mu\text{m}$ . The number of cycles required,  $N$ , may then be determined 25 using the formula:

$$N = K/k_3$$

where  $k_3$  is the thickness of the workpiece material layer to be removed during one cycle of polishing.

The dwell time at each step may be calculated 30 using the formula:

$$t_s = k_3 I / V$$

where  $k_3$  is the thickness of the workpiece material layer to be removed during one cycle of polishing,  $I$  is the coefficient of overlapping, and  $V$  is the material removal rate. The total time  $T$  required to polish the workpiece 35 may then be calculated using the formula:

$$T = t_s n_s N$$

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where  $t_s$  is the dwell time for each step,  $n_s$  is the number of steps per cycle, and  $N$  is the number of cycles required.

5 The polishing may be conducted under conditions which yield uniform material removal from each point of the surface, if it is desired that the surface figure should not be altered, or specific material removal goals for each point on the surface may be achieved by varying the dwell time.

10 When a non-spherical workpiece 204 is to be polished, the procedure is generally the same as described for a spherical workpiece. A non-spherical workpiece 204 may be polished to the desired shape by varying the dwell time depending upon the radius of 15 curvature of the section of the workpiece being polished. In an alternate embodiment for polishing a non-spherical workpiece, workpiece spindle 205 may also be moved vertically during polishing. To polish a non-spherical object, the calculations previously described may be 20 carried out for each section of the workpiece having a different radius of curvature. As it is rocked to angle  $\alpha$ , the radius of curvature of the section of a non-spherical workpiece being polished changes. To bring the momentary radius of curvature for the section of the 25 workpiece 204 being polished into coincidence with pivot point 214, rocking of the workpiece spindle 205 is accompanied with vertical motion by spindle slide 208 when polishing non-spherical objects.

30 The magnetic field strength may also be varied for each stage of treatment during polishing, if desired. The material removal rate  $V$  is a function of the magnetic field intensity  $G$ , as shown in Figure 7. It is therefore possible to change the quantities of the operating parameters, such as dwell time or clearance. Thus the 35 magnetic field strength may be used as another means for controlling the polishing process.

Referring to Figure 3, there is shown an

alternate embodiment of the invention. In Figure 3, the internal wall of the vessel 301 has an additional circular trough which passes through the gap of the electromagnet 306. This configuration of the internal wall of the vessel 301 results in a smaller, more focused, polishing zone 310, and an increase in adhesion between the MP-fluid 302 and the vessel 301 is achieved. The smaller, more focused, polishing zone will result in a smaller contact spot  $R_z$ . In all other respects the embodiment depicted in Figure 3 is the same as that depicted in Figure 2.

### Example 1

The polishing of a glass lens was accomplished, using a device as shown in Figure 2. The workpiece 204 had the following initial parameters:

<u>Component</u>	<u>Weight Percentage</u>
30	
Polirit (cerium oxide)	10
Carbonyl iron powder	60
Aerosil™ (fumed silica)	2.5
Glycerin	5.5
Distilled water	balance

35 To determine the material removal rate, a test workpiece 204 identical to the workpiece to be polished was polished at arbitrarily chosen standard parameters.

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The test workpiece was attached to the workpiece spindle 205 and positioned by spindle slide 208 so that the distance between the workpiece surface to be polished and the pivot point of the rotatable table 216 (axis 214) was 5 equal to 40 mm (the radius of curvature of the workpiece 204 surface). Using rotatable table 216, the axis of rotation of workpiece spindle 205 was set up in a vertical position where angle  $\alpha = 0^\circ$ . The clearance  $h$  between the surface of workpiece 204 to be polished and 10 the bottom of the vessel 201 was set at 2 mm using the table slide 217.

Both the workpiece spindle 205 and the vessel 201 were then rotated. The workpiece spindle rotation speed was 500 rpm, and the vessel rotation speed was 150 15 rpm. The electromagnet 206, having a magnet gap equal to 20 mm, was turned on to a level where the magnetic field intensity near the workpiece surface was about 350 kA/m. All parameters were kept constant, and the workpiece was polished for about 10 minutes, which was sufficient to 20 create a well-defined spot.

Next, the workpiece was removed from the workpiece spindle 205. Using a suitable optical microscope, measurements were then conducted to determine the amount of material  $H$  (in  $\mu\text{m}$ ) removed from the 25 original surface as a function of distance  $R$  (in mm) away from the center of the workpiece. In the example described here, a Chapman Instrument MP2000 optical profiler was used to measure the amount of material removed. Depending on the metrology available, about 20 30 measurements are made over a 20 mm distance. In this example, 16 measurements were made over 19.7 mm. The results of these measurements for this example are plotted in Figure 4. These results define the polishing zone for the machine set-up, and they are used as input 35 for calculating the polishing program required to finish the workpiece. The inputs obtained in this example for calculating the polishing program are as follows:

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## 1. Parameters of the workpiece:

- a) radius of the total sphere,  $R_{sf}$ , mm . . . . . 39.6
- b) radius of workpiece,  $R_w$ , mm . . . . . 24.3

## 2. Parameters of the polishing zone:

- 5 a) radius of the contact spot,  $R_z$ , mm . . . . . 17.9
- b) radius of the point where  $(d/dr)(dH/dr) = 0$ ,  $R_d$ , mm . . . . . 10
- c) maximum of  $H$ ,  $H_{max}$ ,  $\mu\text{m}$  . . . . . 21.5
- d) minimum of  $H$ ,  $H_{min}$ ,  $\mu\text{m}$  . . . . . 0.5

## 10 3. Spatial distribution of removed material in the polishing zone:

	$R$ , mm	$H$ , $\mu\text{m}$
	0.0	15.2
	3.3	19.5
15	5.1	21.5
	6.4	20.9
	7.5	19.2
	8.9	16.8
	10.8	11.9
20	12.4	9.8
	13.8	6.7
	15	5.1
	16.2	3.8
	17.2	3.0
25	18.2	1.9
	18.6	1.3
	19.3	1.3
	19.7	0.5

Using these inputs, the polishing required to 30 finish the workpiece is determined. In a preferred embodiment of the present invention, a computer program is used to calculate the necessary parameters and control the polishing operation. Determination of the polishing requirements includes determination of the number of steps for changing angle  $\alpha$ , the value of angle  $\alpha$  for each step, and the dwell time for each step in order to maintain constant the material removal over the surface 35

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of the workpiece by overlapping polishing zones, as described above.

The parameters of the workpiece, parameters of the polishing zone, and spatial distribution of removed material in the polishing zone given above for this example are used to control the system during the polishing method. In this example, the results were entered into a computer program for this purpose. The results of the calculations were as follows:

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Polishing regime

Table 1

	<u>Angle, <math>\alpha</math></u> mm	<u>Time coefficient</u>	<u>Control radiiuses</u>
15	0.00	1.000	0.00
	1.79	1.000	1.25
	3.58	1.000	2.49
	5.37	1.000	3.74
	7.16	1.000	4.98
20	8.95	1.000	6.22
	10.74	1.208	7.45
	12.53	1.208	8.68
	14.32	1.208	9.89
	16.11	1.416	11.10
25	17.90	1.624	12.29
	19.70	1.832	13.48
	21.49	2.040	14.65
	23.28	2.040	15.81
	25.07	2.040	16.95
30	26.86	1.624	18.07
	28.65	1.832	19.18
	30.44	38.119	20.26

As used here, the control radius represents the relative position of the polishing zone with respect to the central vertical axis of the workpiece. The control radius is determined by the angle  $\alpha$ ; during polishing it is the angle  $\alpha$ , rather than the control radius, that is controlled.

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The dwell times for each angle are then converted to minutes by multiplying the time coefficients in table 1 by a constant factor. The constant factor used to convert the time coefficients to dwell times will 5 depend upon the characteristics of the workpiece. For the example given here, this constant was empirically determined to be 5 minutes.

Using the results from table 1, the programmable controller 212 was programmed. The workpiece 10 204 to be polished was attached to the workpiece spindle 205, and the procedure described for the test workpiece was repeated under the automatic control of the programmable controller 212. The following results were obtained.

15

#### Results of polishing

Final fit to shape, waves . . . . . 1

Final roughness,  $\mu\text{m}$  . . . . . 0.0011

In addition to the embodiments described above, there are numerous alternate embodiments of the device of 20 the present invention. Some of these alternate embodiments are shown in Figures 9 through 30. As illustrated by these figures, only a magnetorheological fluid, a means for inducing a magnetic field, and a means for moving the object to be polished or the means for 25 inducing the magnetic field relative to one another are required to construct a device according to the present invention. For example, Figures 9 through 11 illustrate an embodiment of the invention in which the magnetorheological fluid is not contained within a 30 vessel.

In Figure 9, an MP-fluid 902 is placed at the poles of an electromagnet 906. Electromagnet 906 is positioned so that the magnetic field that it creates acts only upon a particular surface section of the object 35 to be polished 904, thereby creating a polishing zone. In operation, object 904 is put into rotation. Either electromagnet 906, or object 904, or both electromagnet

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906 and object 904, are then moved such that step-by-step the entire surface of the object is polished. Electromagnet 906, object to be polished 904, or both, may be displaced relative to each other in the vertical and/or horizontal planes. During polishing the magnetic field strength is also regulated, as required, to polish the object 904. Rotation of the object 904, movement of the electromagnet 906 and/or the object 904, and regulation of the magnetic field strength according to a predetermined program of polishing permits controlled removal of material from the surface of the object to be polished 904.

Figure 10 illustrates a device for polishing curved surfaces. In Figure 10, an MP-fluid 1002 is placed at the poles of electromagnet 1006. The electromagnet 1006 is configured such that it generates a magnetic field affecting only some surface section of an object to be polished 1004. Object to be polished 1004, which has a spherical or aspherical surface, is put into rotation. Electromagnet 1006 is displaced to an angle  $\alpha$  along the trajectory which corresponds to the radius of curvature of the object 1004, as indicated by the arrows in Figure 10, such that the electromagnet is moved parallel to the surface of the object, according to a predetermined program of polishing, thus controlling material removal along the part surface.

In Figure 11, an MR-fluid 1102 is also placed at the poles of electromagnet 1106. The electromagnet is configured such that it generates a magnetic field acting only upon some surface section of the object to be polished 1104. In operation, an object to be polished 1104 having a spherical or aspherical surface is put into rotation. The object to be polished 1104 is then rocked, such that an angle  $\alpha$ , indicated on Fig. 11, varies from 0 to a value which depends upon the size and shape of the workpiece. Rocking the workpiece 1104 relative to the electromagnet 1106, thus varying the angle  $\alpha$ , according

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to a predetermined program of polishing, controls material removal along the surface of the object to be polished.

5 In Figure 12, MR-fluid 1202 is placed into a vessel 1201. An electromagnet 1206 is positioned beneath vessel 1201 and configured such that the electromagnet 1206 initiates a magnetic field which acts only upon a section, or polishing zone 1210, of the MP-fluid 1202 in the vessel 1201. The MP-fluid in the polishing zone 1210 10 acquires plastic properties for effective material removal in the presence of a magnetic field. Object to be polished 1204 is put into rotation, and electromagnet 1206 is displaced along the surface to be polished. The workpiece may then be polished according to a 15 predetermined program which controls material removal along the surface of the object to be polished.

In Figure 13, an MP-fluid 1302 is placed into a vessel 1301. Electromagnet 1306 is configured such that it induces a magnetic field acting only upon a section, 20 or polishing zone 1310, of the MP-fluid 1302. The MP-fluid 1302 thus acts only upon the section of the object to be polished 1304 positioned in the polishing zone 1310. Object to be polished 1304 and vessel 1301, with 25 their axes coinciding, are put into rotation at the same or different speeds in the same or opposite directions. Displacing electromagnet 1306 radially along the vessel surface according to an assigned program displaces the polishing zone 1310, and controls material removal along the surface of the object to be polished.

30 In Figure 14, an MP-fluid 1402 is placed into a vessel 1401. A casing 1419 which contains a system of permanent magnets 1406 is set under the vessel 1401. An electromagnetic field created by each magnet 1406 affects only a section, or polishing zone 1410, of the object to be polished. In operation, object to be polished 1404 and vessel 1401 are simultaneously put into rotation. 35 The rotation axes of object to be polished 1404 and

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vessel 1401 are eccentric relative to each other. The casing 1419, or the object to be polished 1404, or both, are simultaneously displaced according to a predetermined program of polishing, thus controlling material removal 5 along the object to be polished surface.

In Figure 15, an MP-fluid 1502 is placed into a vessel 1501. Electromagnet 1506 is positioned under the vessel such that its magnetic field affects only a section, or polishing zone 1510, of the MP-fluid 1502 in 10 the vessel 1501. Object to be polished 1504, which has a spherical or curved shape, and vessel 1501 are put in rotation in the same or opposite directions. While polishing, object 1504 is rocked such that an angle  $\alpha$ , indicated on Fig. 15, varies from 0 to a value which 15 depends upon the size and shape of the object 1504. The rotation of the object 1504 and the vessel 1501, and the angle  $\alpha$ , are controlled according to a predetermined program of polishing. As a result, material removal along the surface of the object to be polished is 20 controlled.

In Figure 16, an MP-fluid 1602 is placed into a longitudinal vessel 1601. The shape of the inner cavity of the vessel 1601 is chosen to parallel the surface of the object 1604, such that the inner wall of the vessel 25 is equi-distant from the generatrix of object 1604 at  $\alpha = 0$ . An electromagnet 1606 is positioned below the vessel 1601 such that it induces a magnetic field in a section, or polishing zone 1610, of the MP-fluid 1602. In operation, the electromagnet 1606 is displaced along the bottom of the vessel 1601 while the object 1604 and the vessel 1601 are rotating. The object is also rocked to 30 an angle  $\alpha$  during the polishing program. Rotation of the object 1604 and vessel 1601, movement of the electromagnet 1606, and rocking the object 1604 according 35 to a predetermined program of polishing permits controlled removal of material from the surface of the object to be polished 904.

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In Figure 17, MP-fluid 1702 is placed into a circular vessel with an annular cavity 1701. Electromagnet 1706 is positioned under the vessel 1701. Electromagnet 1706 is chosen such that its magnetic field 5 affects a section, or polishing zone 1710, of the MP-fluid 1702. Object to be polished 1704 and vessel 1701 are put into rotation in the same or opposite directions at equal or different speeds. Displacing electromagnet 1706 radially along the bottom of the annular cavity of 10 the vessel 1701, according to a program of polishing, controls material removal along the surface of the object to be polished 1704.

In Figure 18, an MP-fluid 1802 is placed into a circular vessel with an annular cavity 1801. The vessel 15 bottom is coated with a nap material 1815, which hinders slippage of the MP-fluid 1802 relative to the vessel bottom 1801, and enhances the rate of material removal from the surface of the object. Electromagnet 1806 is mounted under the vessel cavity 1801. The pole pieces of 20 the electromagnet 1806 are chosen such that its field will affect only a section, or polishing zone 1810, of the MP-fluid, and therefore it will only affect a portion of the surface of the object to be polished 1804.

The object to be polished 1804, the 25 longitudinal vessel 1801, or both, are put into rotation at the same or different speeds, in the same or opposite directions. Electromagnet 1806 is also displaced relative to the surface of the object to be polished 1804 according to a program of polishing.

In Figure 19, MP-fluid 1902 is placed into an 30 annular cavity in a circular vessel 1901. The radius of curvature of the vessel cavity is chosen to correspond to the desired radius of curvature of the object 1904 after polishing, such that the inner wall of the cavity 1901 35 will equi-distant to the surface of the polished object 1904. Object to be polished 1904, which is mounted on a spindle 1905, and vessel 1901 are put into rotation at

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equal or different speeds in the same or opposite directions. Electromagnet 1906 is displaced along the bottom of the vessel cavity 1901 according to a predetermined program, thus controlling material removal along the surface of the object to be polished.

In Figure 20, the MP-fluid 2002 is also placed into a circular vessel with an annular cavity 2001. An electromagnet 2006 is mounted under the vessel 2001. The pole pieces of the electromagnet 2006 are chosen such that its field will affect only a section, or polishing zone 2010, of the MP-fluid 2002, and therefore will affect only a surface section of the object to be polished 2004.

Object to be polished 2004 and the vessel 2001 are put into rotation at the same or different speeds in the same or opposite directions. The object to be polished 2004 is also rocked, or swung, relative to the vessel. The object is rocked from a vertical position to an angle  $\alpha$  during polishing according to a predetermined program, thereby controlling material removal along the surface to be polished.

In Figure 21, an MP-fluid 2102 is placed in a circular vessel 2101 with an annular cavity having a valley 2120. The pole pieces of electromagnet 2106 are chosen such that its magnetic field will affect only a portion, or polishing zone 2110, of the MP-fluid 2101. In Fig. 21, the portion of the MP-fluid 2102 affected by the magnetic field is located within, or above, the valley 2120.

An object to be polished 2104 is put into rotation. The object to be polished 2104 is also rocked, or swung, relative to its axis normal to the vessel rotation plane to an angle  $\alpha$ , according to an assigned program, thus controlling material removal along the surface of the object to be polished.

In Figure 22, an MP-fluid 2202 is placed into a cylindrical vessel 2201. Objects to be polished 2204a,

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2204b, etc. are fixed on spindles 2205a, 2205b, etc., which are, mounted on a disc 2221 capable of rotating in the horizontal plane. An electromagnet 2206 is installed under the vessel such that it creates a magnetic field along the entire surface of vessel 2201.

5 Disc 2221, vessel 2201, and objects to be polished 2204a, 2204b, etc. are put into rotation in the same or opposite directions with equal or different speeds. By regulating the magnetic field intensity and 10 the rotation of the disc, the vessel, and the objects, the rate of removal of material from the surface of the object to be polished is controlled.

15 In Figure 23, an MP-fluid 2302 is placed into a vessel 2301. An electromagnet 2306 is installed below the vessel bottom. The pole pieces of the electromagnet are chosen such that it will create a magnetic field which acts only upon a portion, or polishing zone 2310, 20 of the MP-fluid 2302 in the vessel 2301. Objects to be polished 2304a, 2304b, etc. are mounted on spindles 2305a, 2305b, etc., which are capable of rotating relative to a disc 2321 on which they are installed. Disc 2321 is also capable of rotating relative to vessel 2301.

