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Patil et al.

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(54) **HIGH ENERGY DENSITY TURBOMACHINES**

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F04D 29/22 (2006.01)
F04D 7/02 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***F04D 29/2266*** (2013.01); ***F04D 7/02*** (2013.01); ***F04D 13/08*** (2013.01); ***F04D 29/041*** (2013.01);
(Continued)

(58) **Field of Classification Search**
CPC .. F04D 29/041; F04D 29/051; F04D 29/2266; F04D 29/18; F04D 29/284; F04D 29/286
See application file for complete search history.

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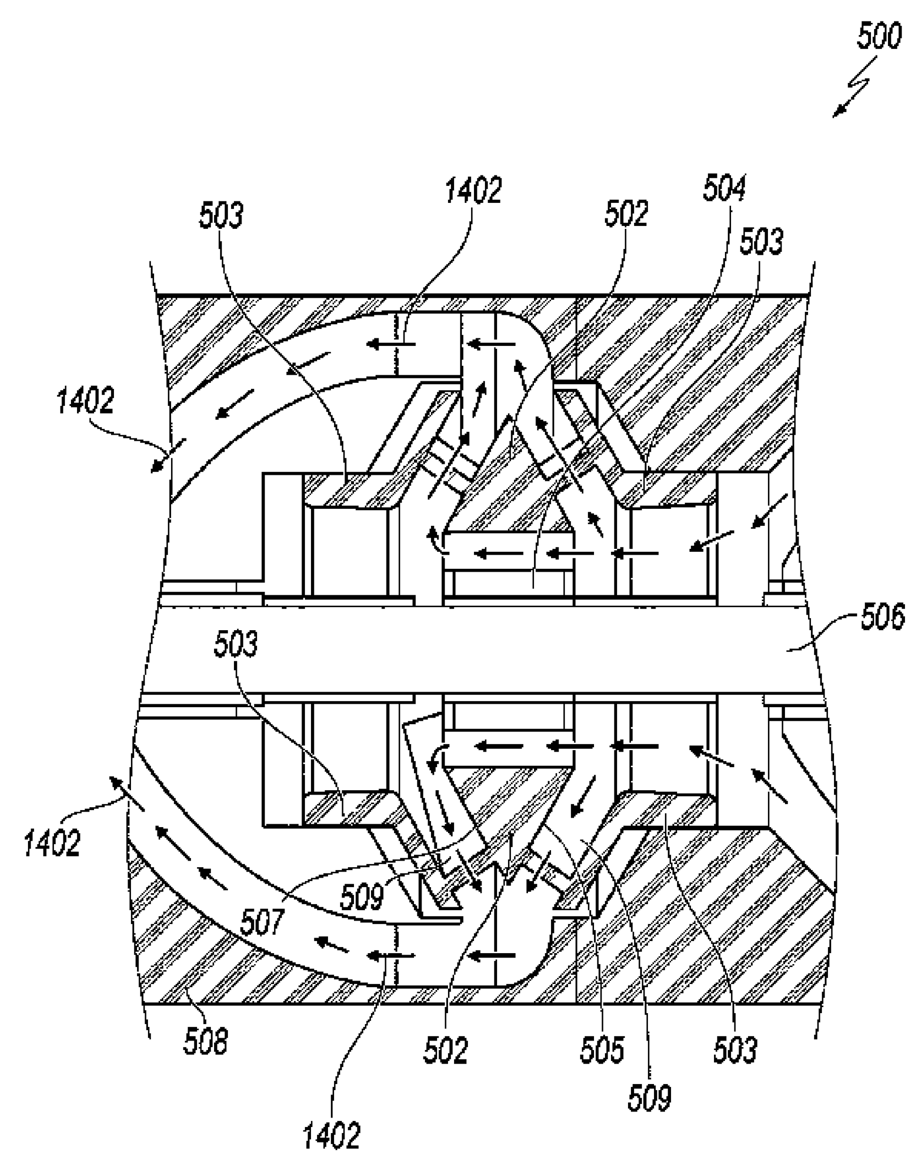
(57) **ABSTRACT**

A turbomachine includes a housing having an inlet and an outlet. A shaft is rotationally disposed in the housing. The shaft is rotatable about a longitudinal axis. An impeller is coupled to the shaft between the inlet and the outlet and rotates with the shaft. The impeller includes a single impeller inlet and an impeller outlet, a first set of vanes disposed on a first side of the impeller, and a second set of vanes disposed on a second side of the impeller. A passage is formed through a thickness of the impeller. The passage facilitates transmission of fluid from the first side of the impeller to the second side of the impeller such that fluid is supplied to the first set of vanes and the second set of vanes via the single impeller inlet. Transmission of fluid through the impeller reduces net axial thrust imparted to at least one of the impeller and the shaft.

20 Claims, 28 Drawing Sheets



(51) **Int. Cl.**
F04D 13/08 (2006.01)
F04D 29/041 (2006.01)
F04D 29/051 (2006.01)
F04D 29/18 (2006.01)
F04D 29/28 (2006.01)

(52) **U.S. Cl.**
CPC ***F04D 29/051*** (2013.01); ***F04D 29/18*** (2013.01); ***F04D 29/284*** (2013.01); ***F04D 29/286*** (2013.01); *F05D 2240/30* (2013.01)

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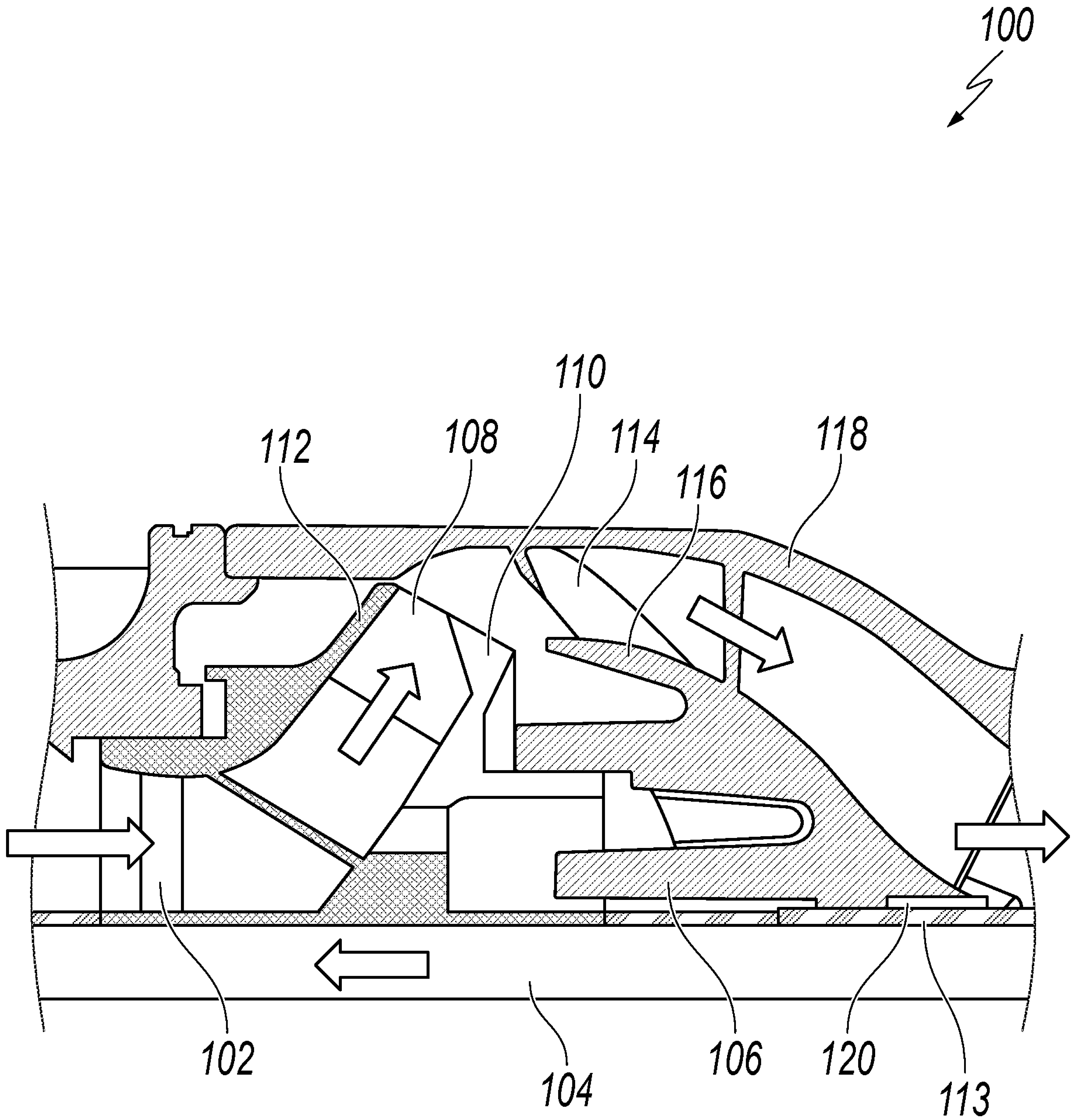