25 Disc 2321, objects to be polished 2304a, 2304b, etc., and vessel 2301 are put into rotation at equal or different speeds, in the same or opposite directions. Electromagnet 2306 is also radially displaced along the 30 surface of the vessel. This rotation, and displacing electromagnet 2306 along the vessel surface, are regulated to control material removal from the surface of the object to be polished.

35 In Figure 24, an MP-fluid 2402 is placed into a vessel 2401. Electromagnets 2406a, 2406b, etc. are mounted near the vessel bottom. The pole pieces of electromagnets 2406a, 2406b, etc. are chosen such that each will create a field acting only upon a section, or polishing zone 2410a, 2410b, etc., of the vessel fluid

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2402. Objects to be polished 2404a, 2404b, etc. are mounted on spindles 2405a, 2405b, etc. which are capable of rotating relative to a disc 2421 on which they are installed. Disc 2421, objects to be polished 2404a, 5 2404b, etc. and vessel 2401 are put into rotation with equal or different speeds, in the same or opposite directions. Electromagnets 2406a, 2406b, etc. are also radially displaced along the bottom surface of the vessel 2401. This rotation, and displacing electromagnets 10 2406a, 2406b, etc. along the vessel surface, are regulated to control material removal from the surface of the object to be polished.

In Figure 25, an MP-fluid 2502 is placed into a circular vessel 2501 with an annular cavity. Objects to 15 be polished 2504a, 2504b, etc. are mounted on spindles 2505a, 2505b, etc. Electromagnets 2506a, 2506b, etc. are mounted under the vessel 2501 such that the electromagnet-induced magnetic field will affect the entire volume of the MP-fluid, and thus the entire 20 surface of the objects to be polished. Vessel 2501 and objects to be polished 2504a, 2504b, etc. are rotated in the same or opposite directions, with equal or different speeds. The electromagnet-induced magnetic field intensity is also controlled. This results in controlled 25 material removal from the surface of the object to be polished.

In Figure 26, an MP-fluid 2602 is placed into a circular vessel 2601 with an annular cavity. Objects to be polished 2604a, 2604b, 2604c, 2604d, etc. are mounted 30 on spindles 2605a, 2605b, 2605c, 2605d, etc., which are installed on a disc 2621 which is capable of rotating in the horizontal plane.

Electromagnets 2606a, 2606b, etc. are installed under the vessel surface. The pole pieces of the 35 electromagnets are chosen such that the electromagnets will create a magnetic field over the entire vessel width.

Rotating vessel 2601, disc 2621, and objects to be polished 2604a, 2604b, 2604c, 2604d, at equal or different speeds, in the same or different directions, controls the material removal rate for a given magnetic field intensity.

In Figure 27, an MP-fluid 2702 is placed into a circular vessel 2701 having an annular cavity. An electromagnet 2706 induces a magnetic field along the entire surface of vessel 2701. Objects to be polished 2704a, 2704b, 2704c, 2704d, etc. are mounted on spindles 2705a, 2705b, 2705c, 2705d, etc. Spindles 2705a, 2705b, 2705c, 2705d, etc. are mounted on discs 2721a, 2721b, etc., which are capable of rotating in a horizontal plane. Discs 2721a, 2721b, etc. are mounted on spindles 2724a, 2724b, etc. This figure illustrates one possible design for simultaneously polishing numerous objects.

In Figure 28, an MP-fluid 2802 is placed into vessel 2801. Two units 2822a and 2822b equipped with permanently mounted magnets 2823 are installed inside the vessel 2801.

A flat object to be polished 2804 is mounted between units 2822a and 2822b. Units 2822a and 2822b are rotated about their horizontal axes. These units are rotated at the same speed such that a magnetic field, and polishing zones 2810, will be created when different-sign poles are on the contrary with each other. Object to be polished 2804 is moved in such a way that polishing zones are created for both object surfaces. The material removal rate is controlled by the rotation speed of units 2822a, 2822b and the speed at which the object 2804 is vertically displaced.

In Figure 29, an MP-fluid 2902 is placed into vessel 2901. Units 2922 equipped with magnets 2923 are mounted inside vessel 2901 and are capable of rotating along the axis normal to the displacement direction of the object to be polished 2904. The magnets are mounted in the unit so that the permanent magnets mounted side by

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side would have different-sign poles relative to each other, so as to create a polishing zone 2910 between the magnets.

5 The polishing is carried out by rotating unit 2922 and giving a scanning motion to object to be polished 2904 in the vertical plane. The material removal rate is controlled by changing the rotational speeds of units 2922 and the speed at which object to be polished 2904 is displaced.

10 Figure 30 illustrates an apparatus for polishing spherical objects. The objects 3004a, 3004b, etc. are placed in a channel 3025 formed between a top vessel 3001b and a bottom vessel 3001a. The channel 3025 is filled with an MP-fluid 3002, which is affected by a 15 magnetic field induced by an electromagnet 3006. In operation, top vessel 3001b and bottom vessel 3001a are rotated counter to one another. The rotation of the MP-fluid 3002 with the vessels 3001a and 3001b causes the spherical objects to be polished.

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CLAIMS:

1. A magnetorheological fluid for finishing workpiece surfaces, comprising:

soft magnetic particles;

abrasive particles;

a stabilizer; and

a carrying fluid,

wherein the soft magnetic particles are coated with an oxidation inhibiting polymer and wherein the carrying fluid comprises water.

2. The magnetorheological fluid of claim 1, wherein said oxidation inhibiting polymer comprises Teflon™.

3. The magnetorheological fluid of claim 1, wherein said magnetorheological fluid comprises 22% water by weight.

4. The magnetorheological fluid of any one of claims 1 to 3, wherein said carrying fluid comprises glycerin.

5. The magnetorheological fluid of claim 4, wherein said magnetorheological fluid comprises 5.5% glycerin by weight.

6. The magnetorheological fluid of any one of claims 1 to 5, wherein said soft magnetic particles comprise carbonyl iron particles.

7. The magnetorheological fluid of claim 6, wherein said magnetorheological fluid comprises at least 60% carbonyl iron particles by weight.

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8. The magnetorheological fluid of any one of claims 1 to 7, wherein said abrasive particles comprise CeO<sub>2</sub>.
9. The magnetorheological fluid of claim 8, wherein said magnetorheological fluid comprises 10% CeO<sub>2</sub> by weight.
10. The magnetorheological fluid of any one of claims 1 to 9, wherein said stabilizer comprises fumed silica.
11. The magnetorheological fluid of any one of claims 1 to 9, wherein said stabilizer comprises Aerosil™.
12. The magnetorheological fluid of claim 11, wherein said magnetorheological fluid comprises 2.5% Aerosil™ by weight.
13. The magnetorheological fluid of any one of claims 1 to 12, wherein said oxidation inhibiting polymer is resistant to mechanical stress.
14. The magnetorheological fluid of any one of claims 1 to 13, wherein application of a magnetic field causes the magnetorheological fluid to acquire characteristics of a plasticized solid having a yield point that depends on intensity of the magnetic field and viscosity of the magnetorheological fluid.

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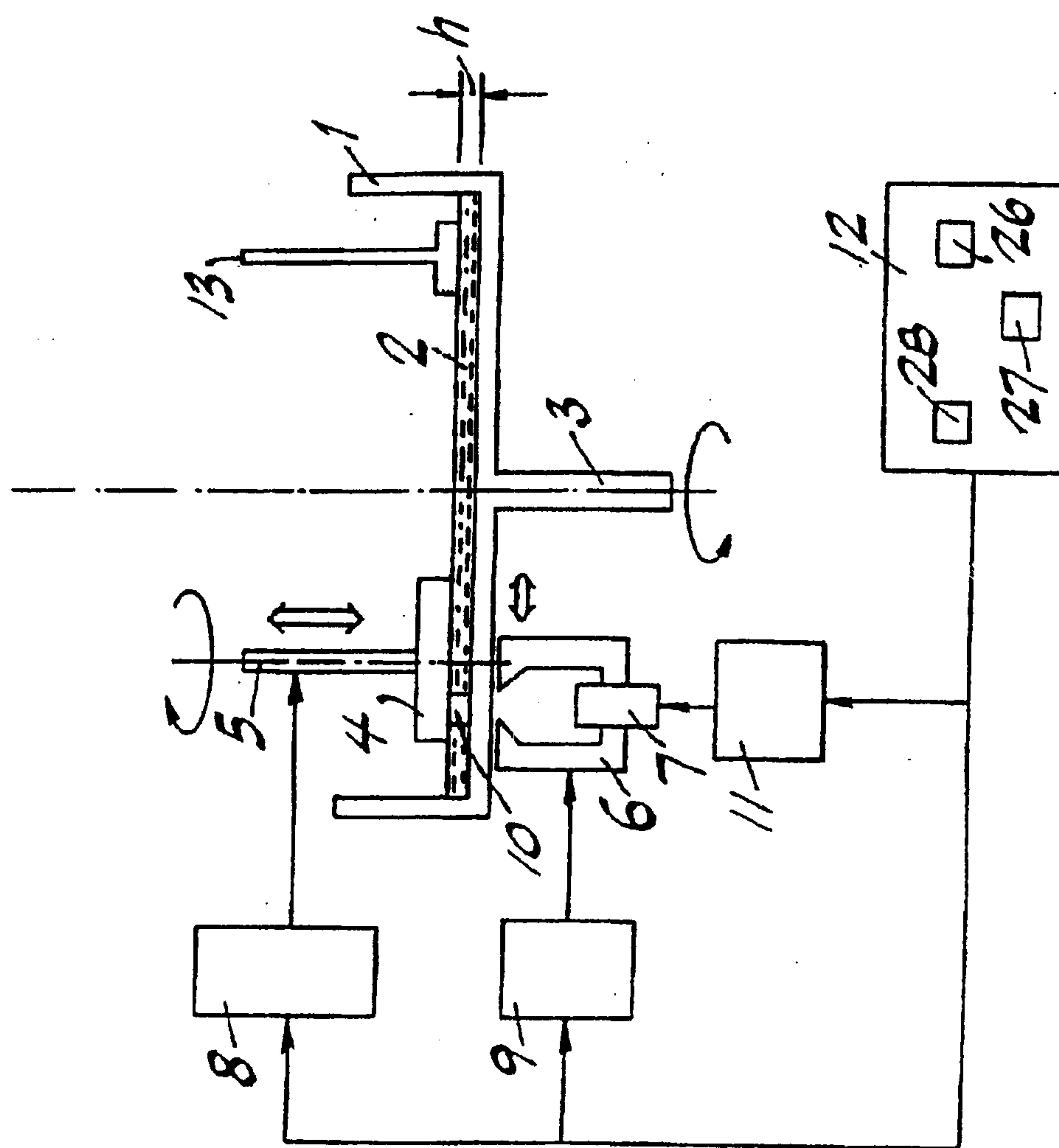


FIG. 1

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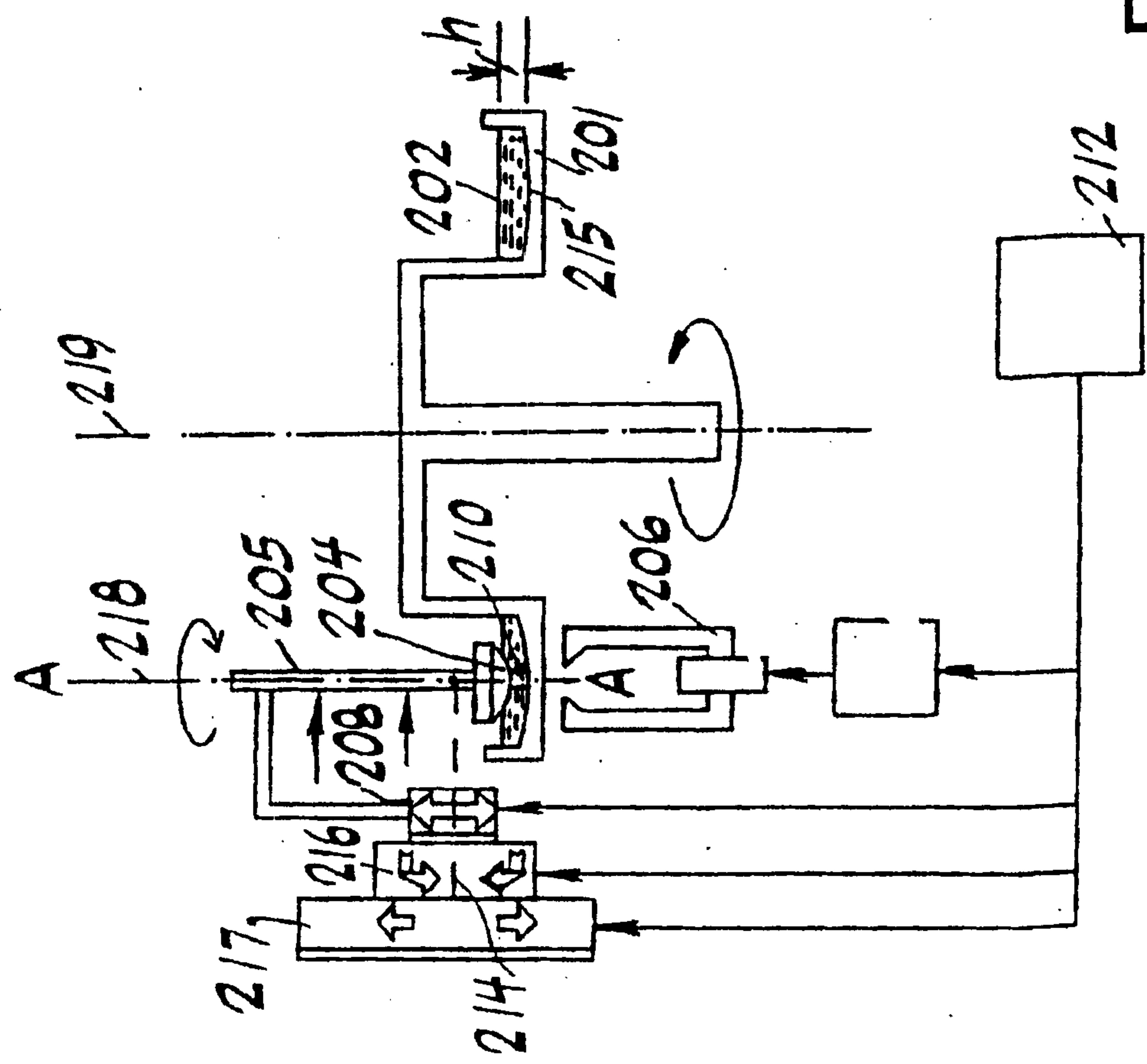
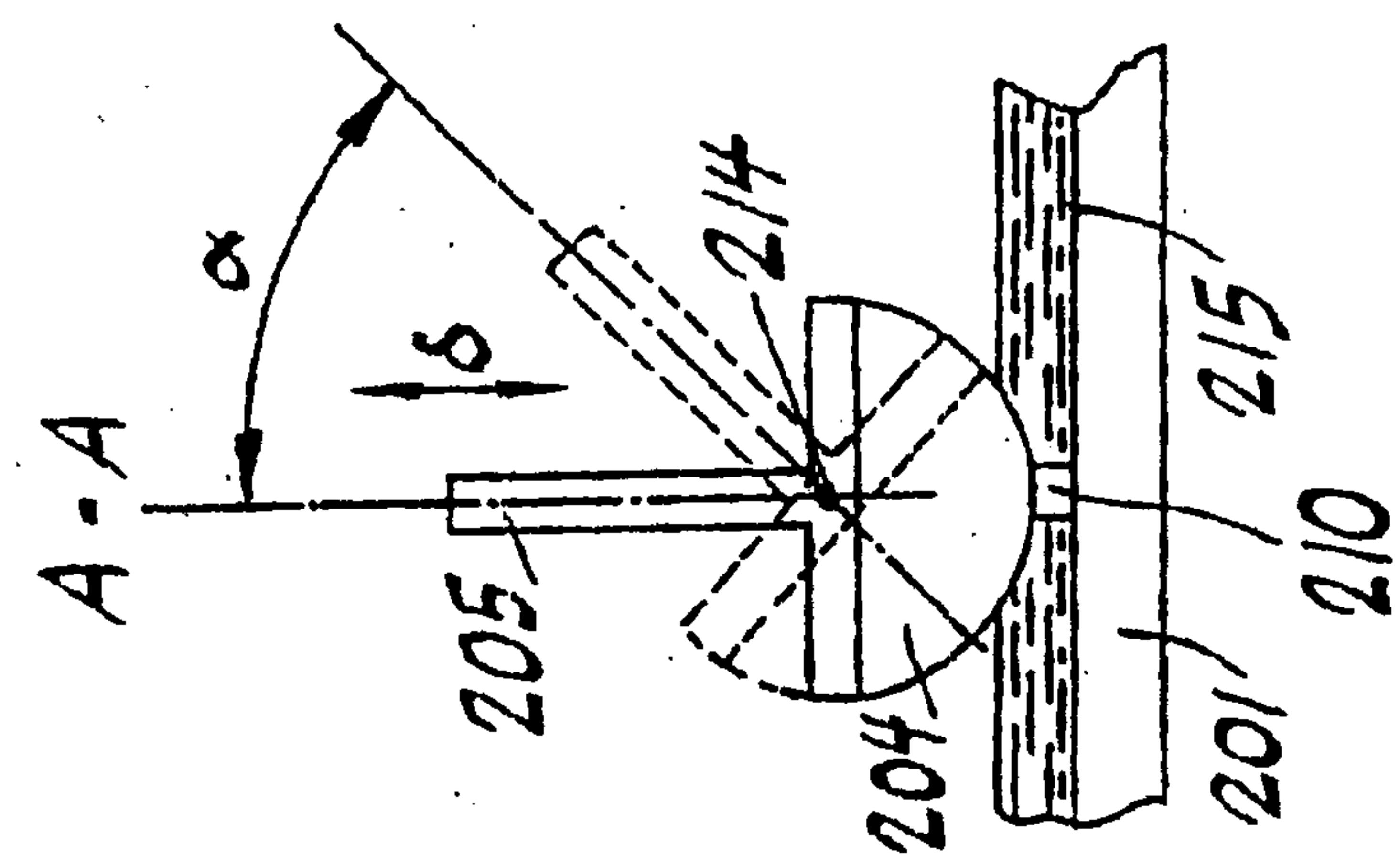


FIG. 2

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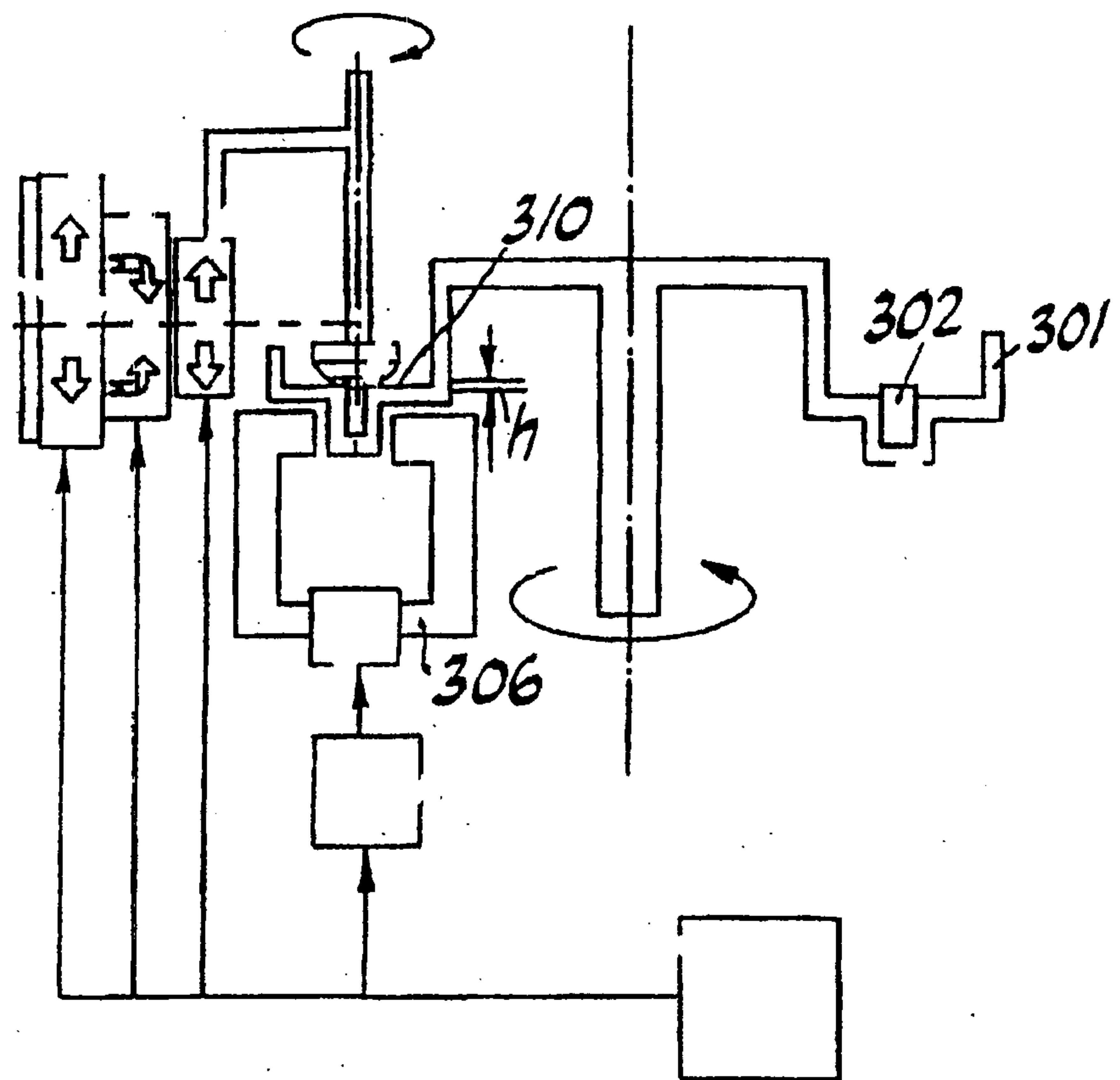


FIG. 3

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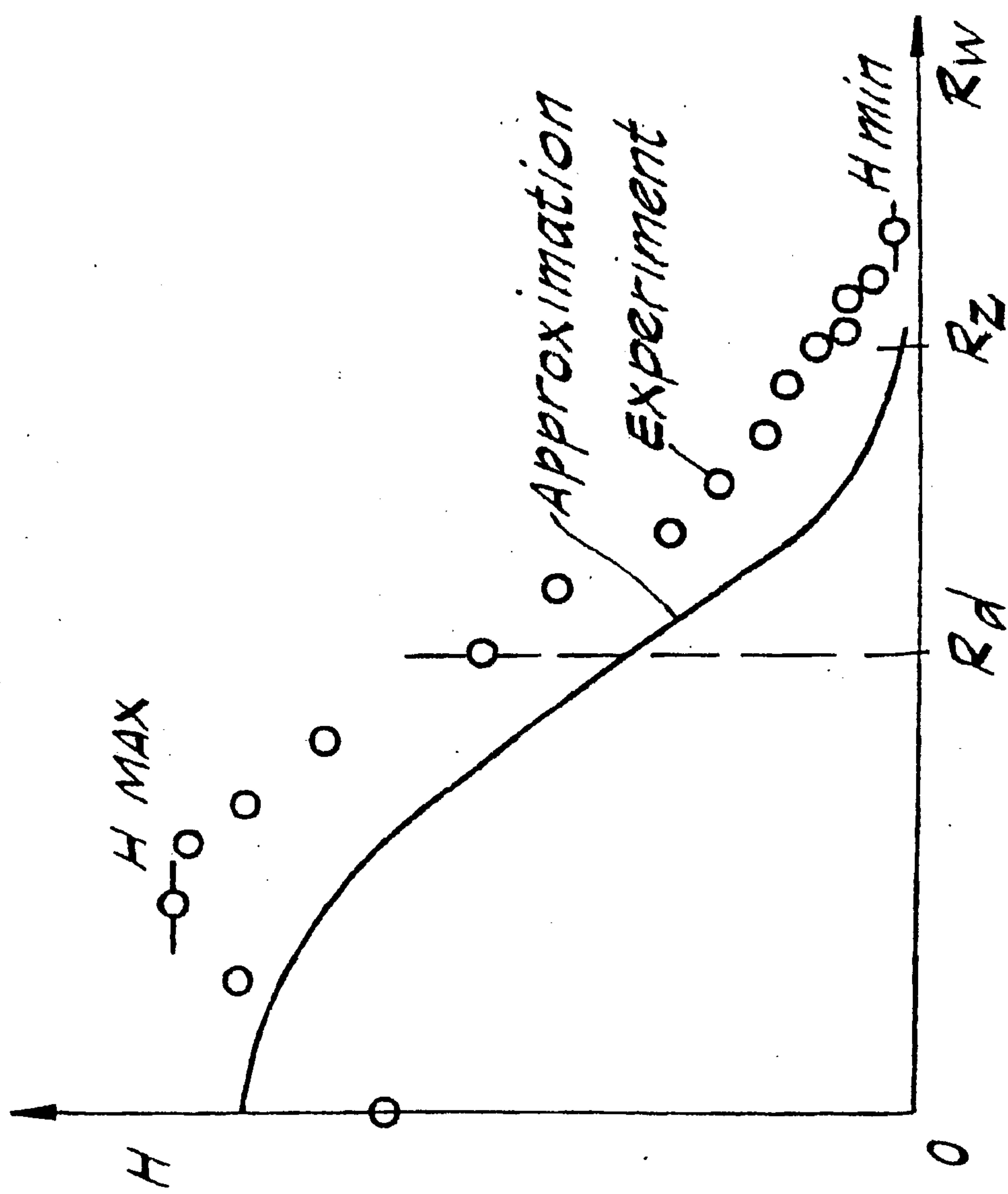


FIG. 4

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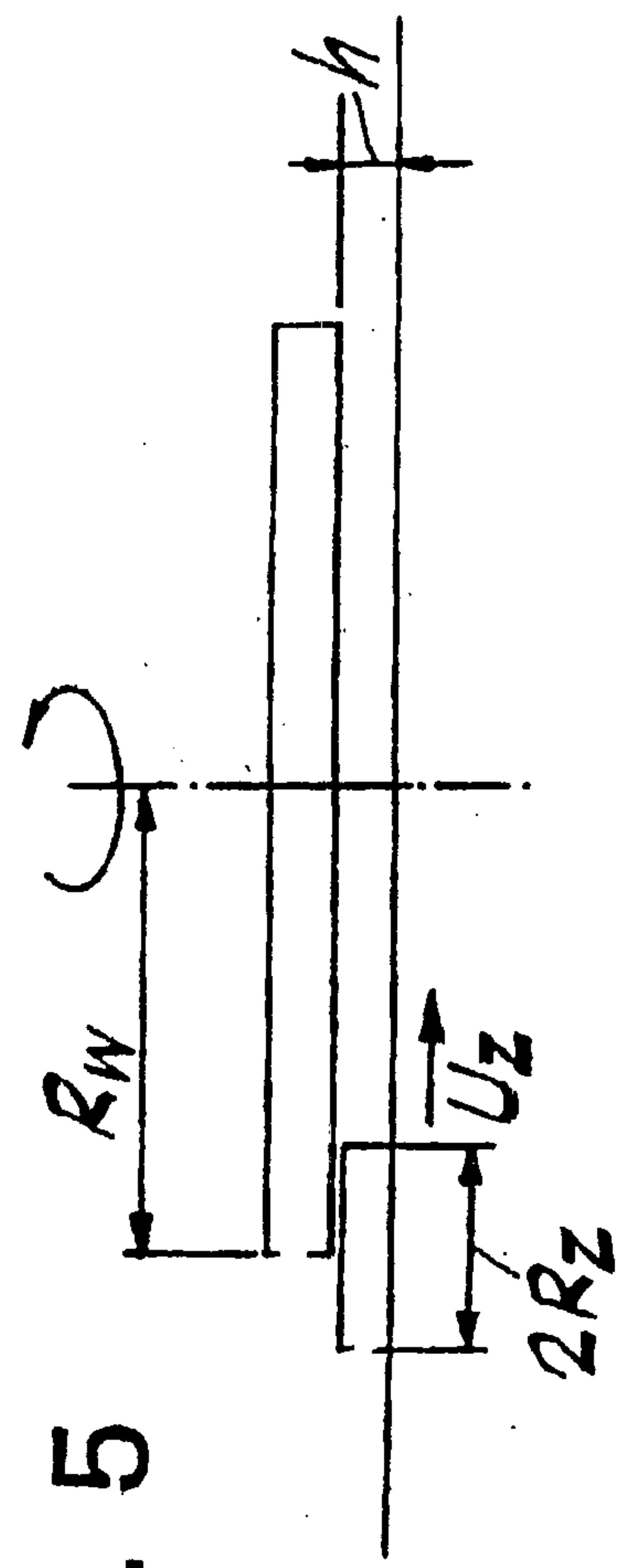


FIG. 5

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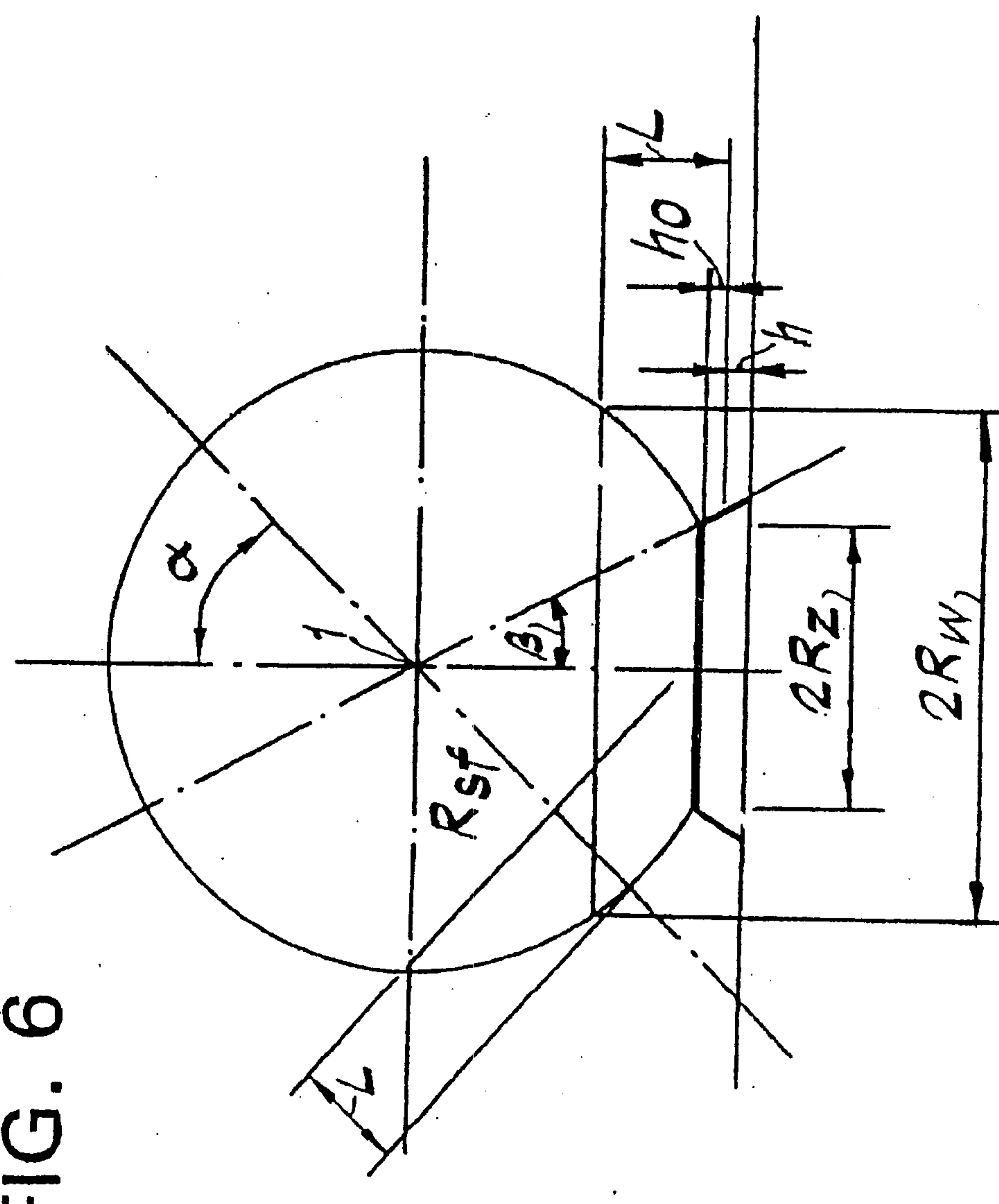


FIG. 6

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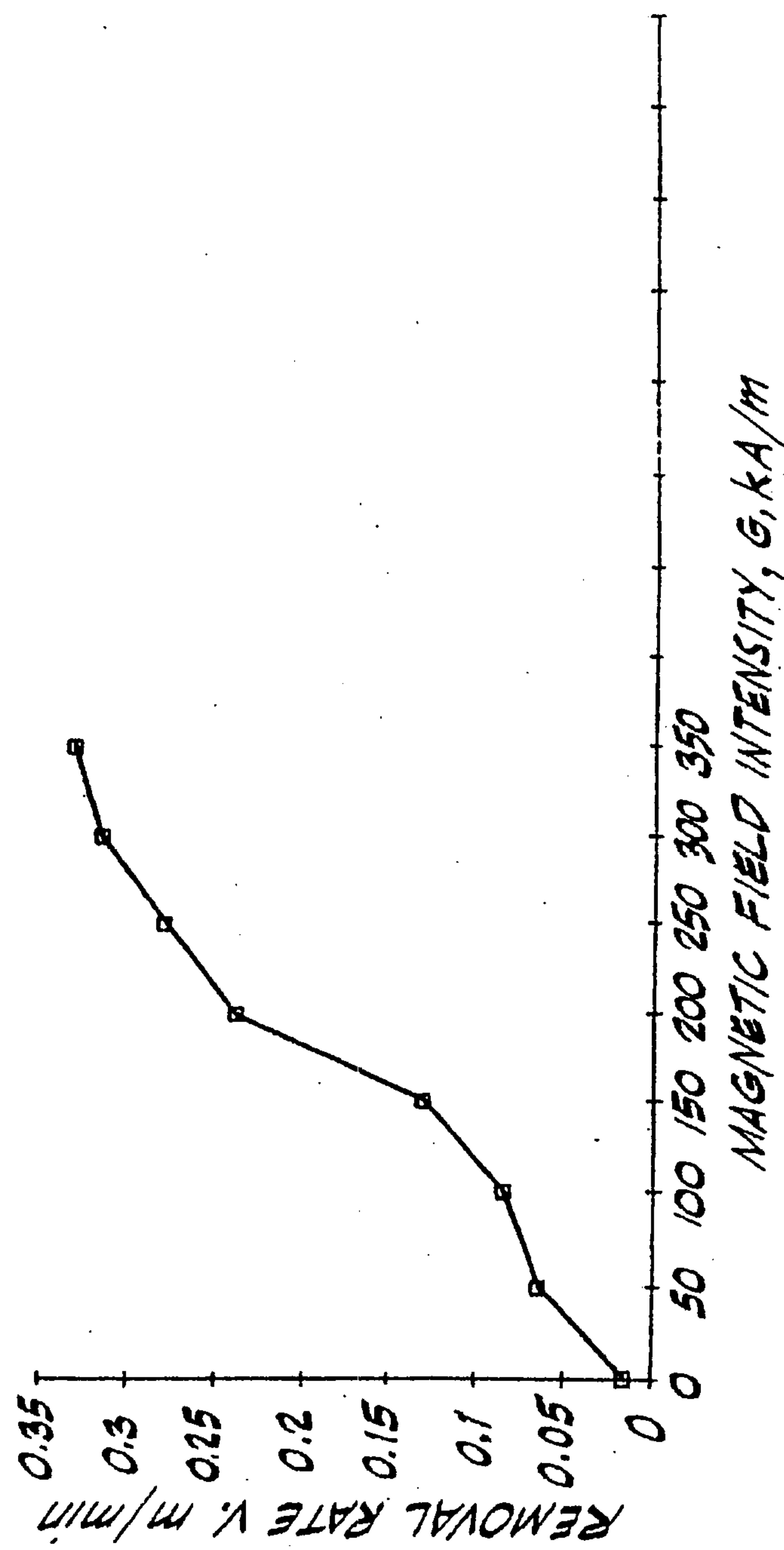