FIG. 1

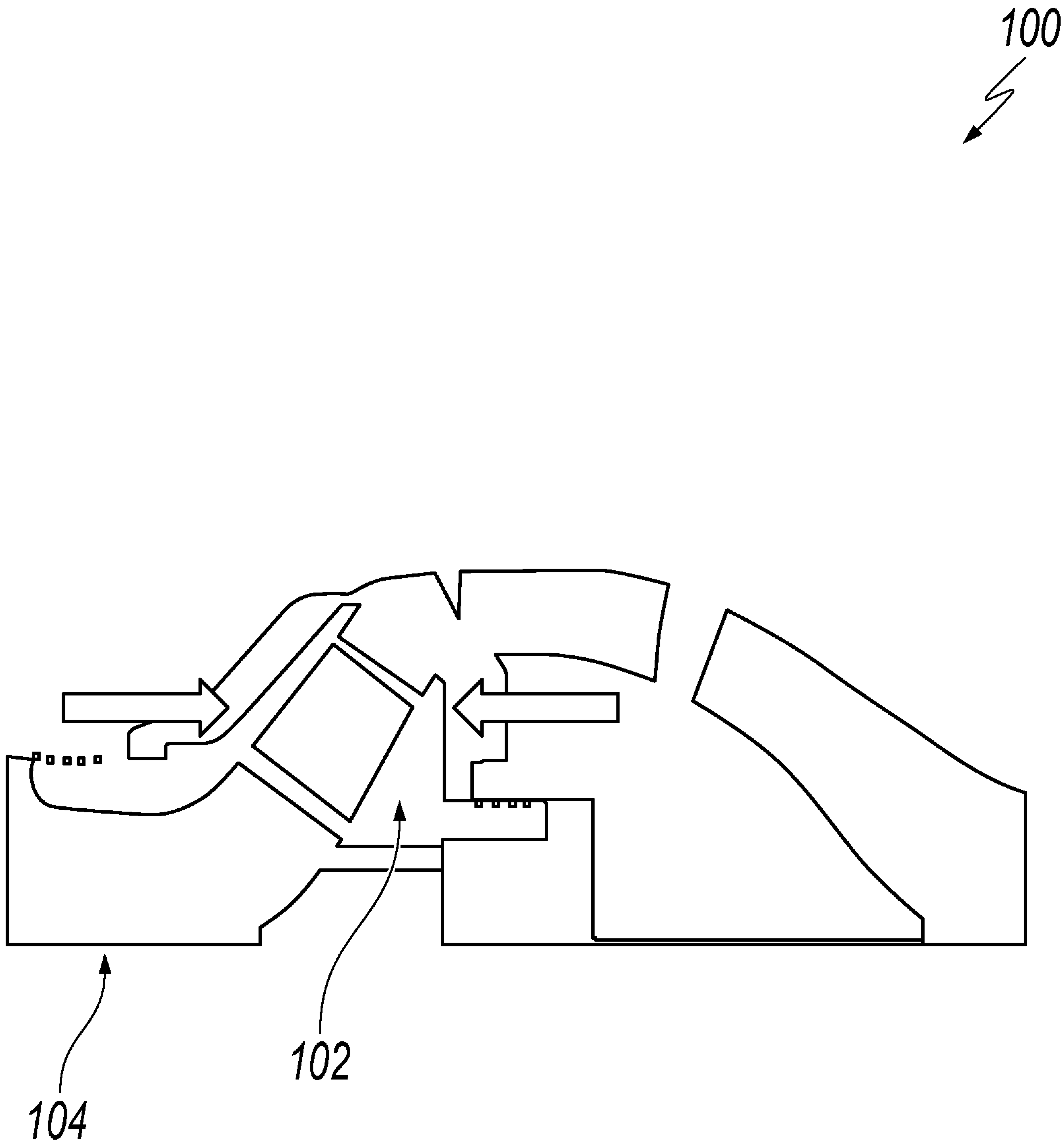


FIG. 2

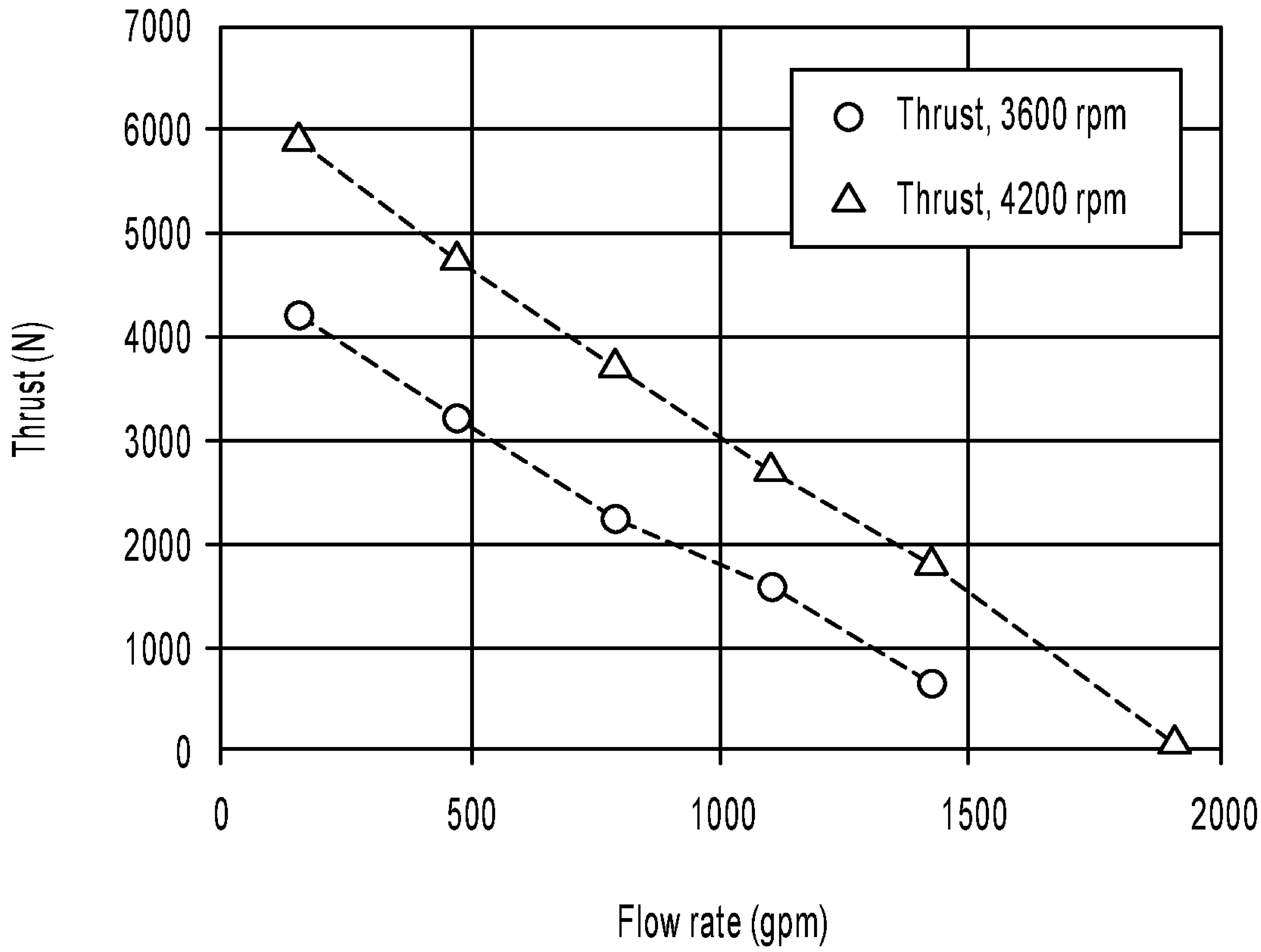

7000
6000
5000
4000
3000
2000
1000
0
Thrust (N)
Thrust, 3600 rpm
Thrust, 4200 rpm
0
500
1000
1500
2000
Flow rate (gpm)

FIG. 3

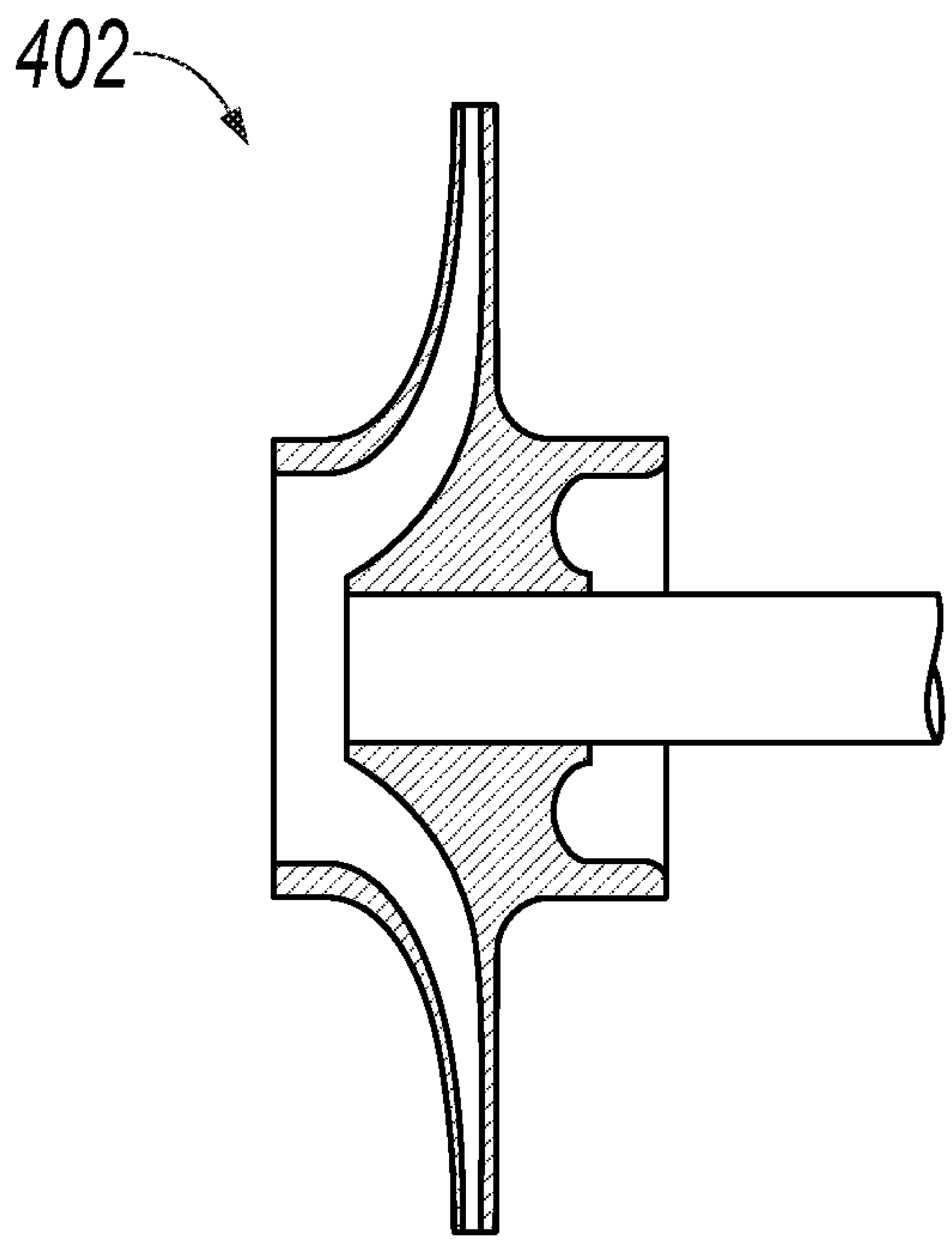


FIG. 4A

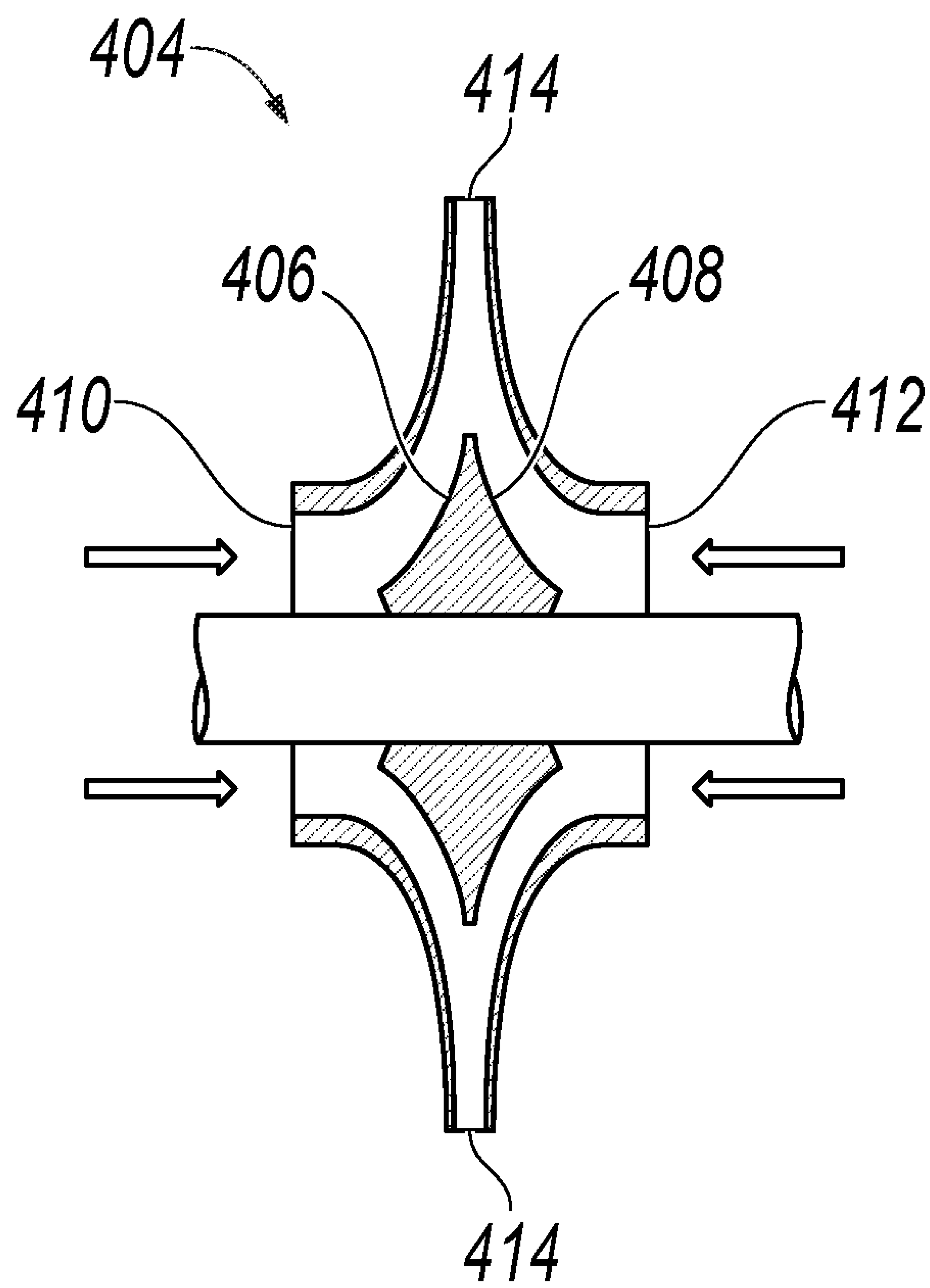


FIG. 4B