FIG. 7

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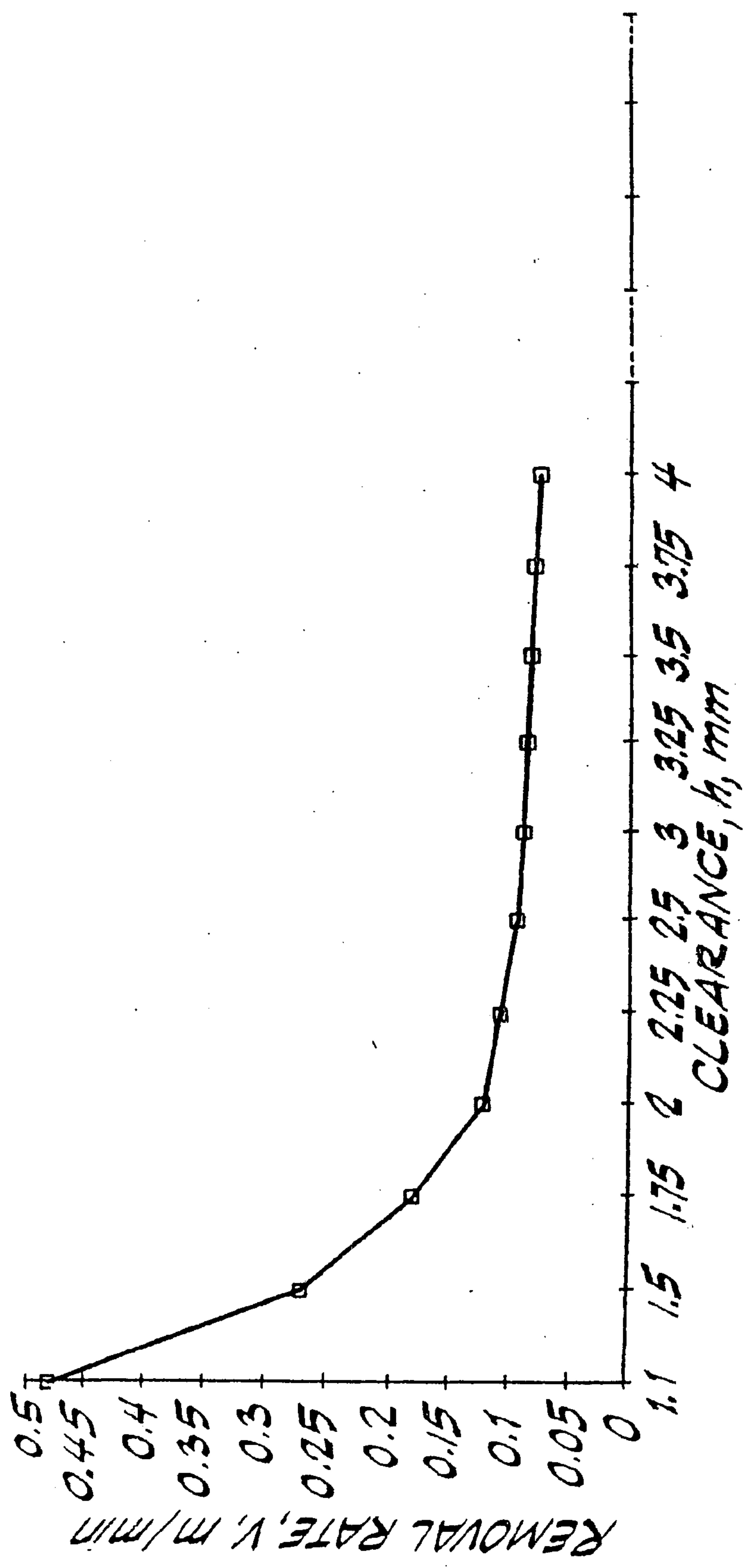


FIG. 8

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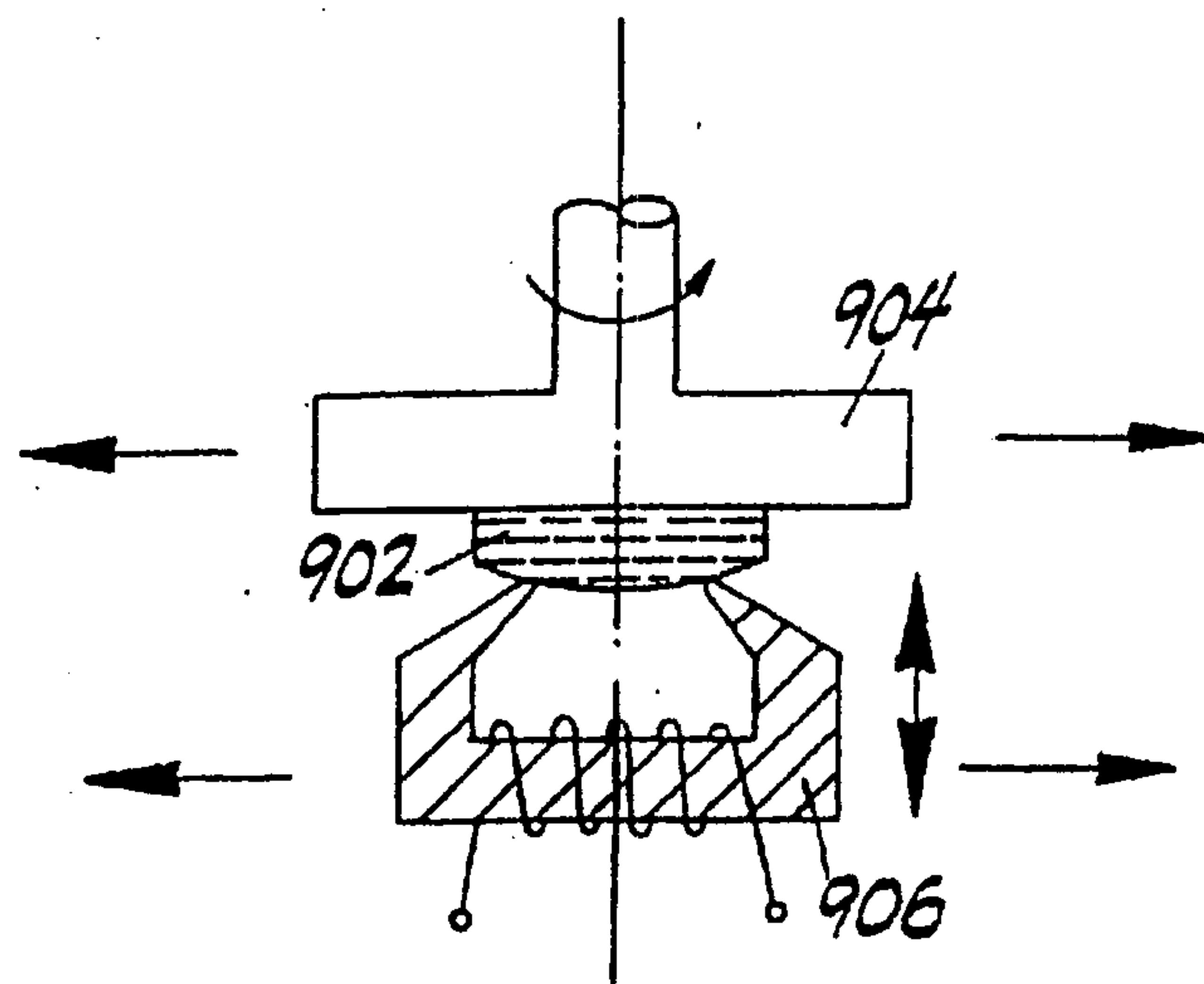


FIG. 9

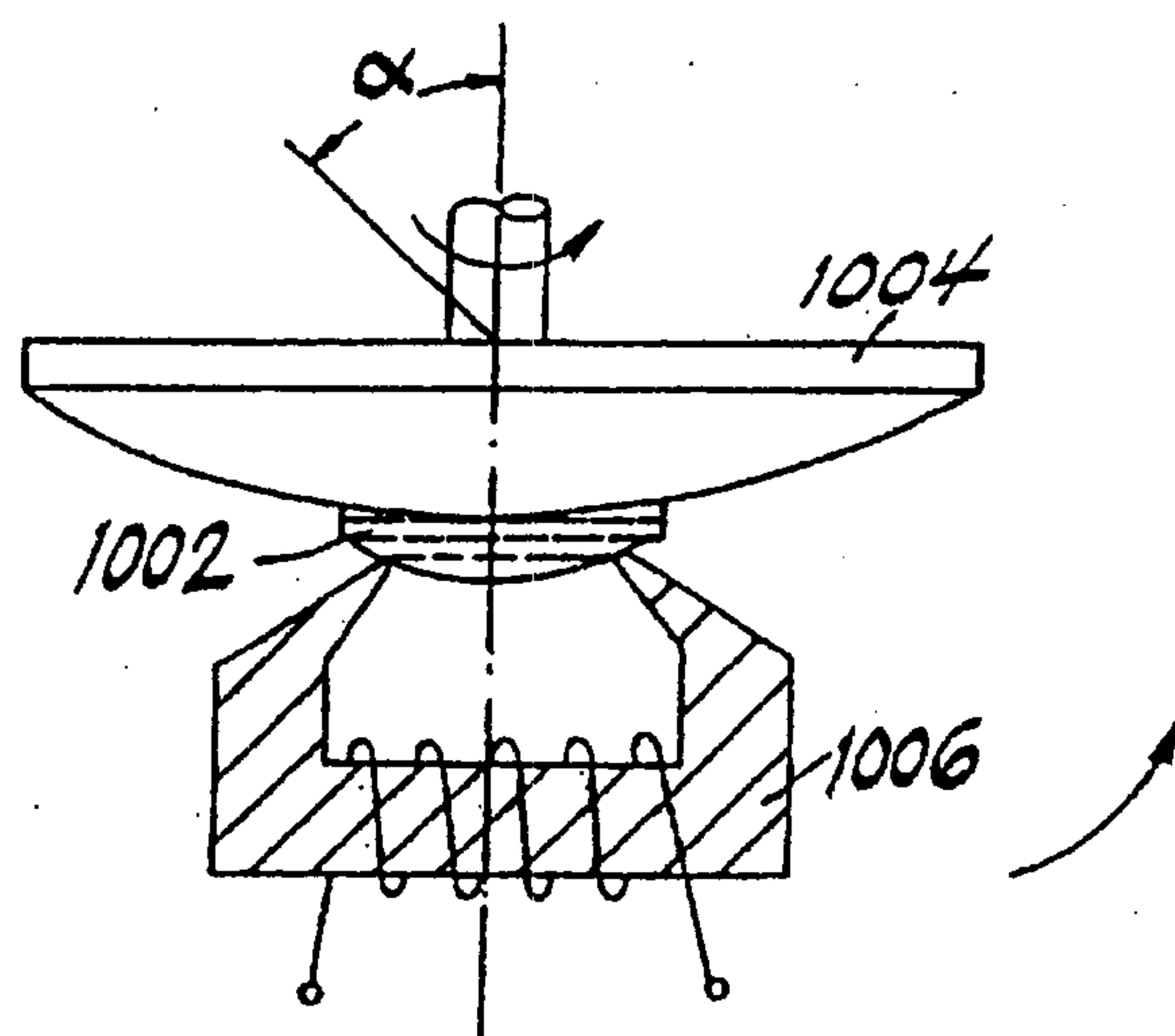


FIG. 10

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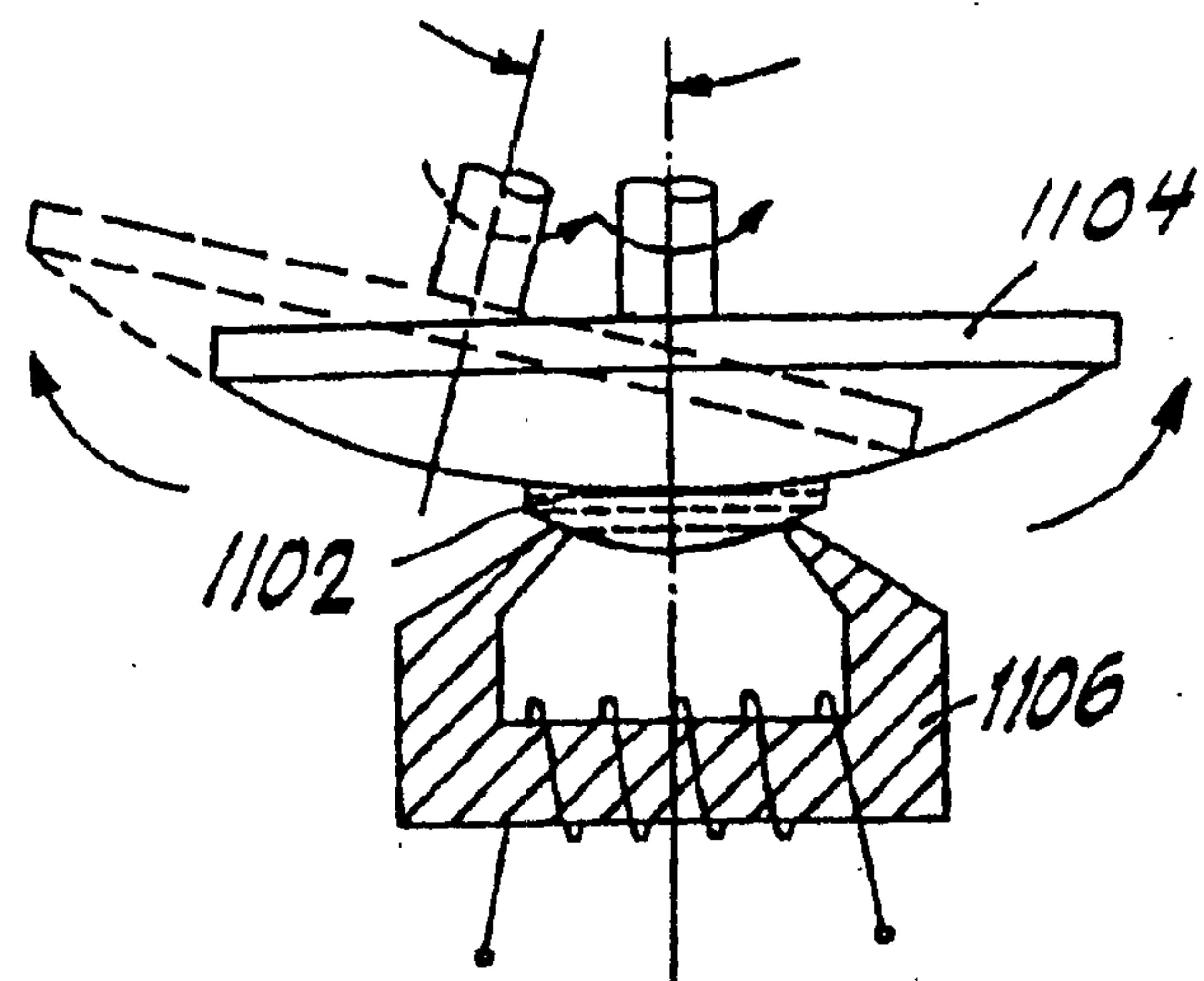