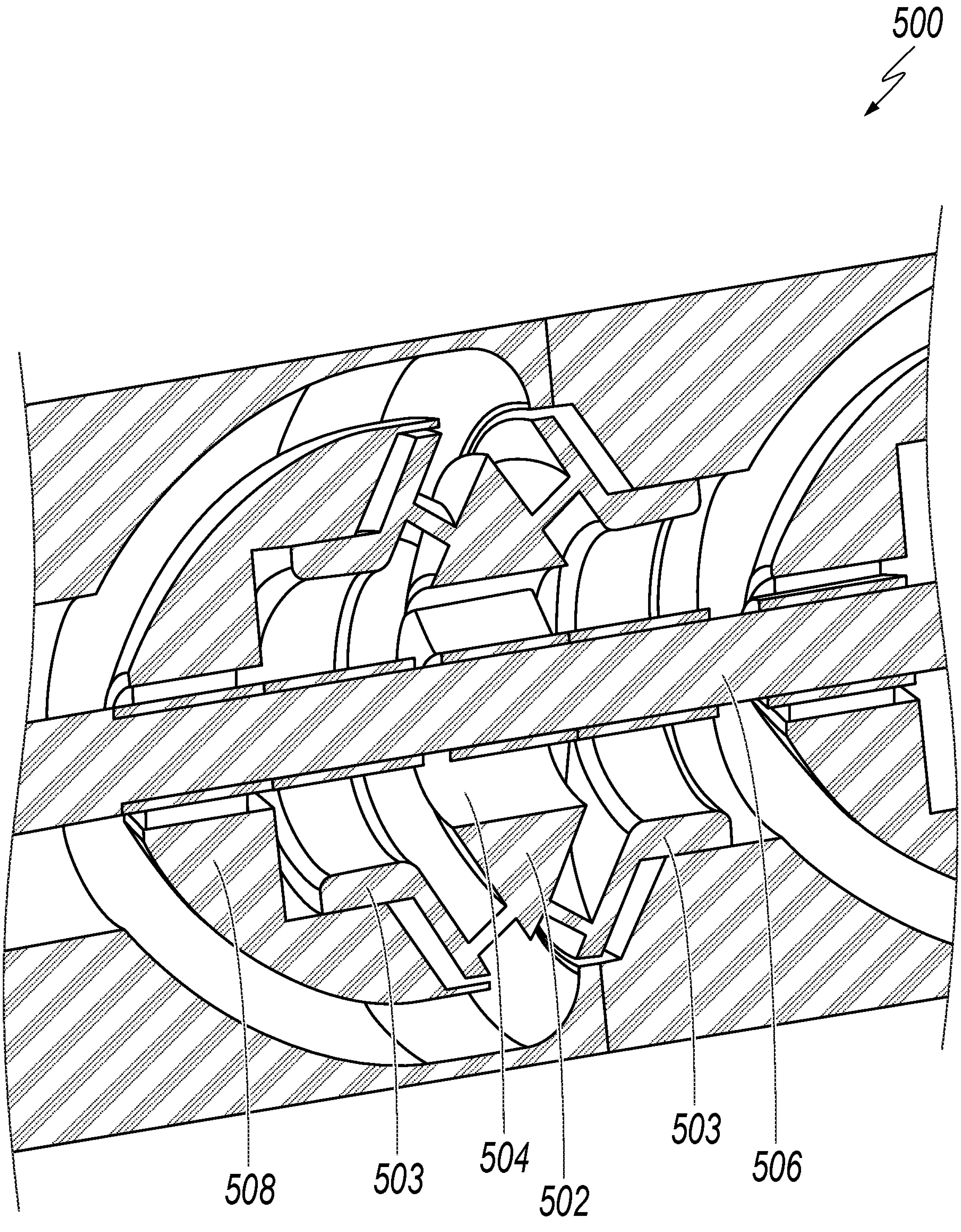


FIG. 5

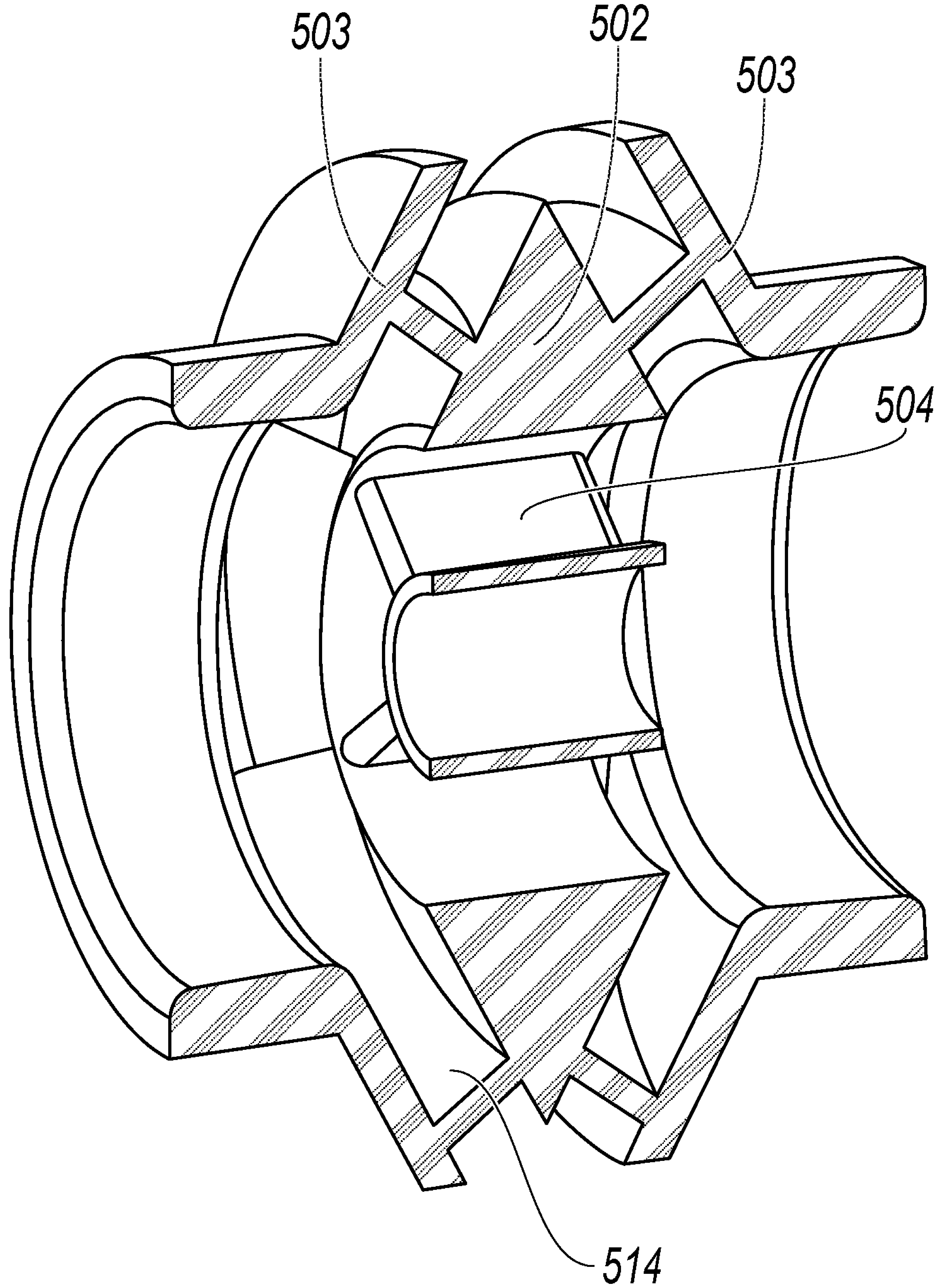


FIG. 6

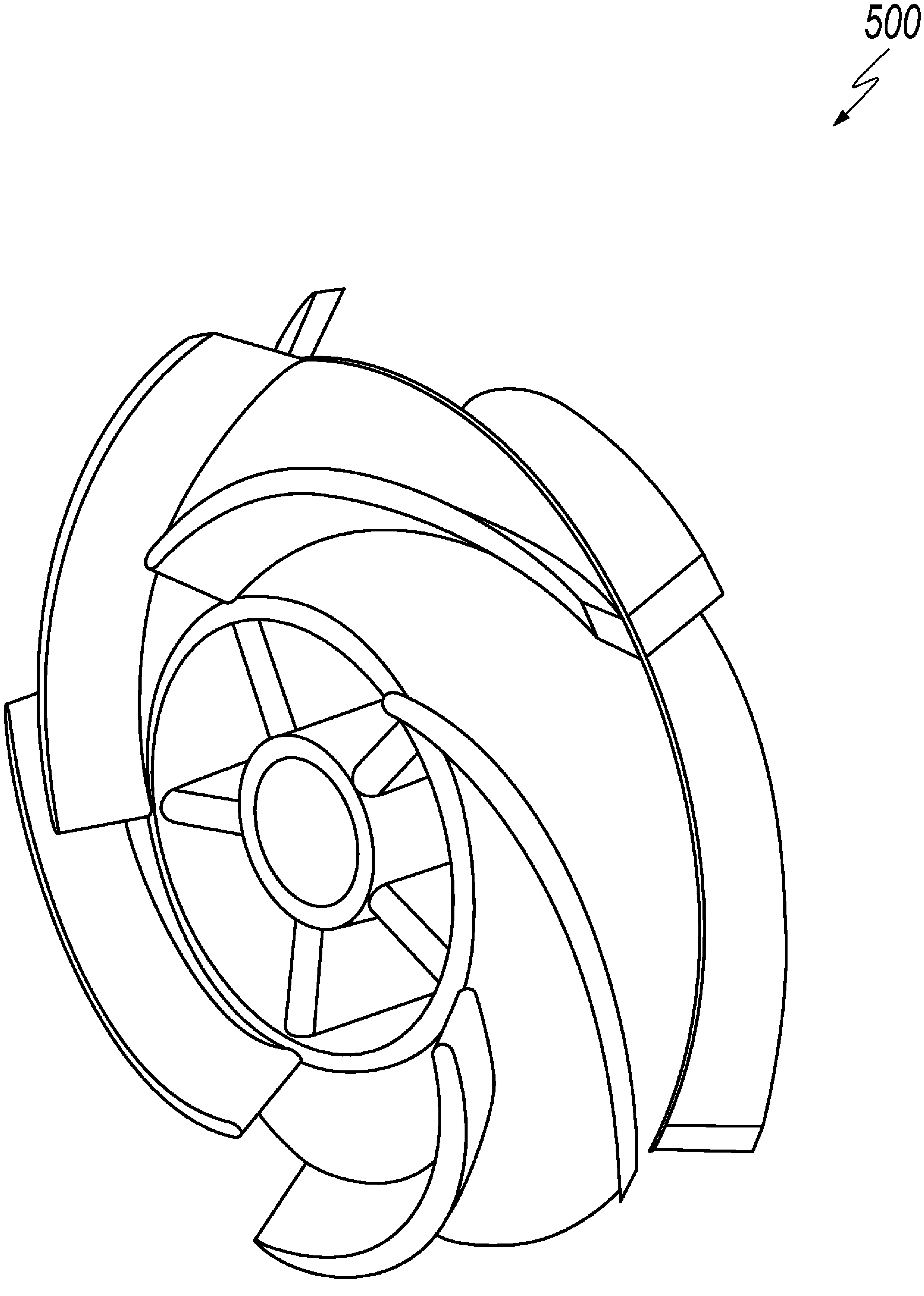


FIG. 7A

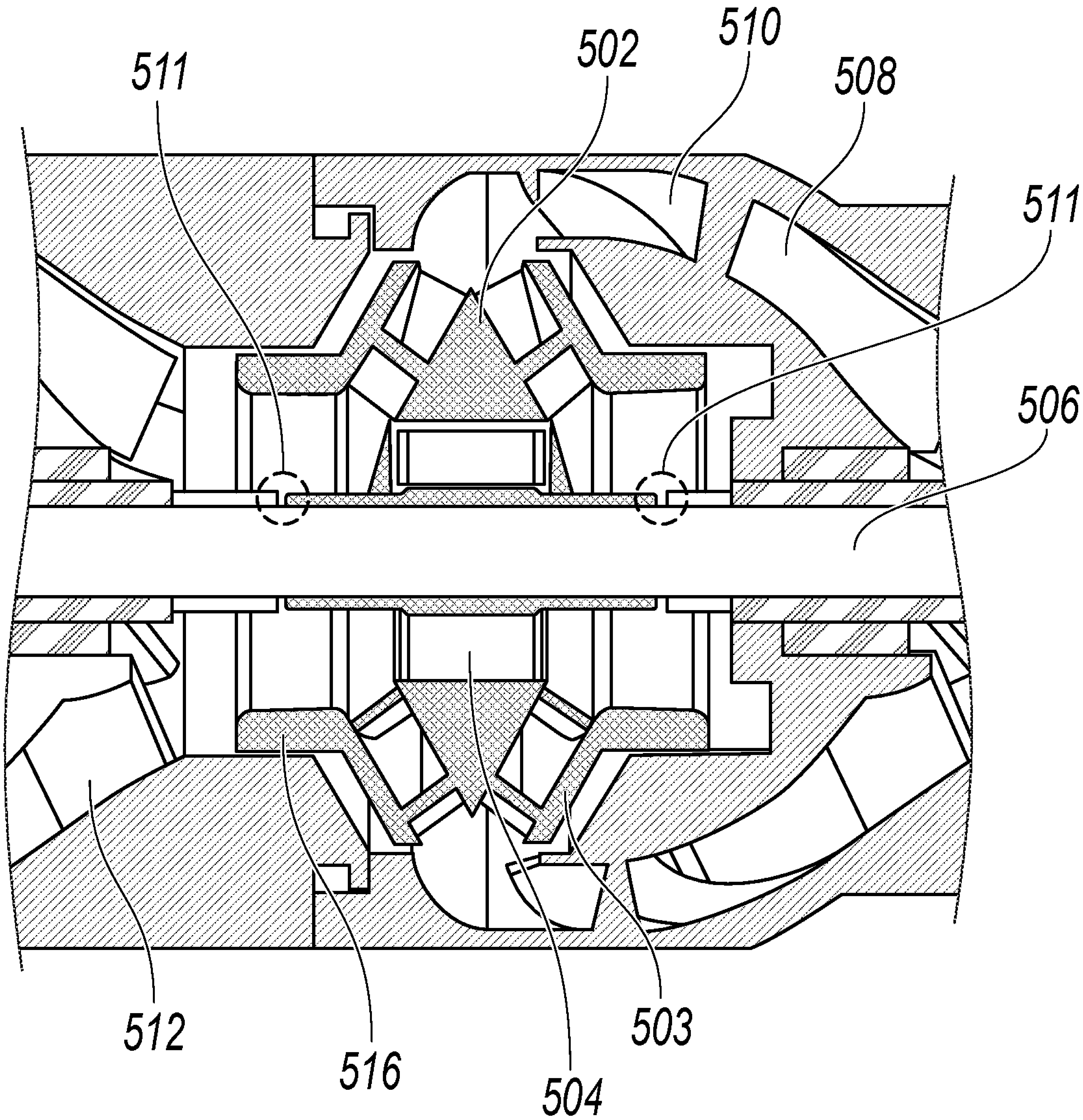


FIG. 7B

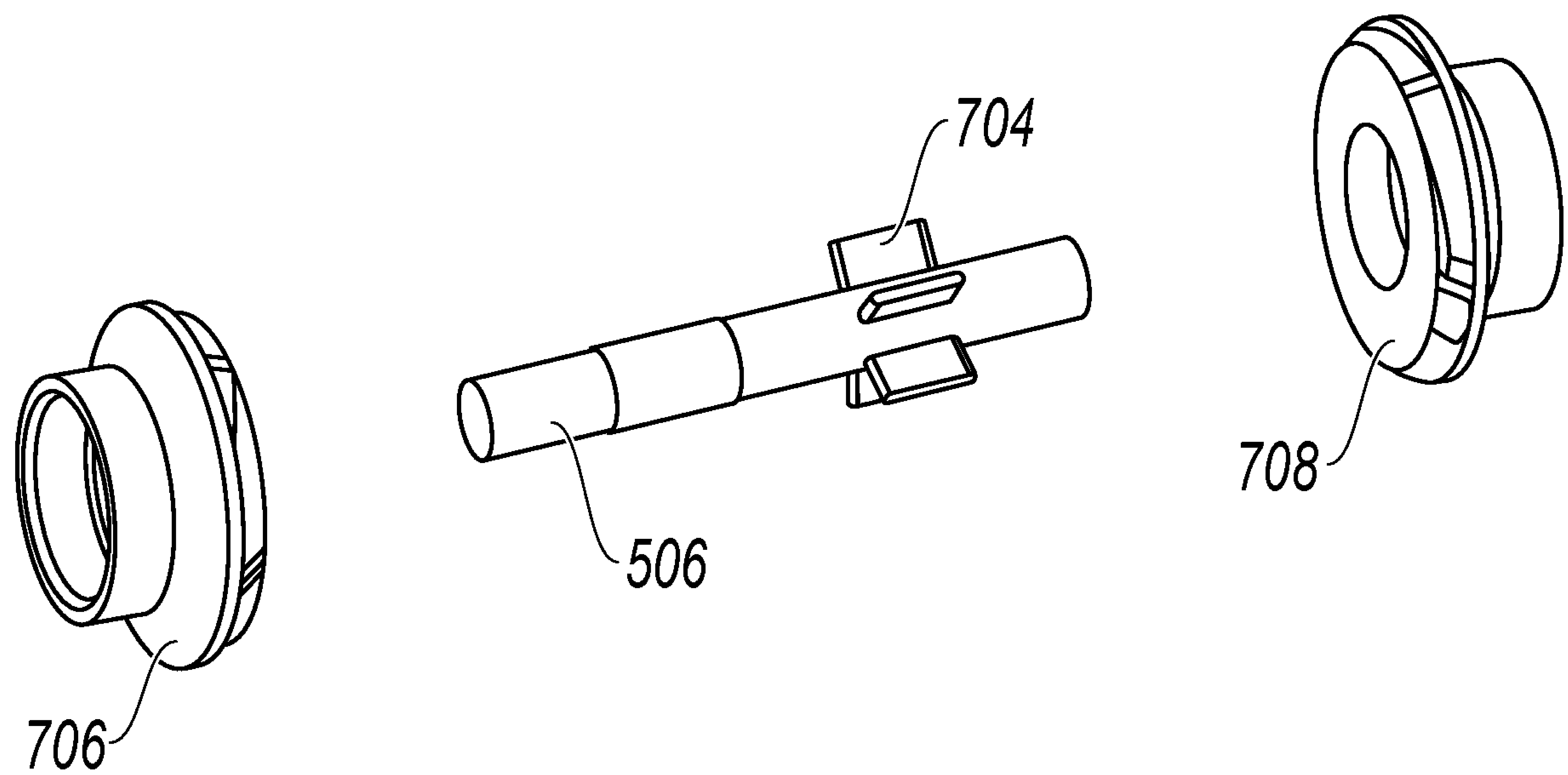


FIG. 8

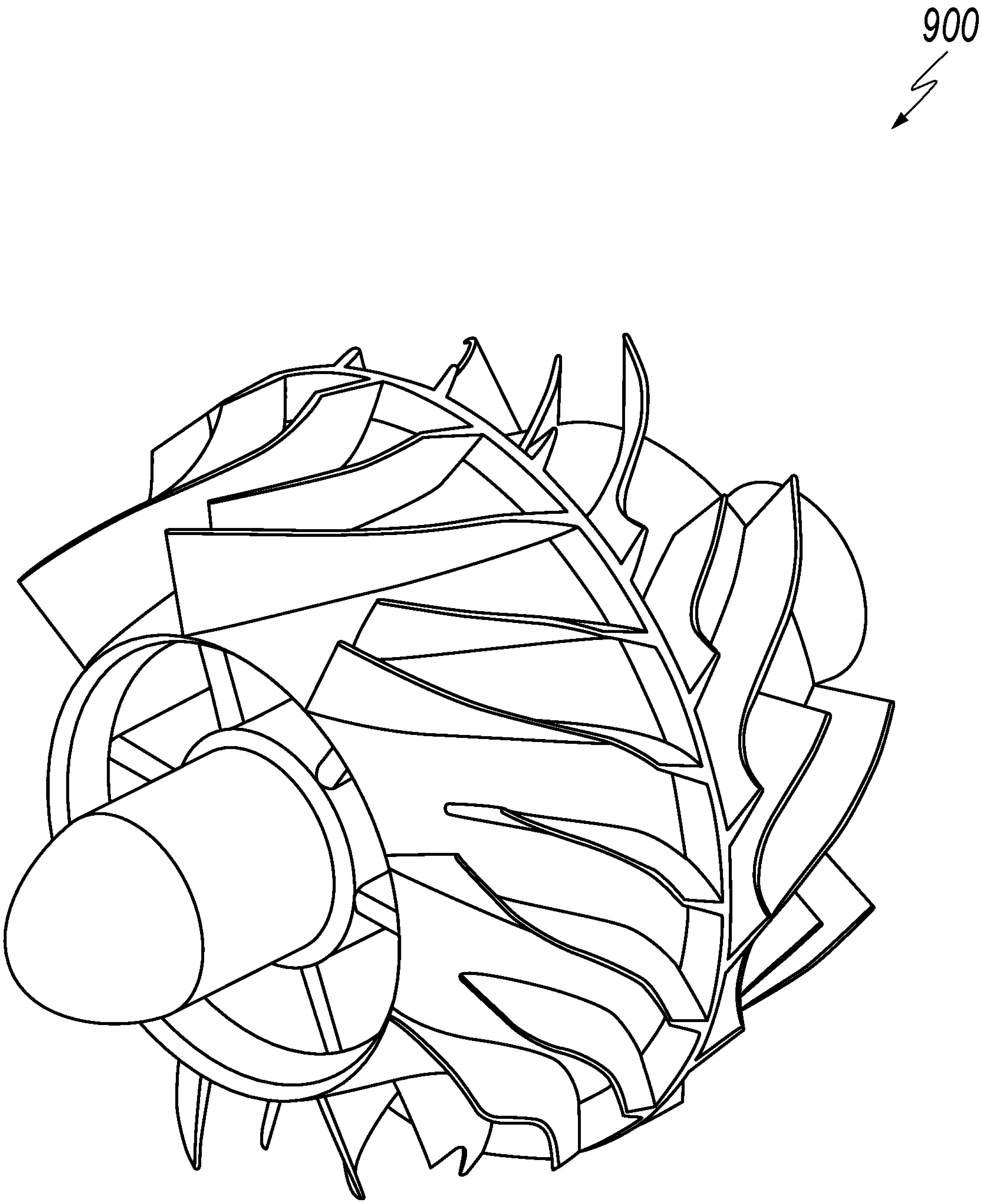