FIG. 11

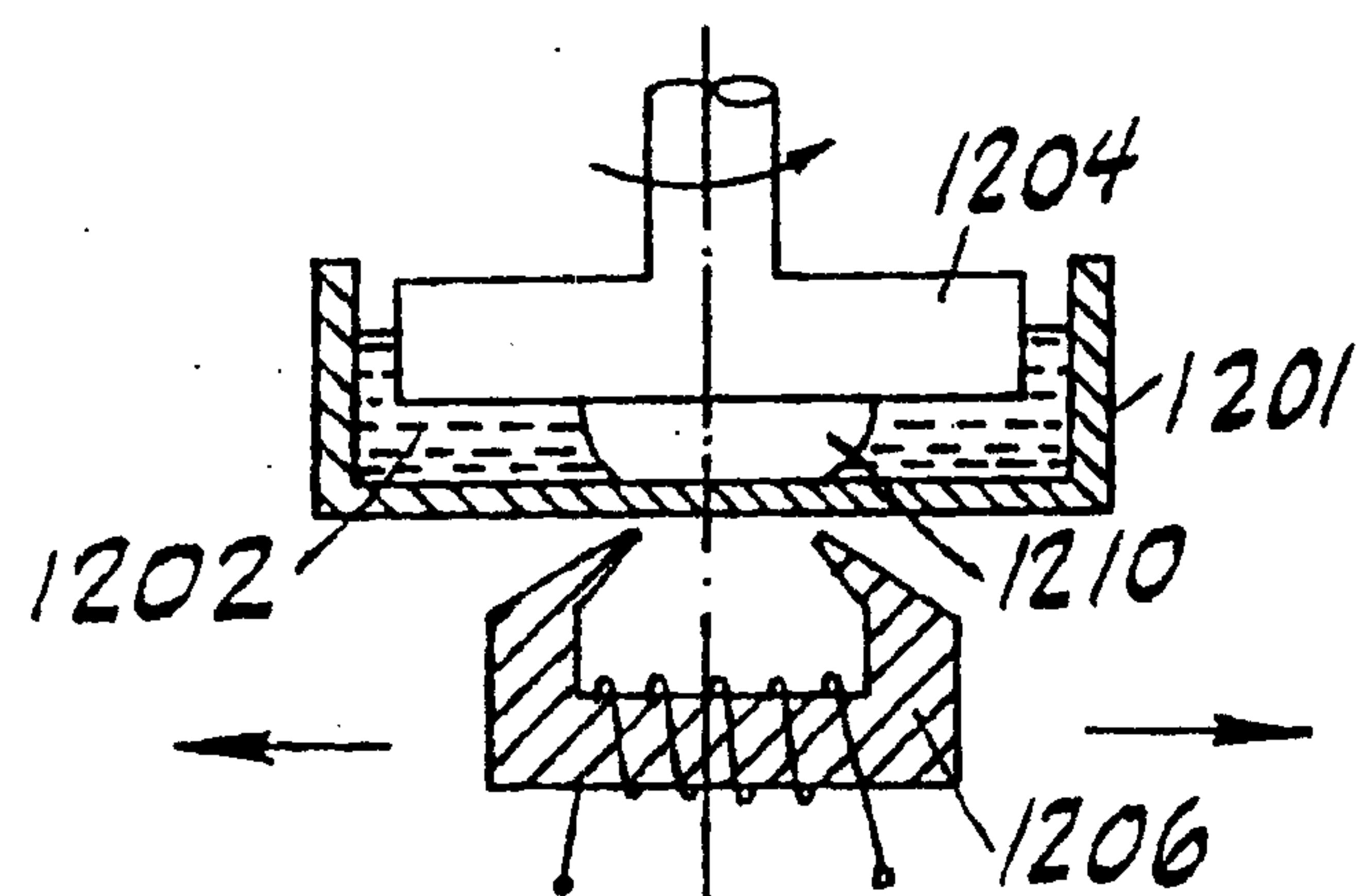


FIG. 12

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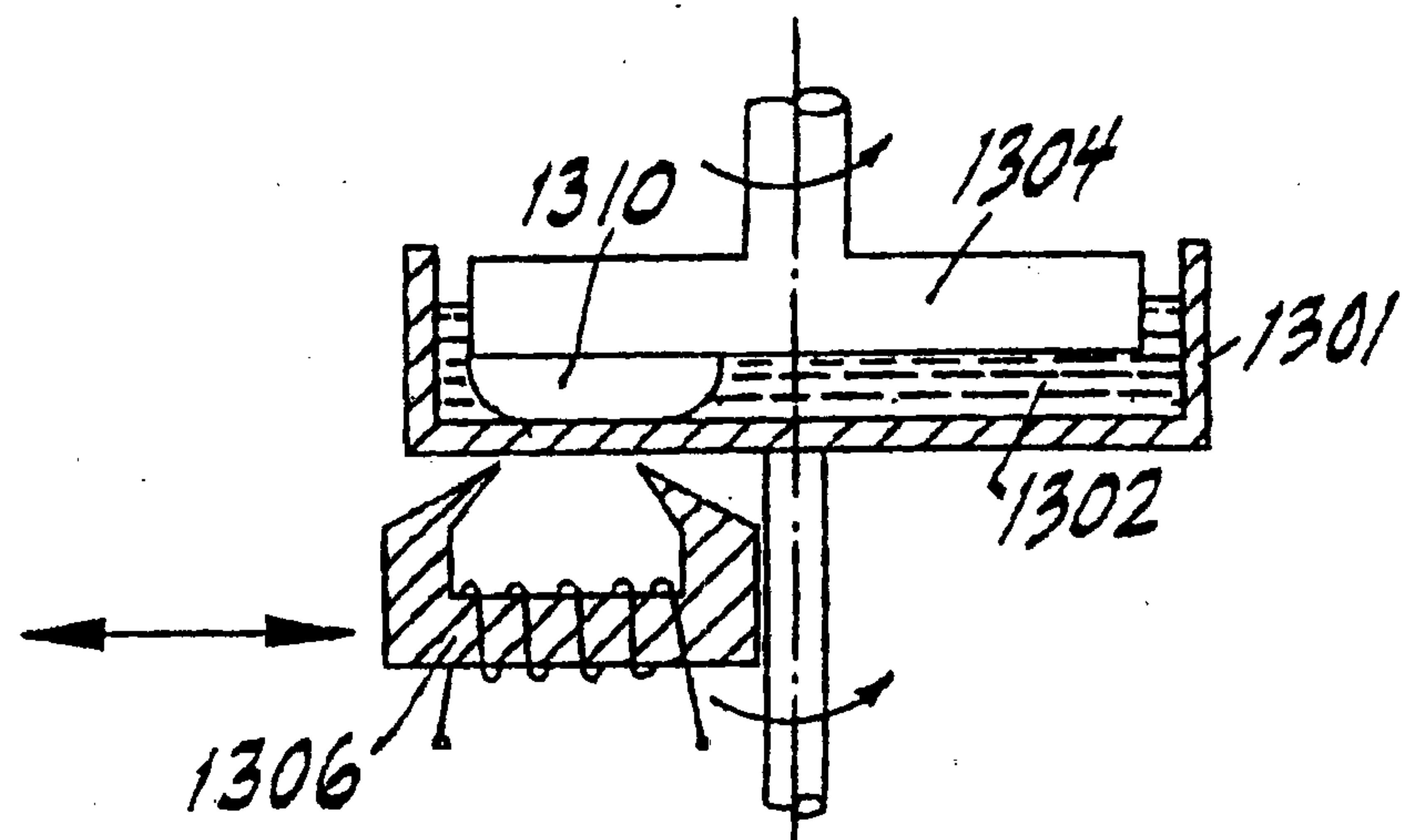


FIG. 13

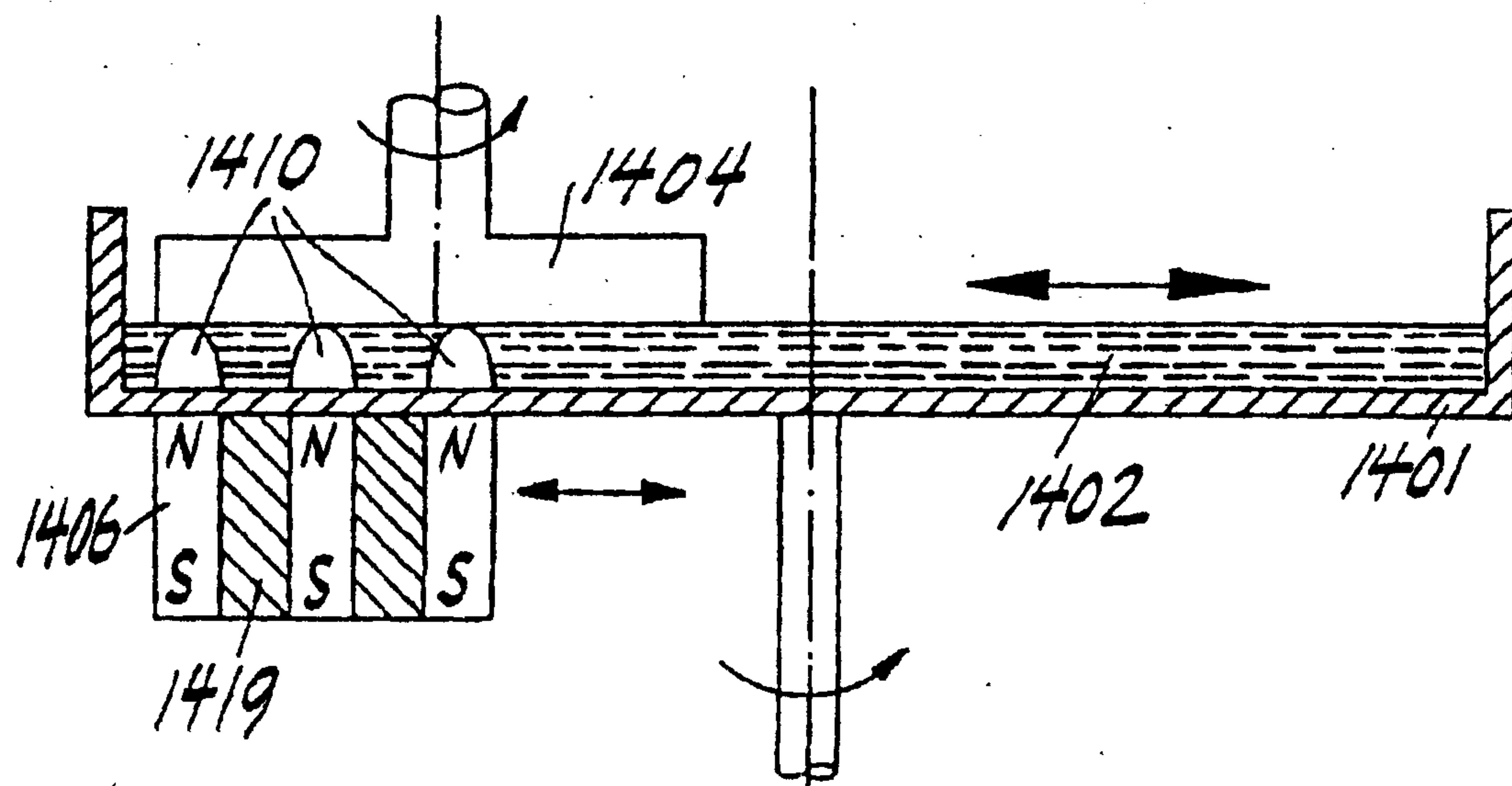


FIG. 14

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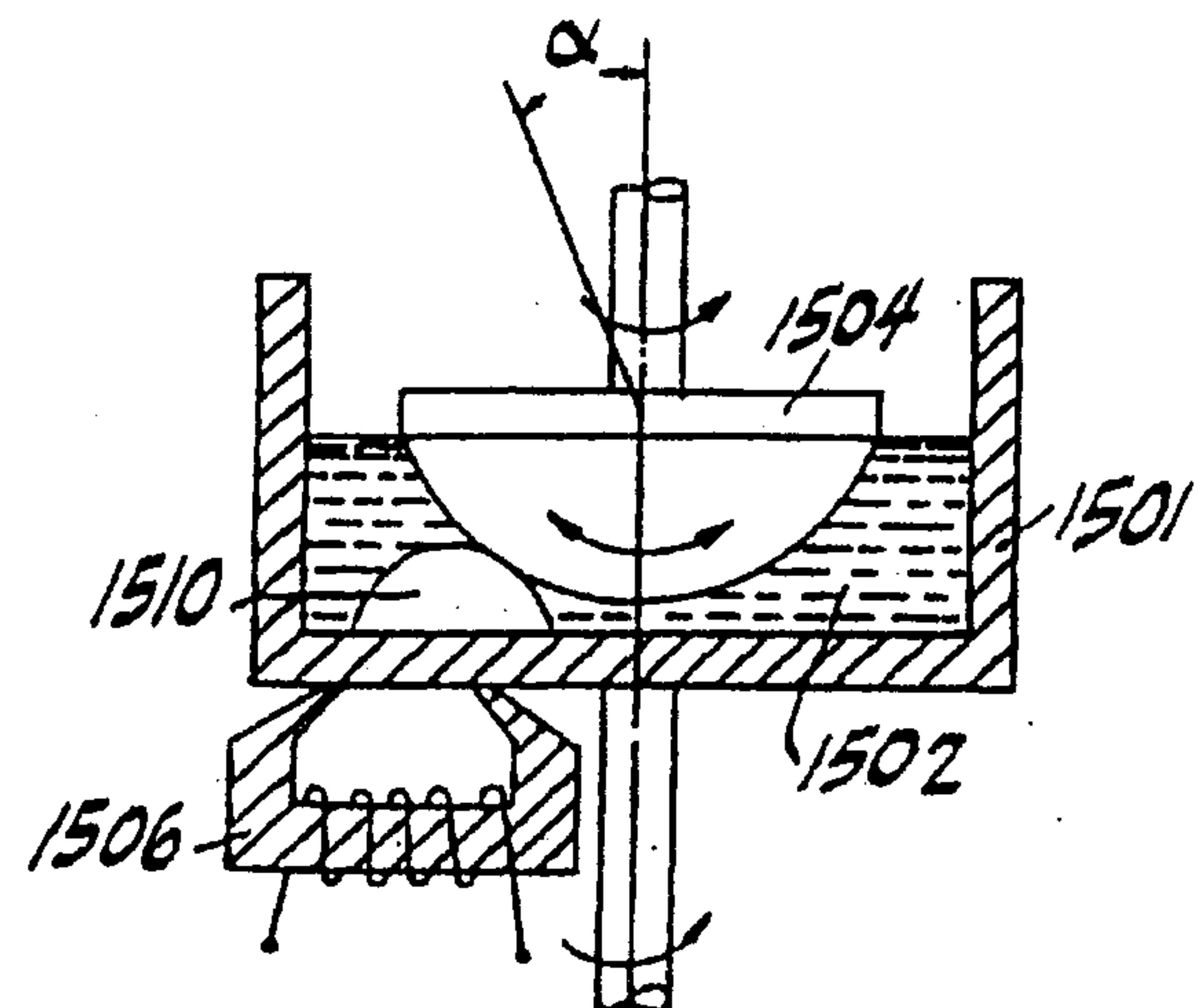