FIG. 9A

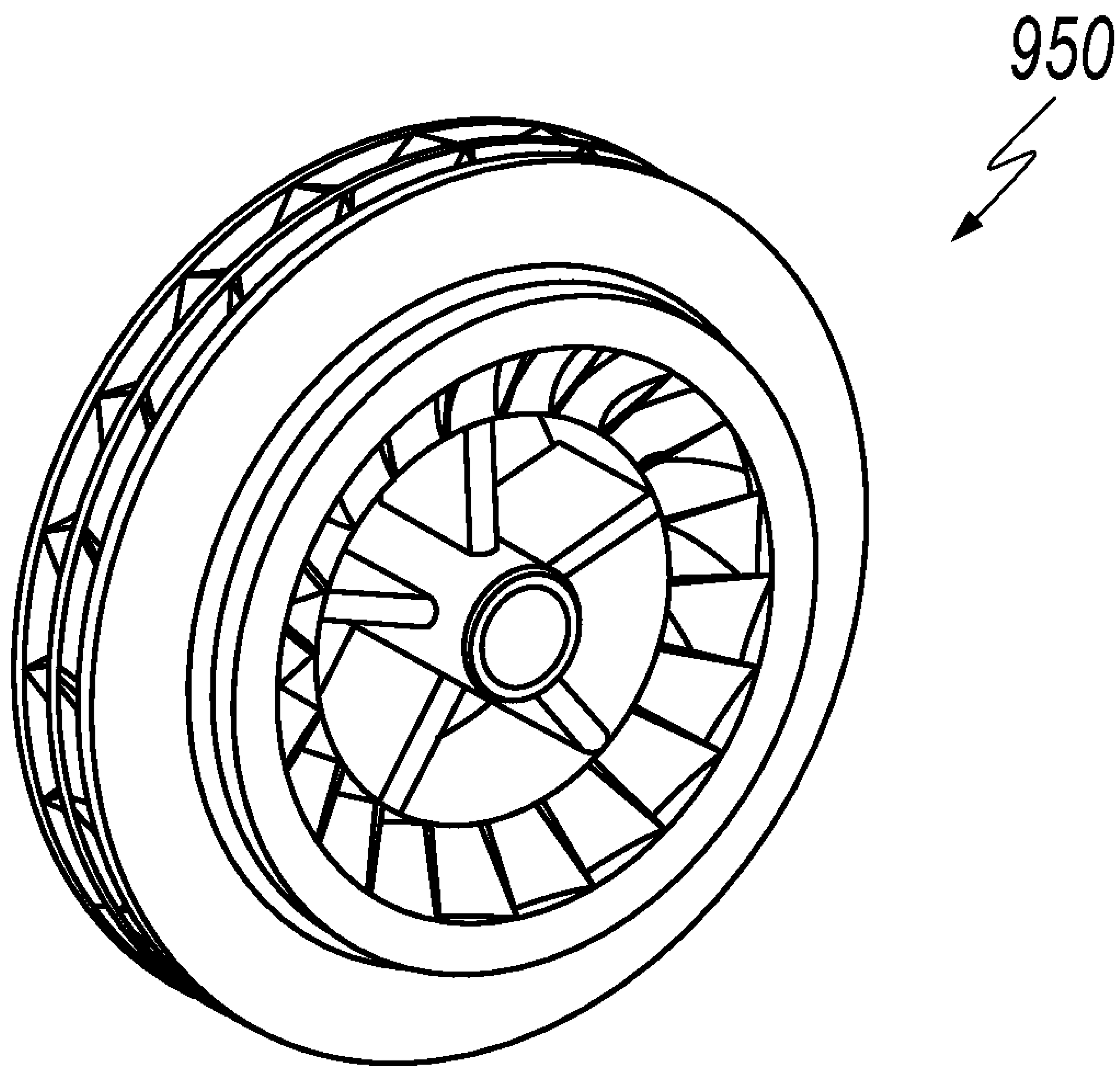


FIG. 9B

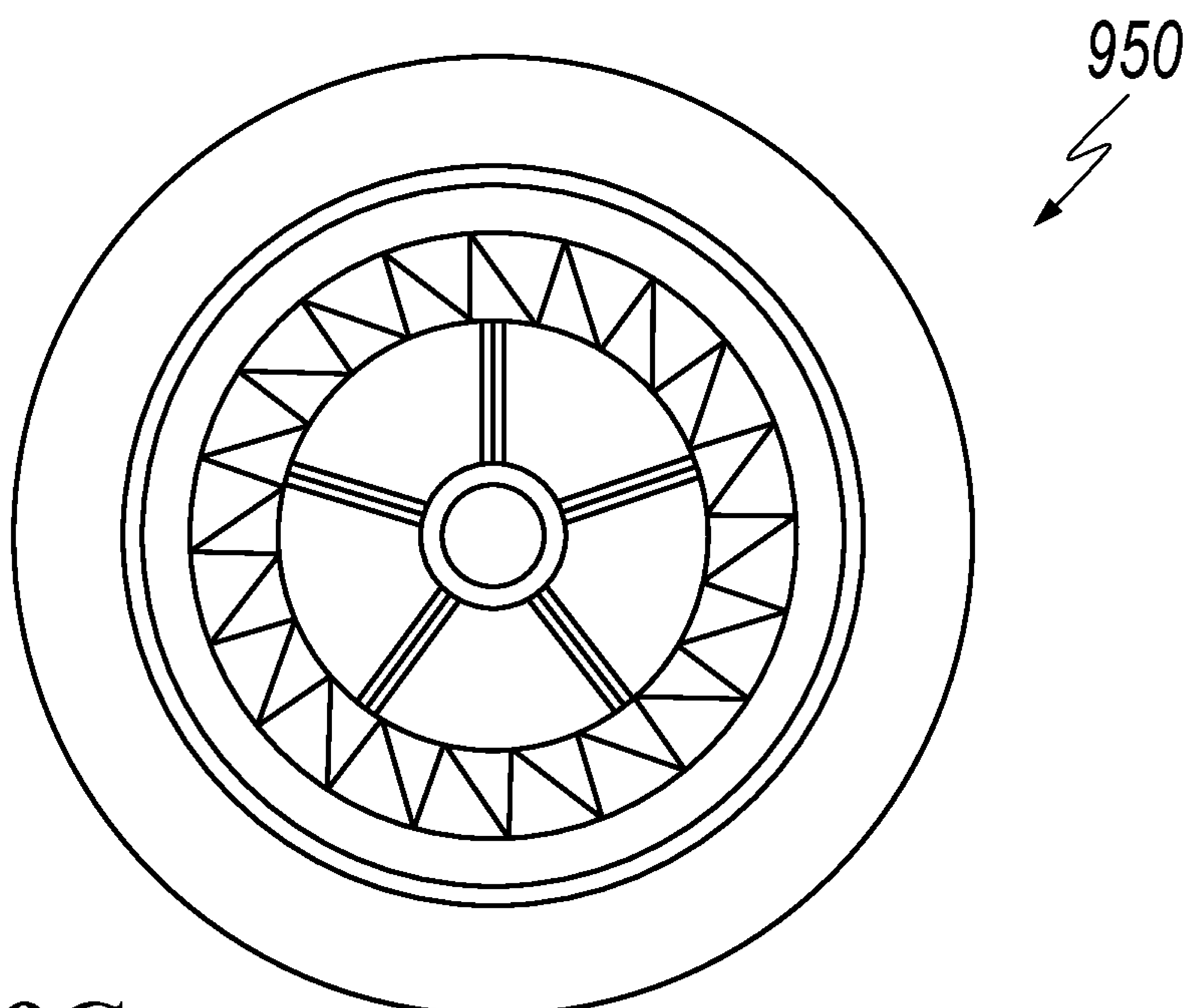


FIG. 9C

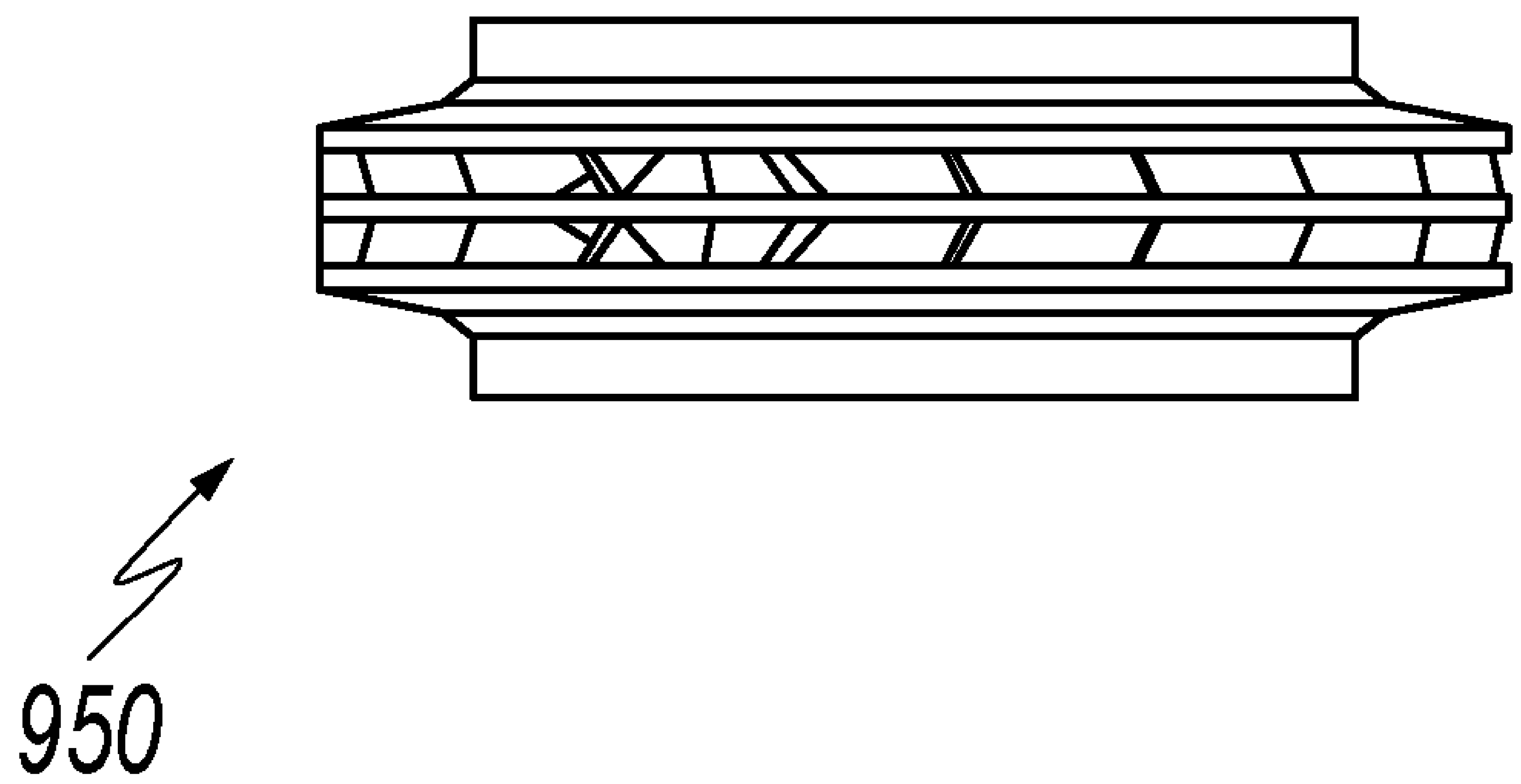


FIG. 9D

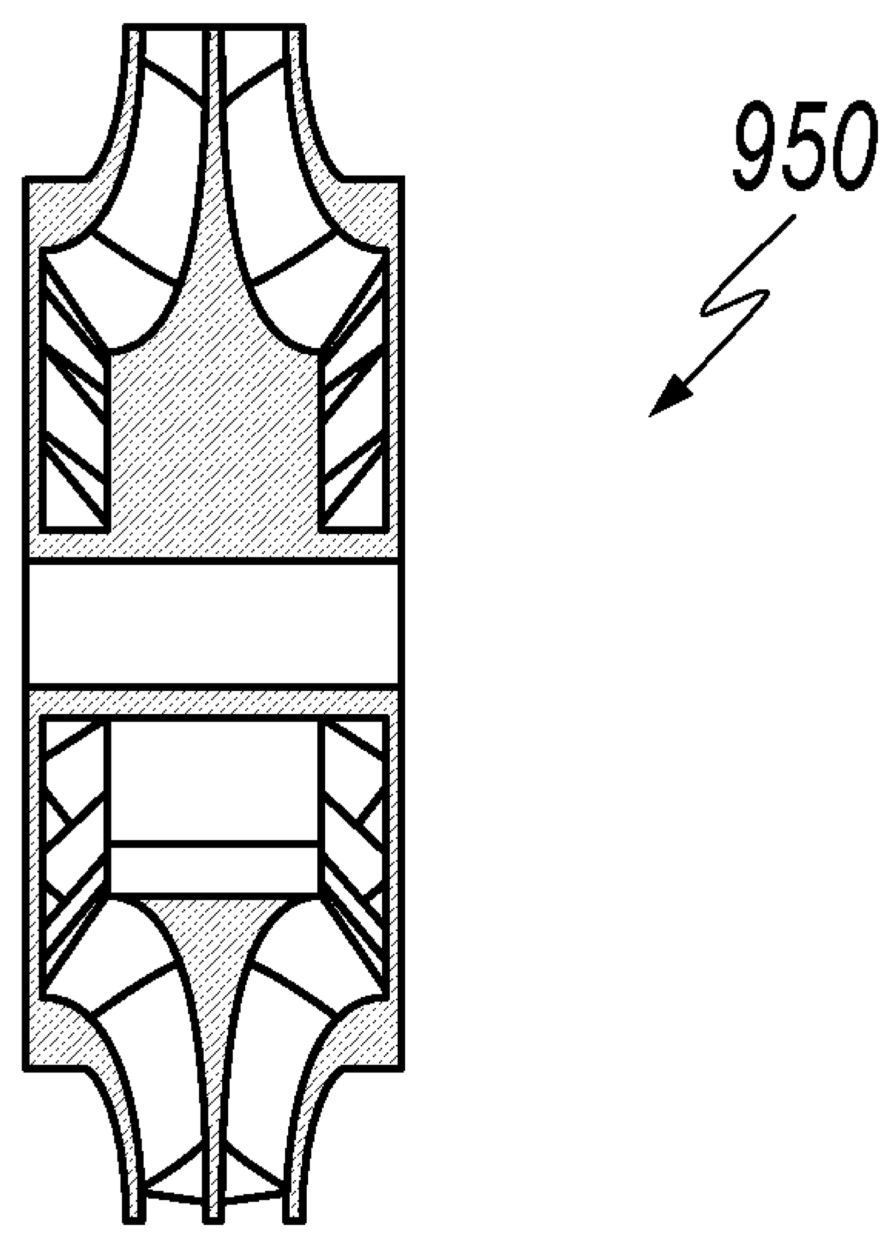


FIG. 9E

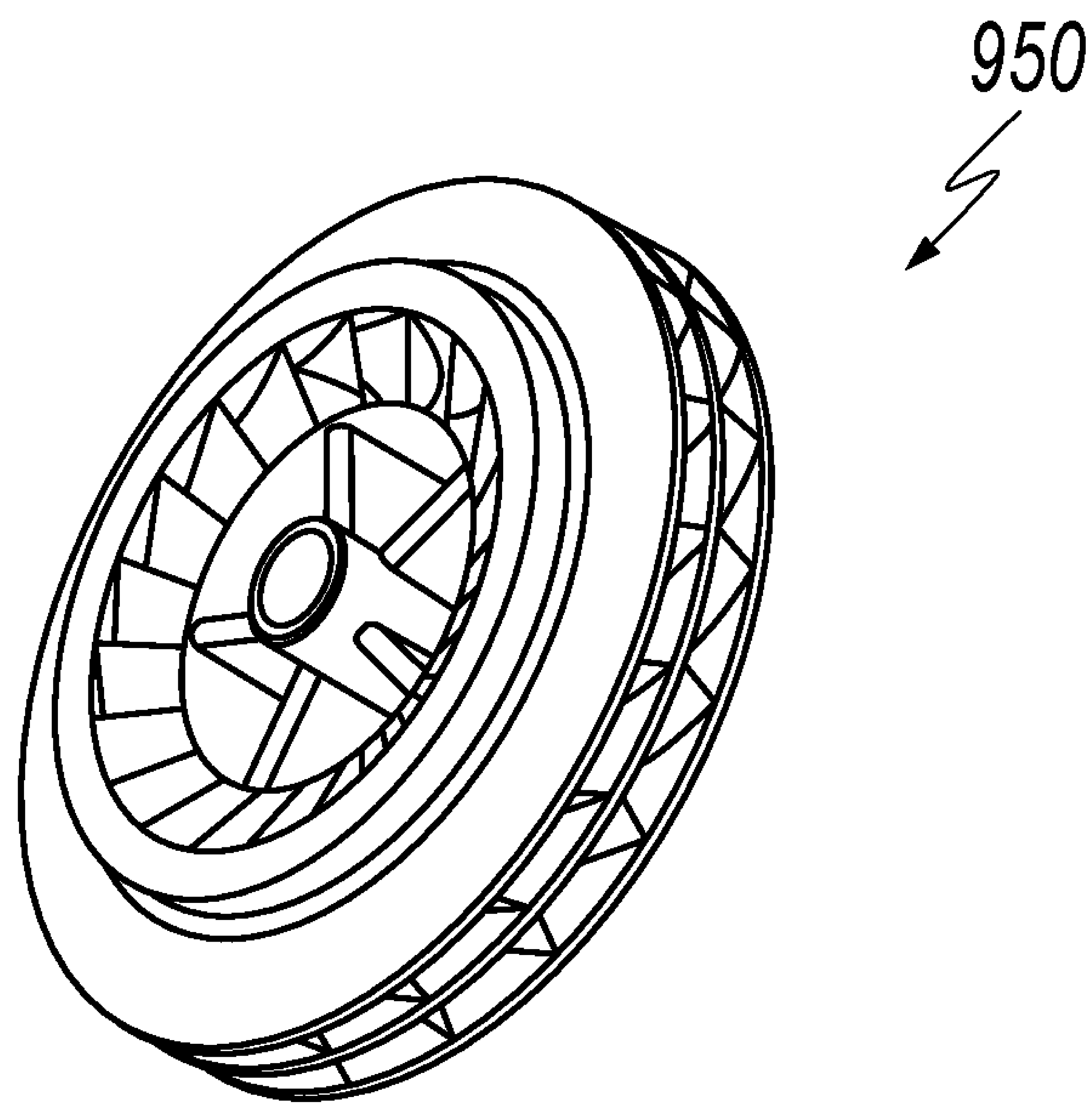