FIG. 15

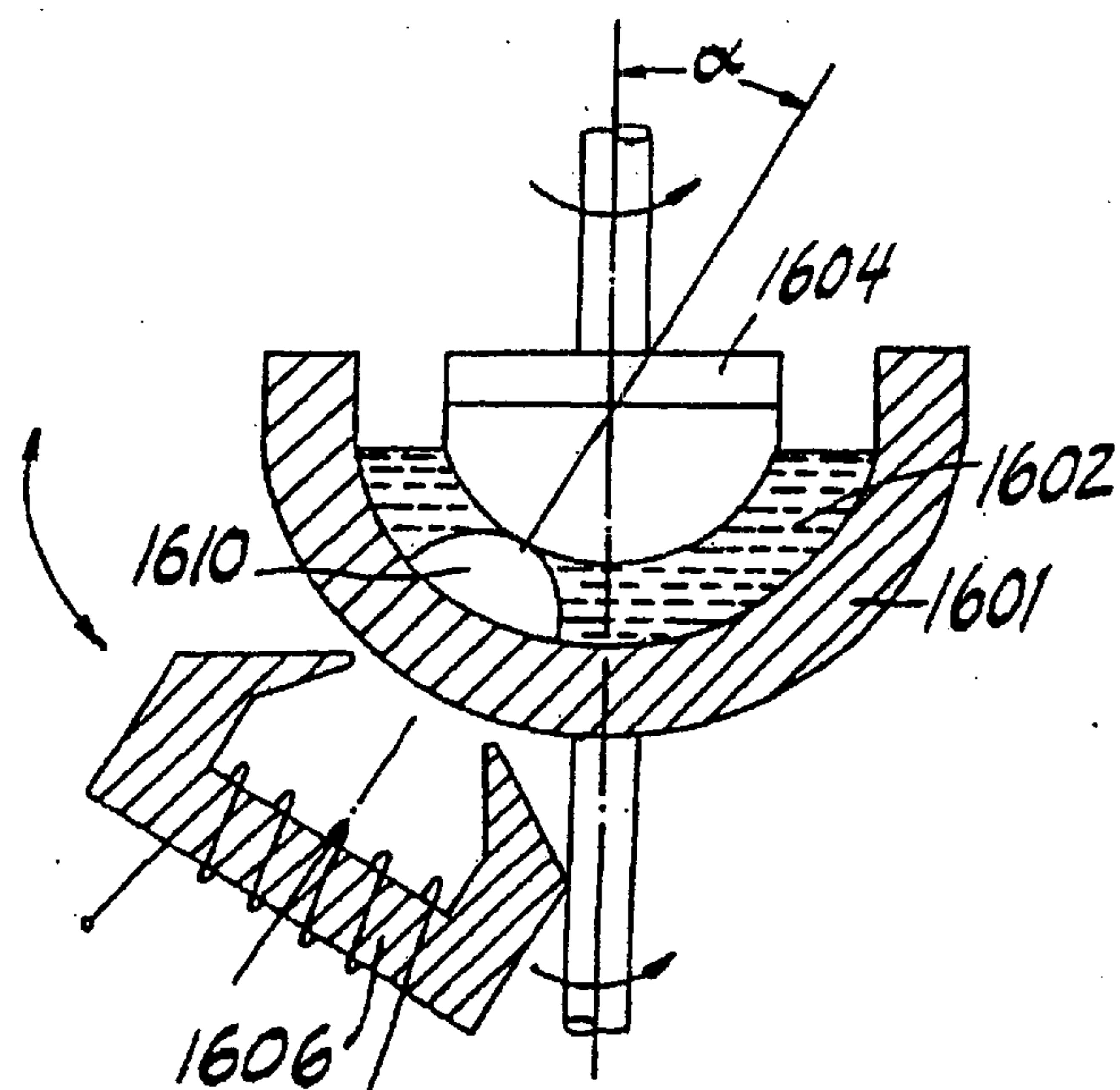


FIG. 16

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FIG. 17

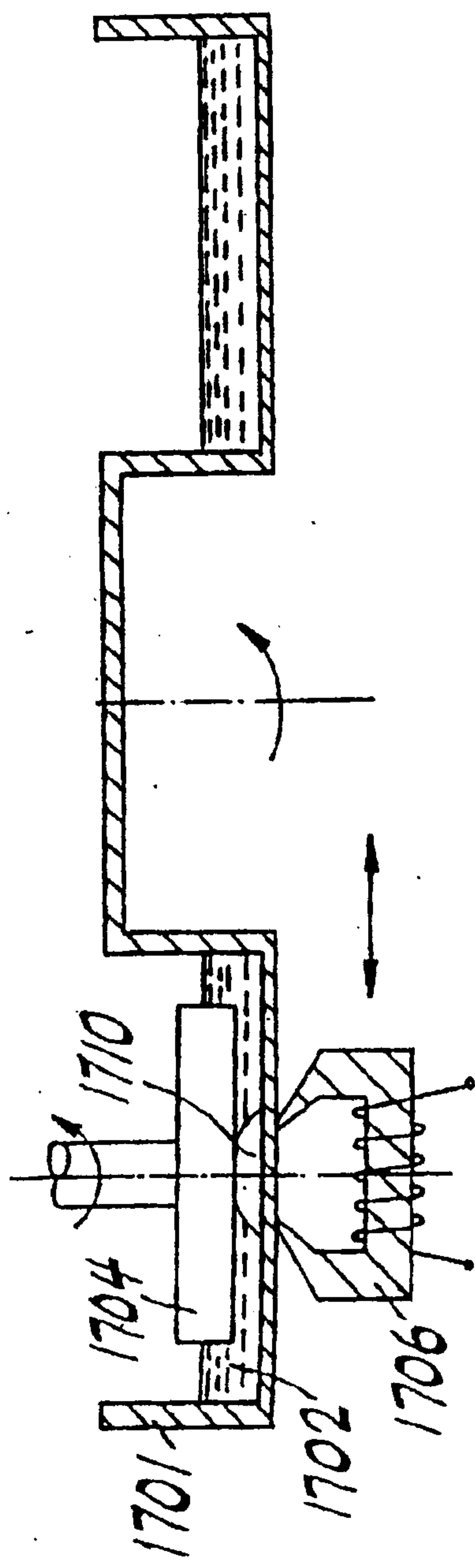
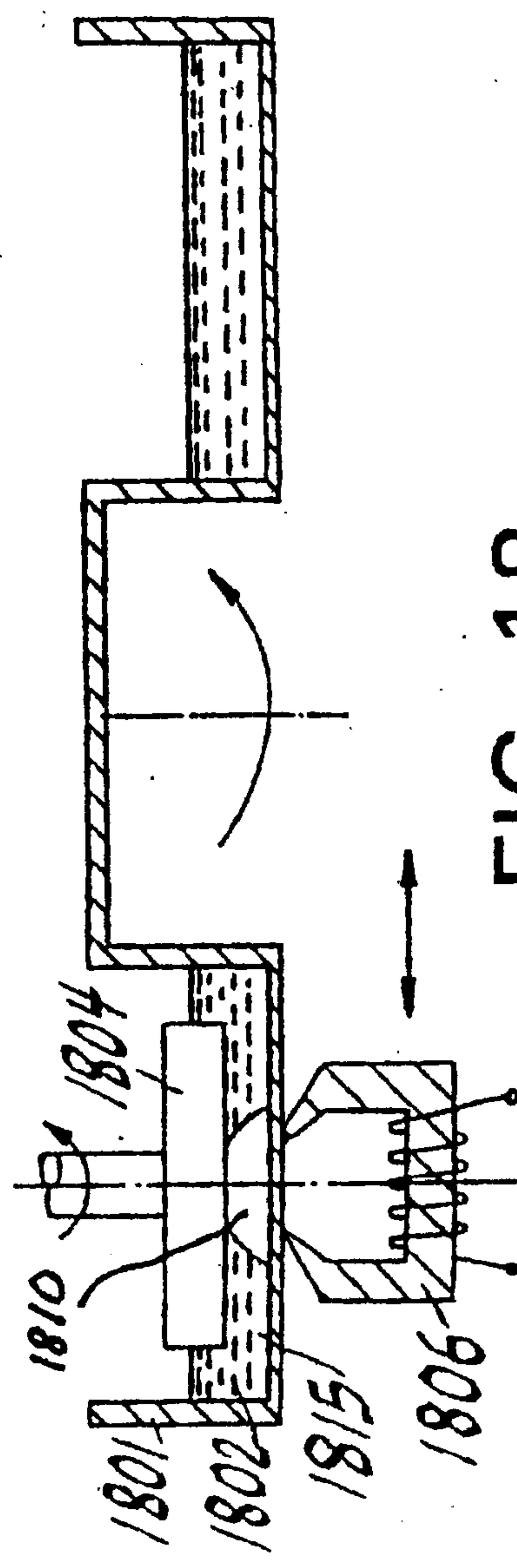


FIG. 18



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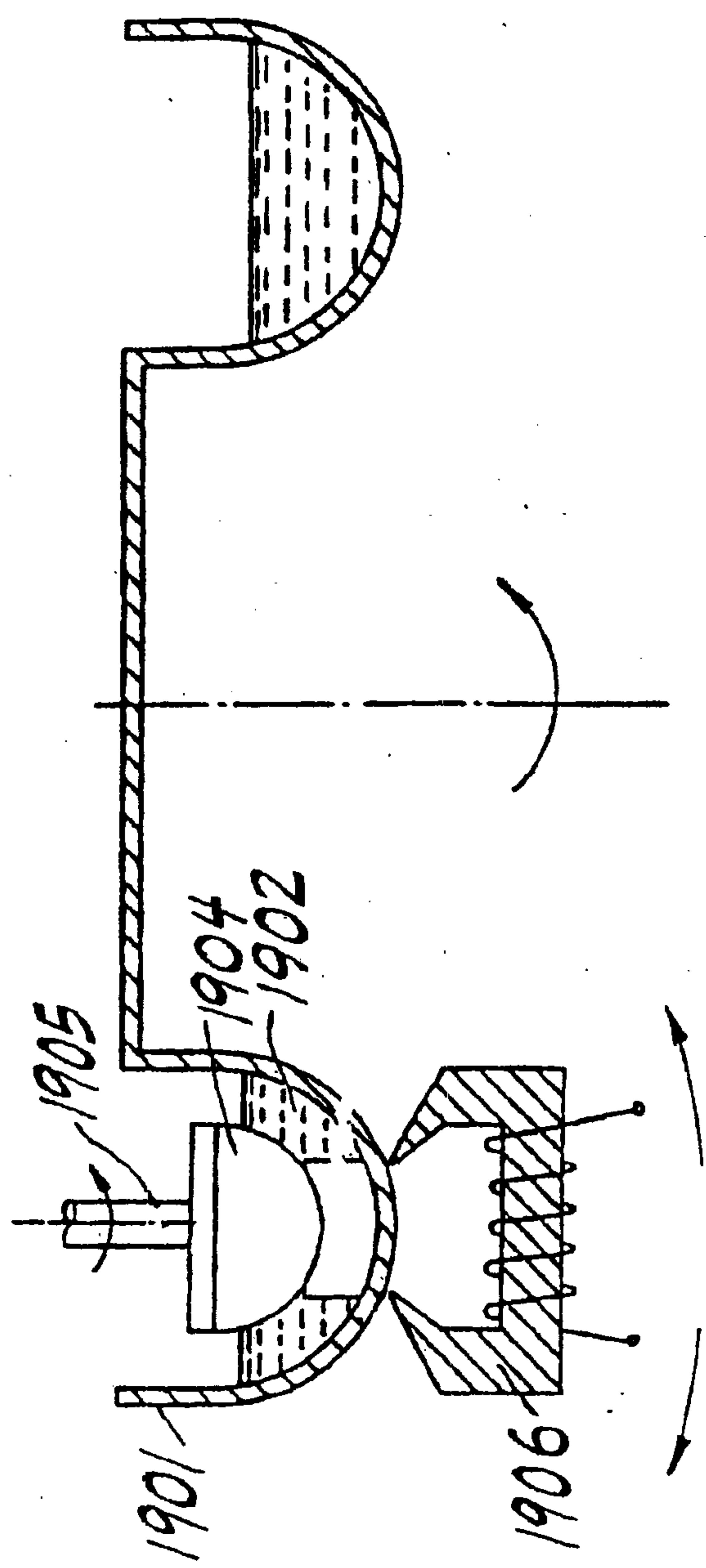


FIG. 19

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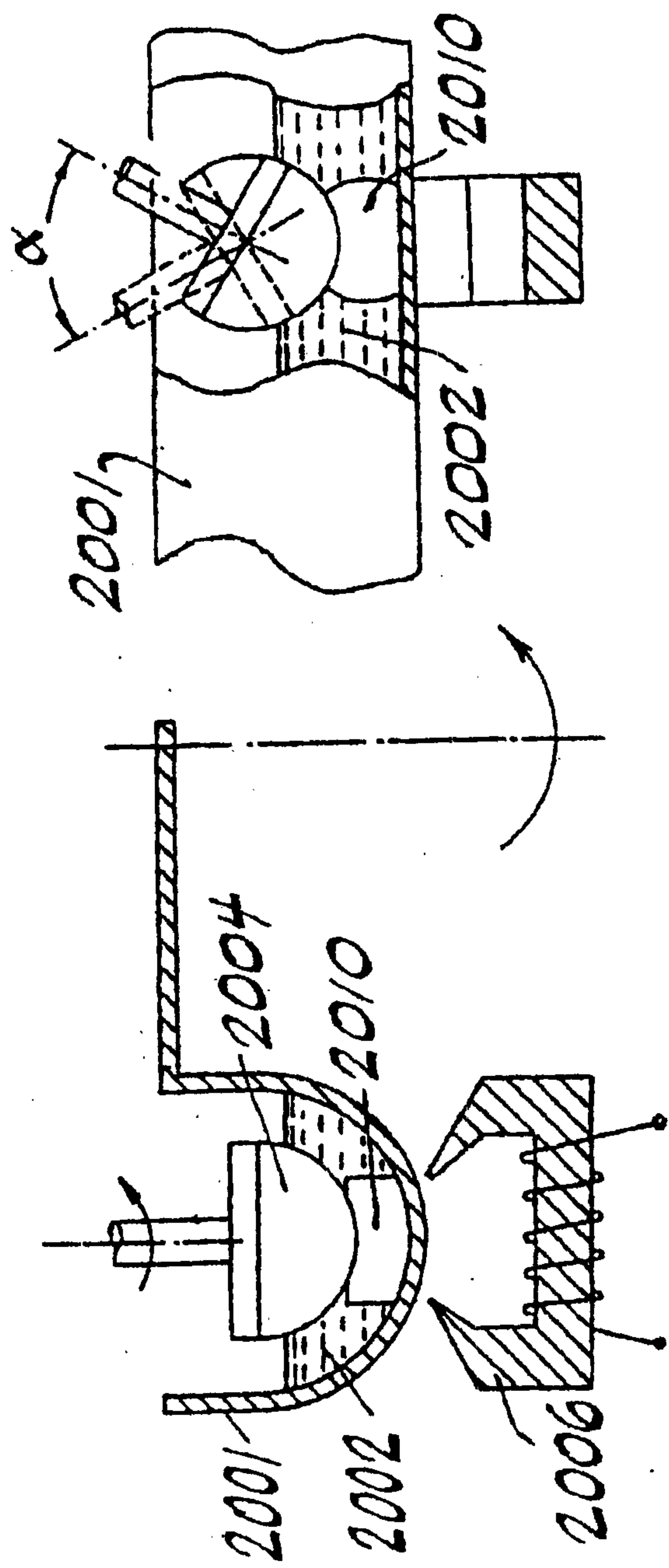


FIG. 20

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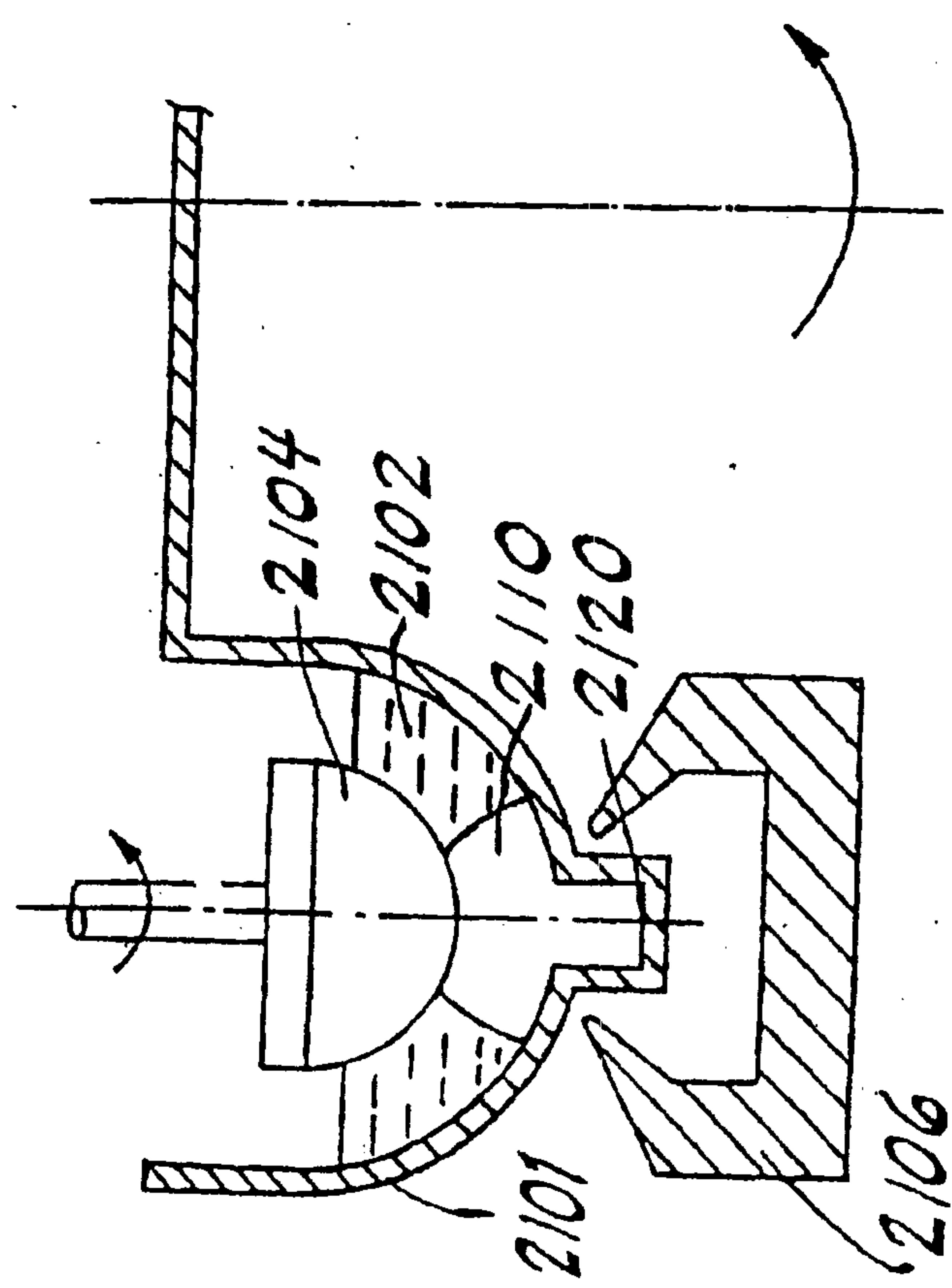
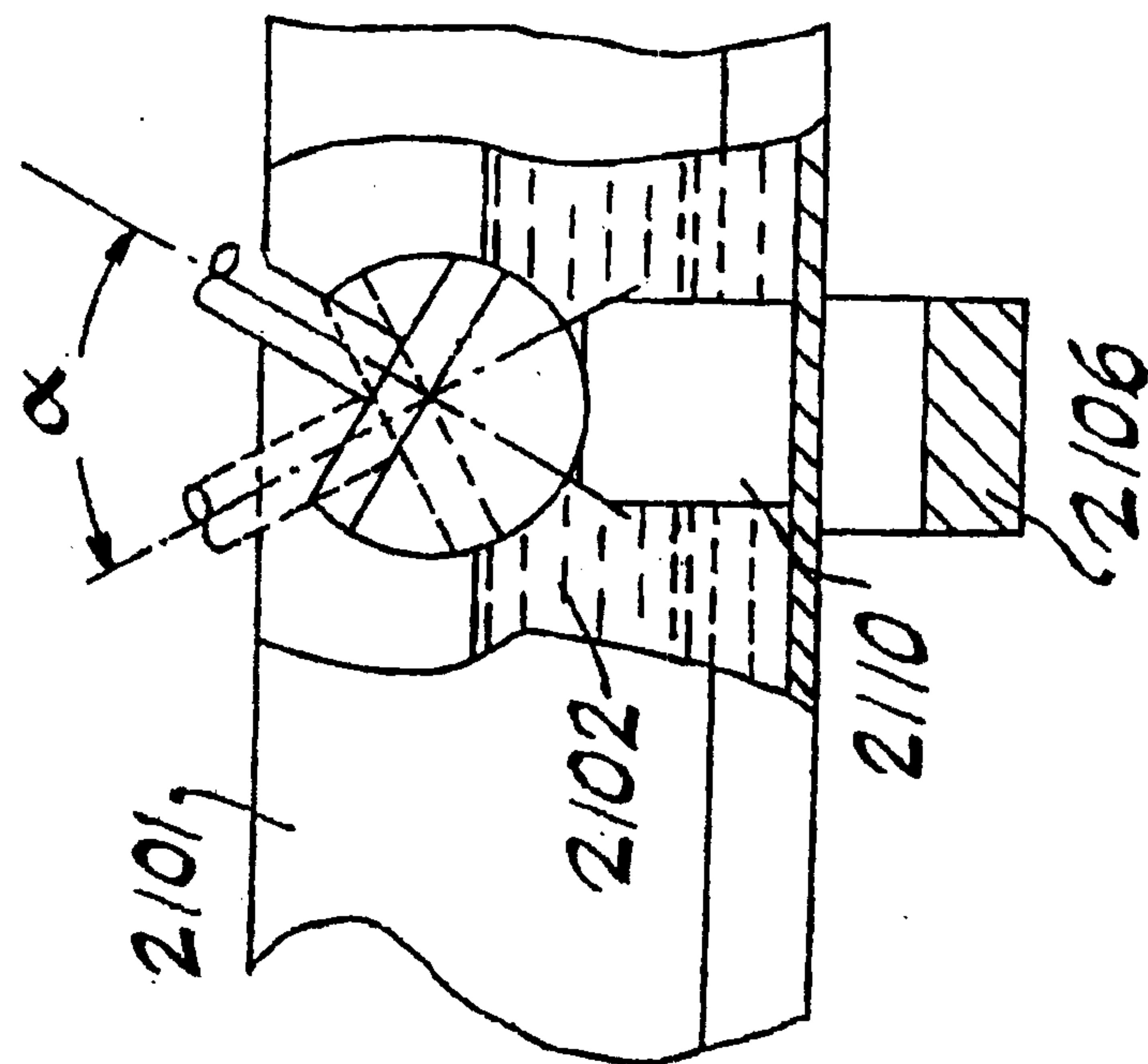


FIG. 21

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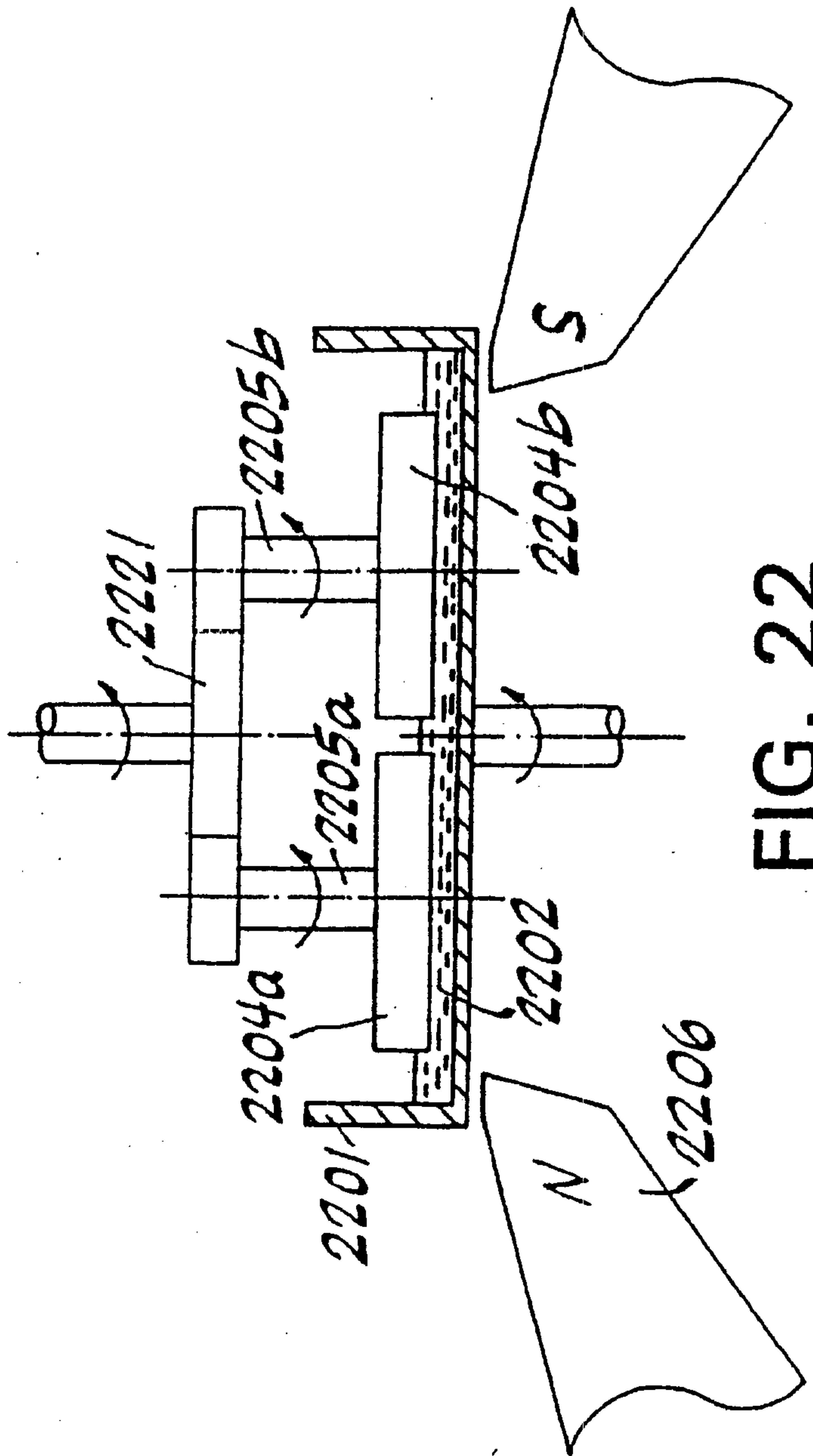


FIG. 22

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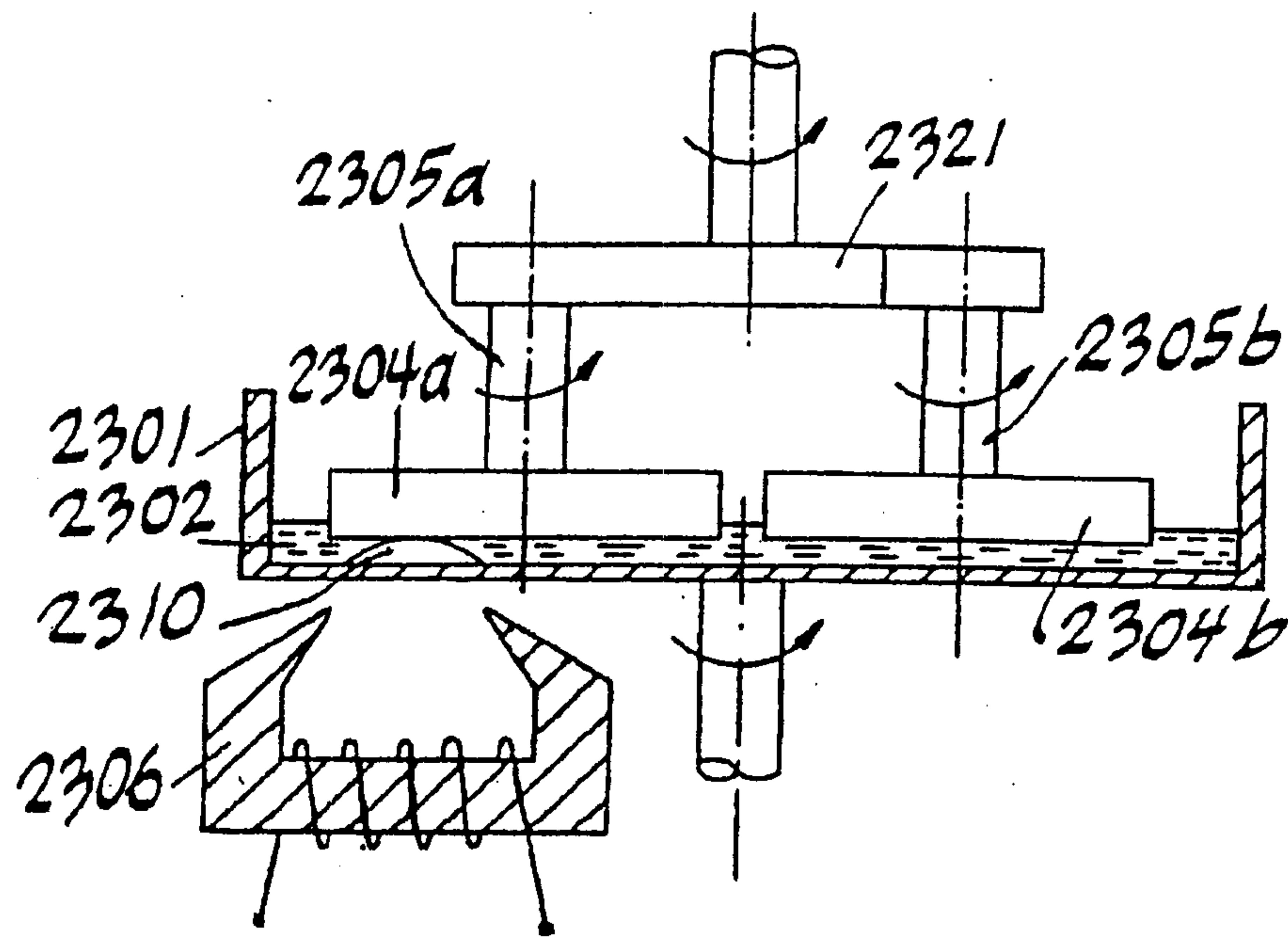


FIG. 23

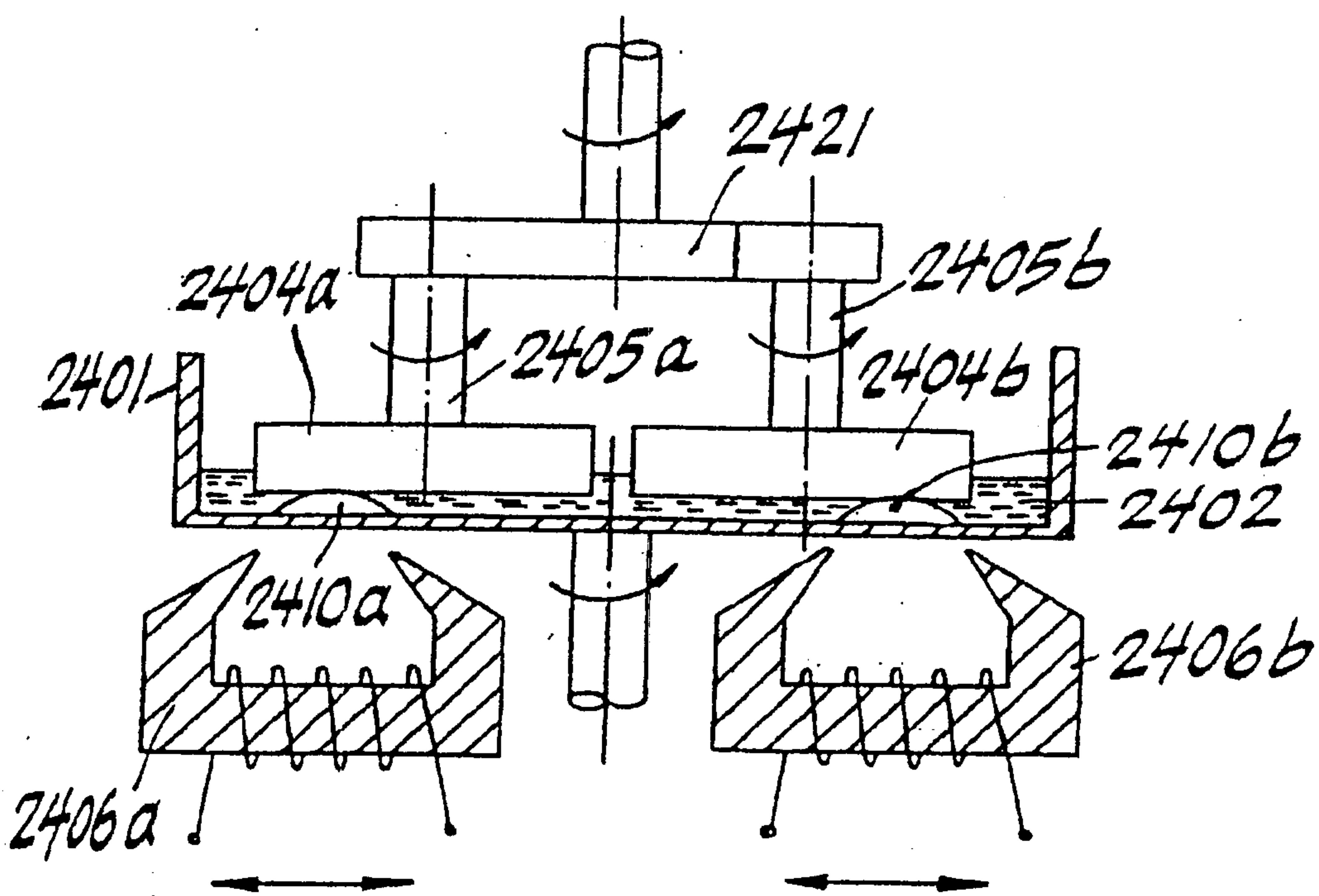


FIG. 24

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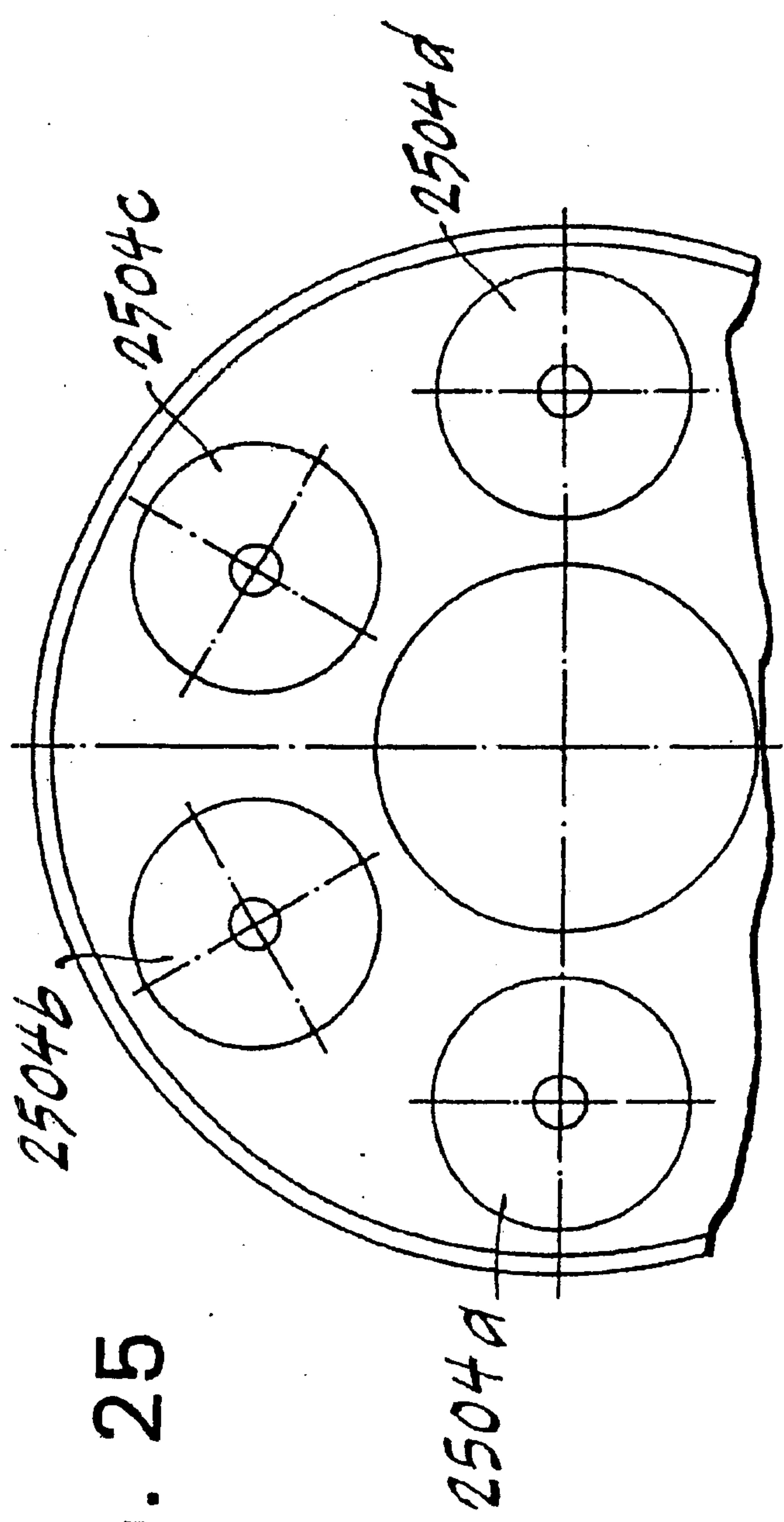
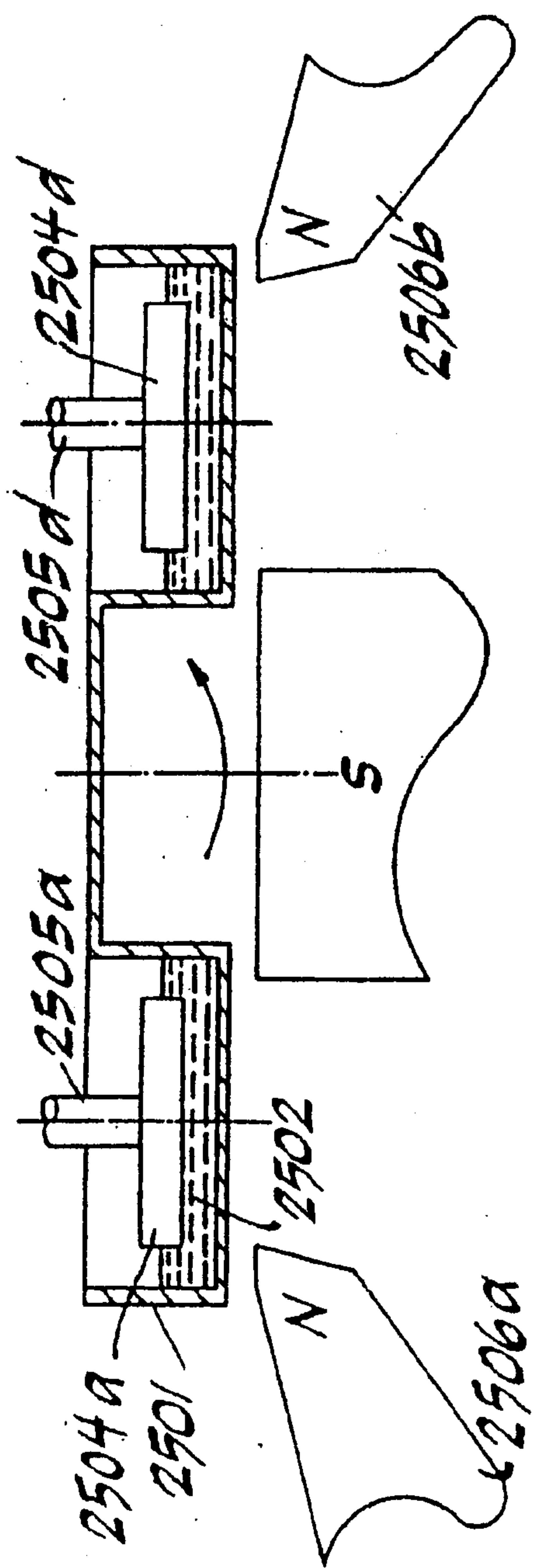


FIG. 25

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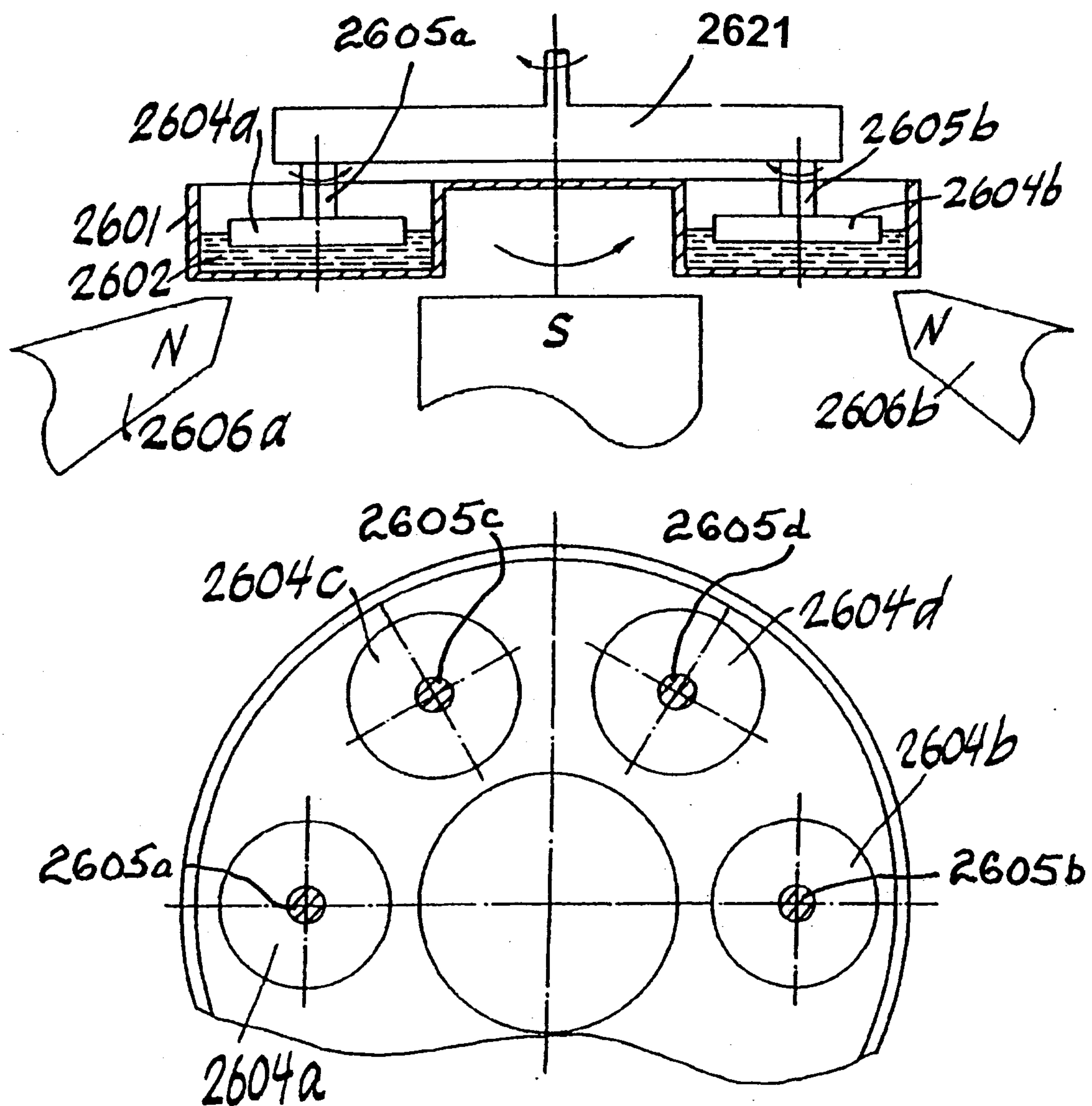


FIG. 26

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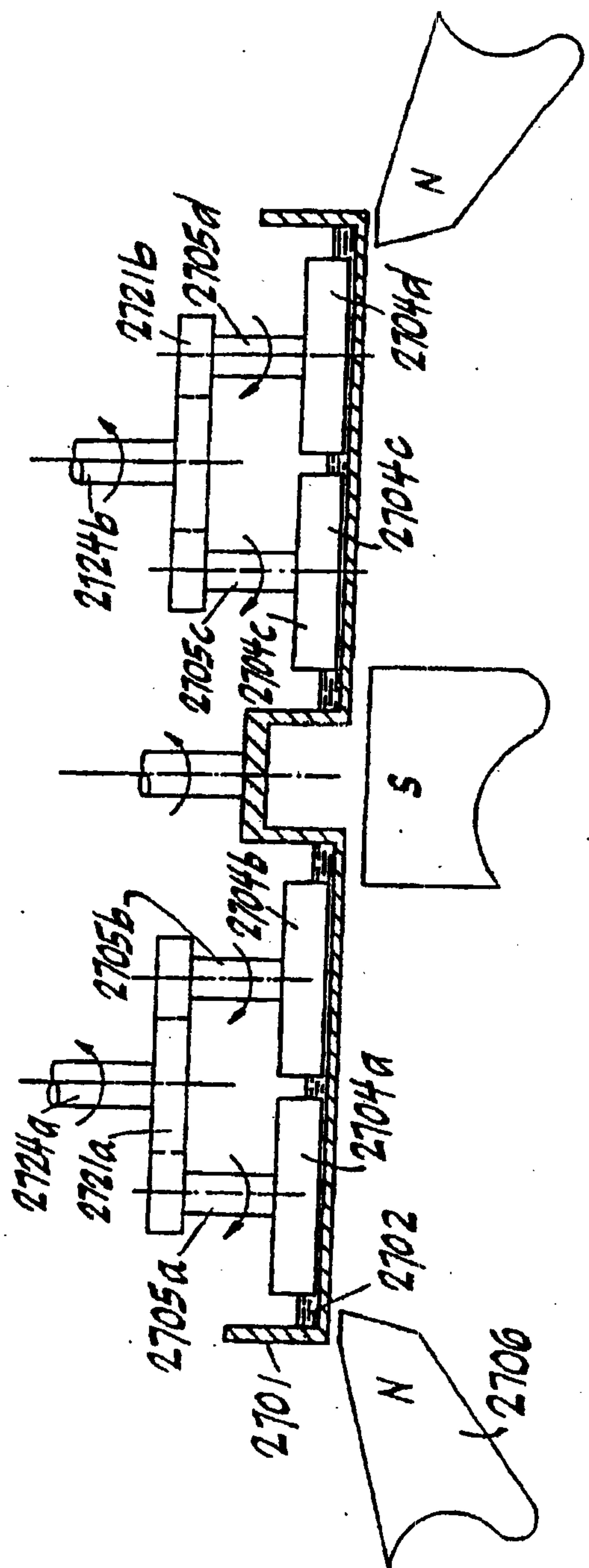


FIG. 27

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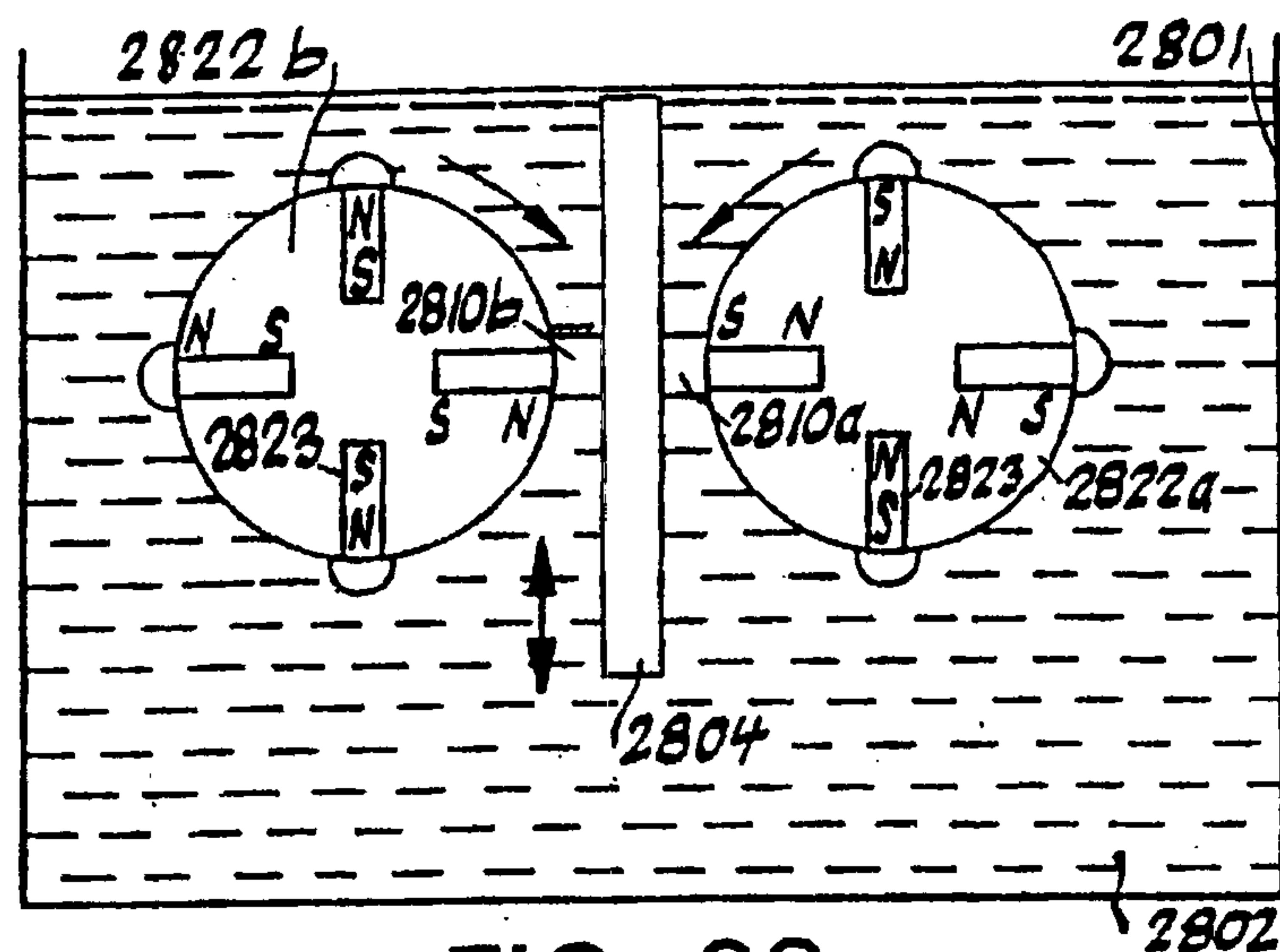


FIG. 28

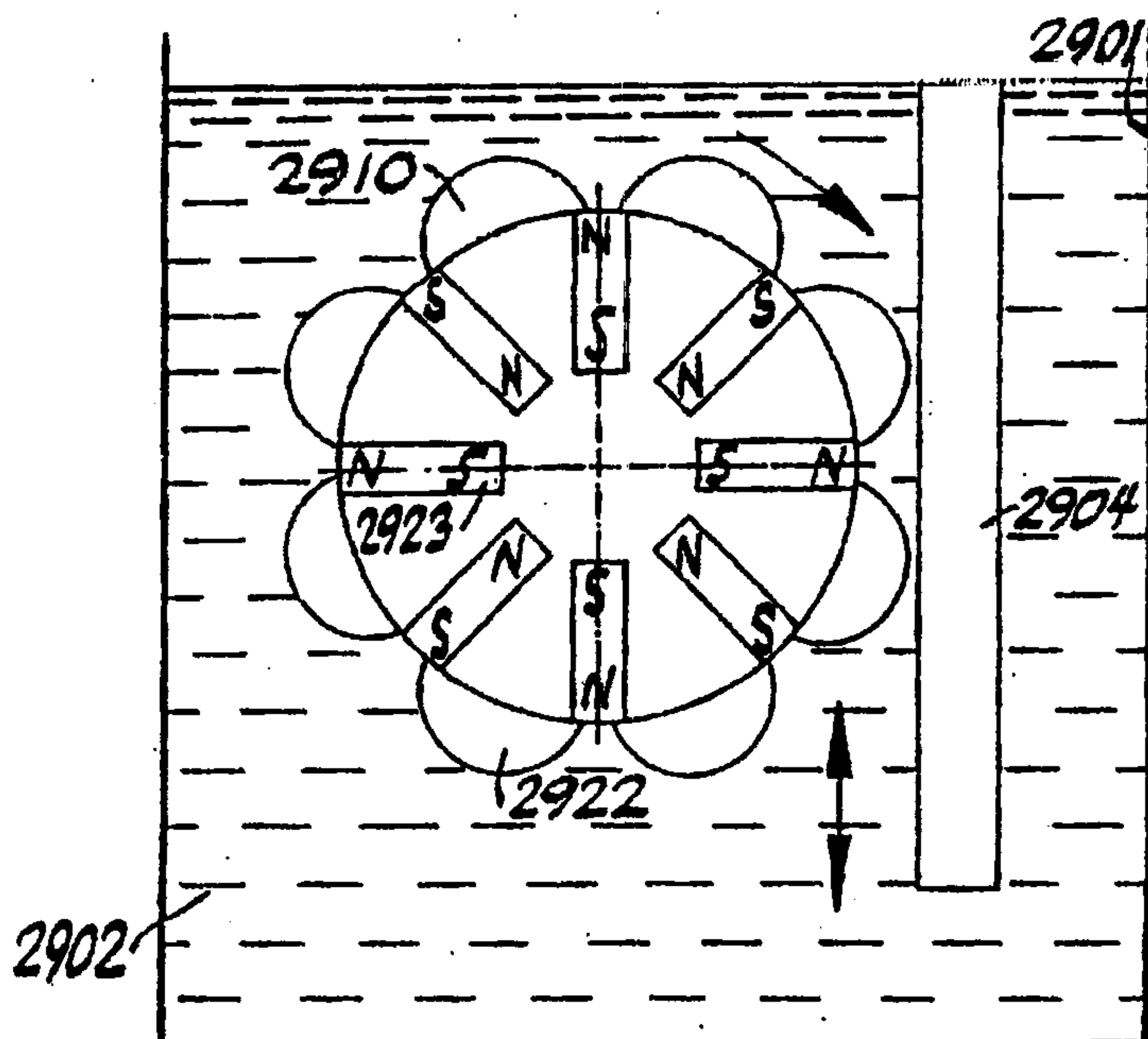


FIG. 29

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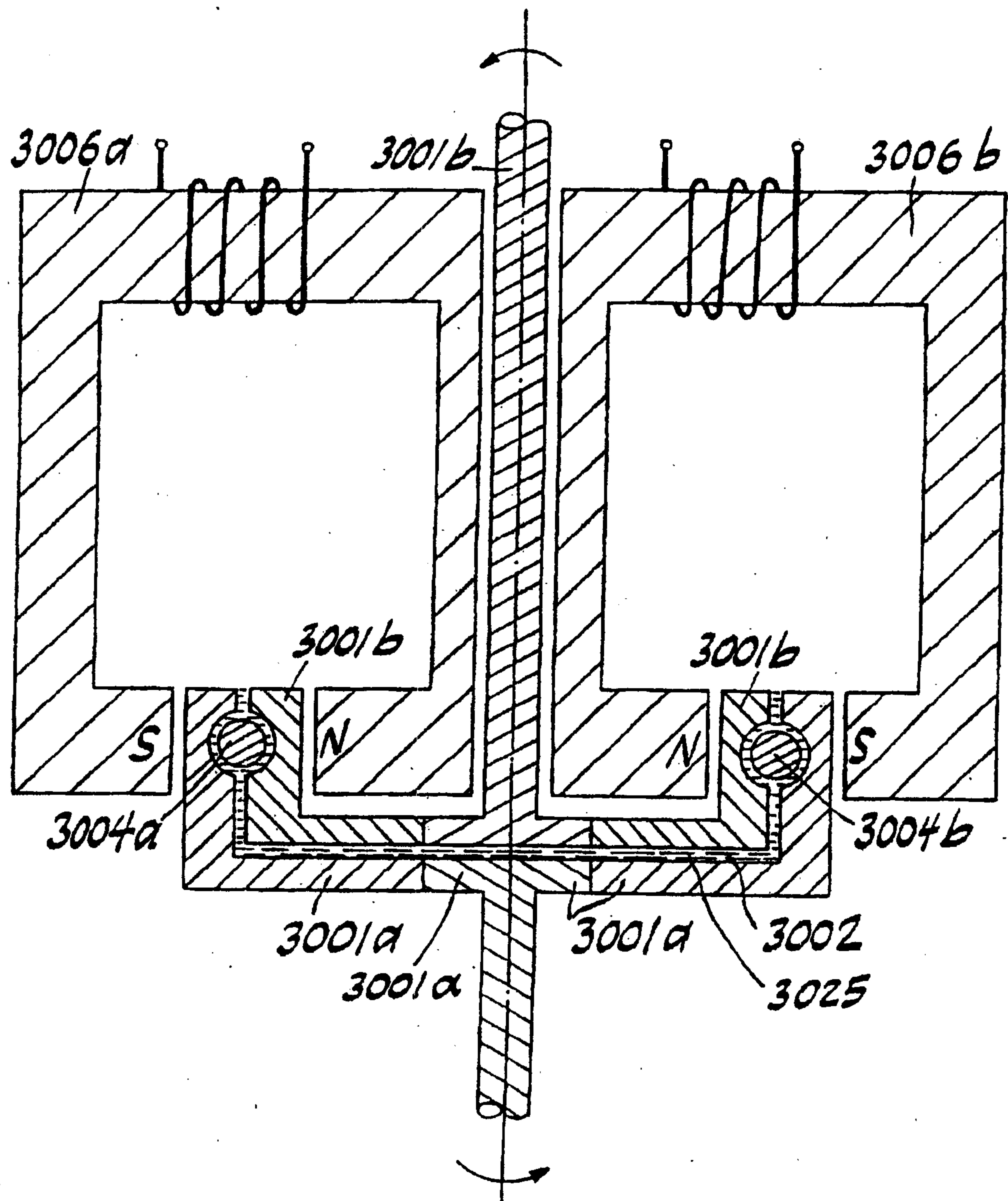


FIG. 30