FIG. 9F

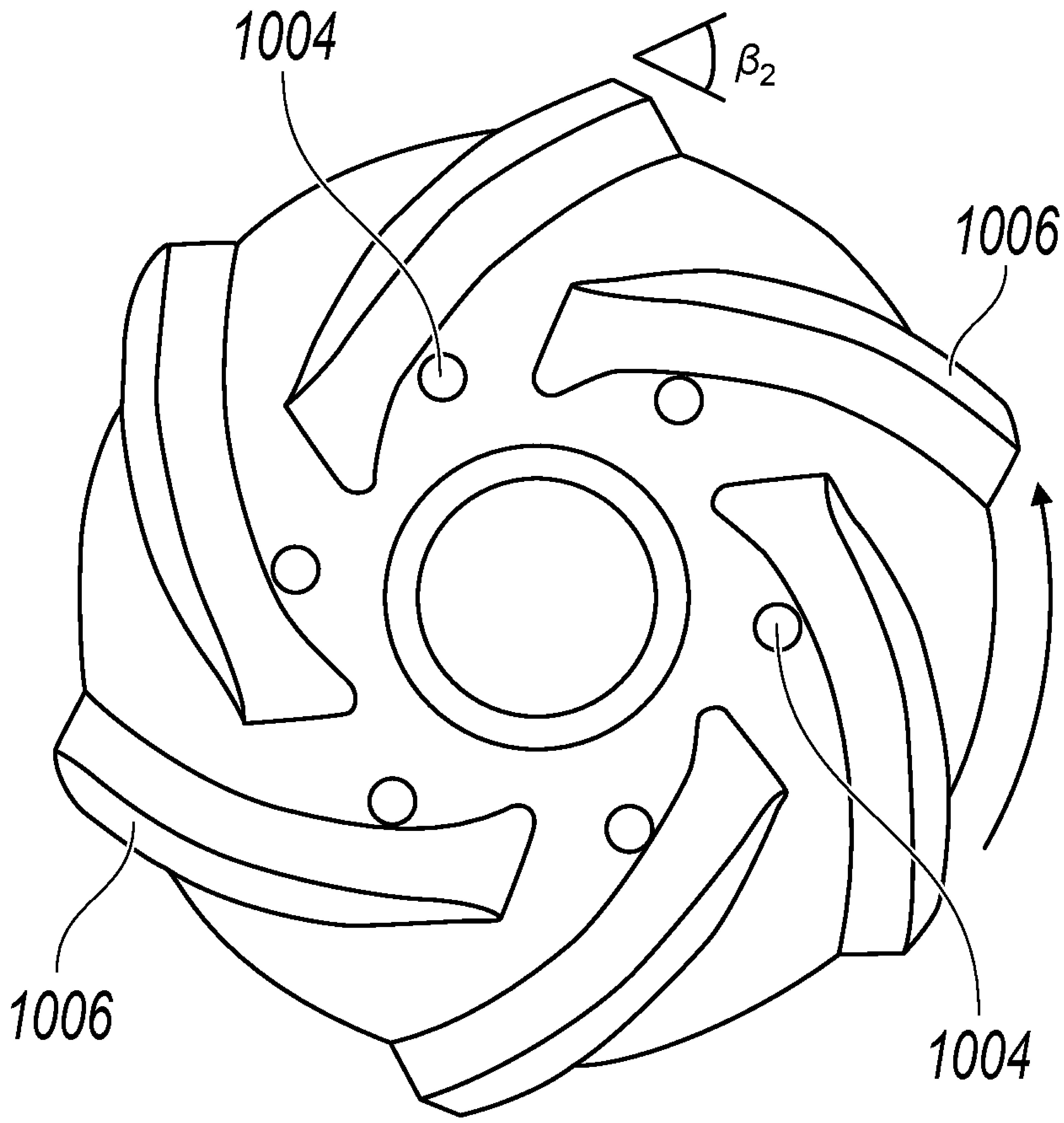


FIG. 10

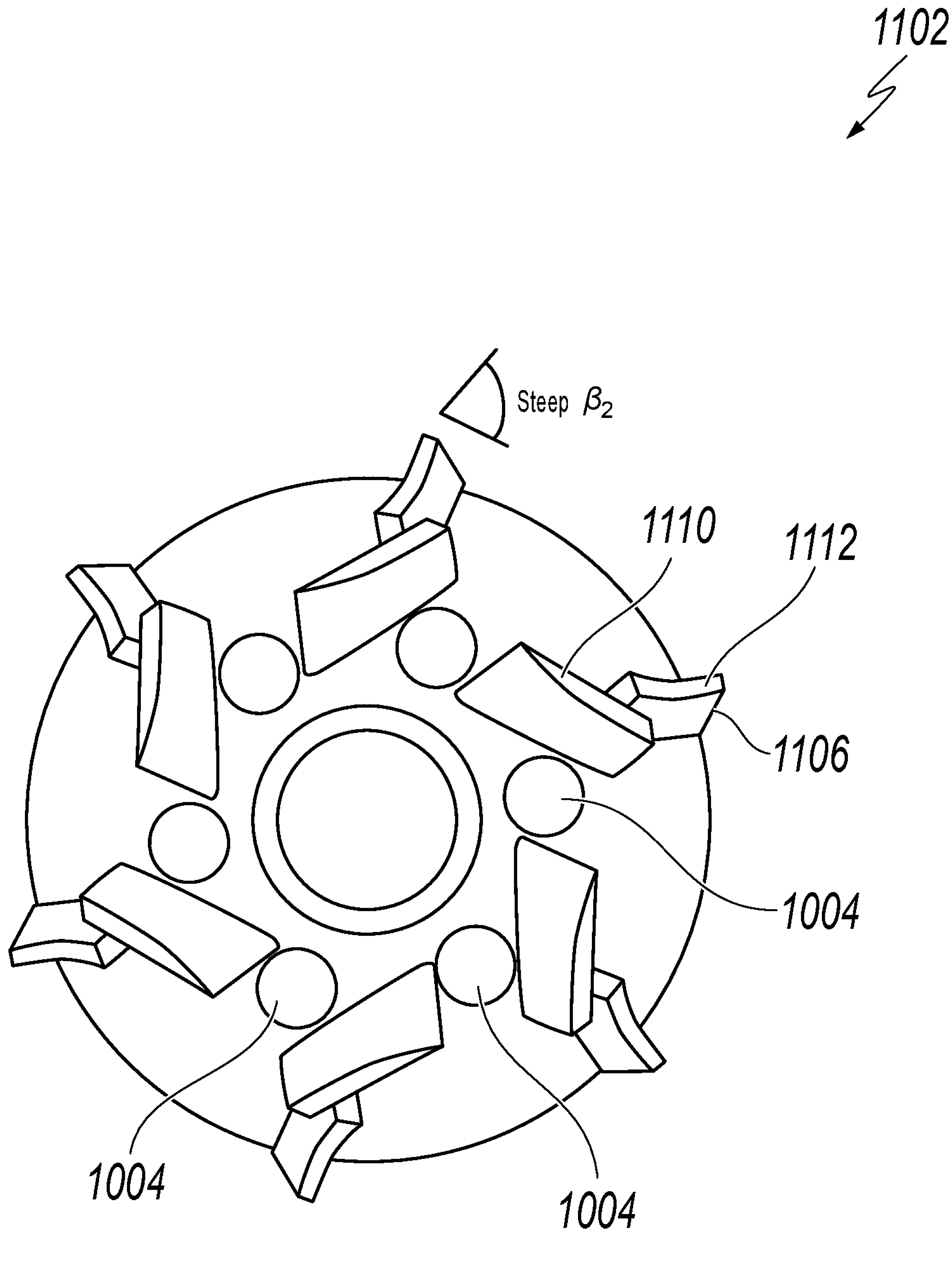


FIG. 11A

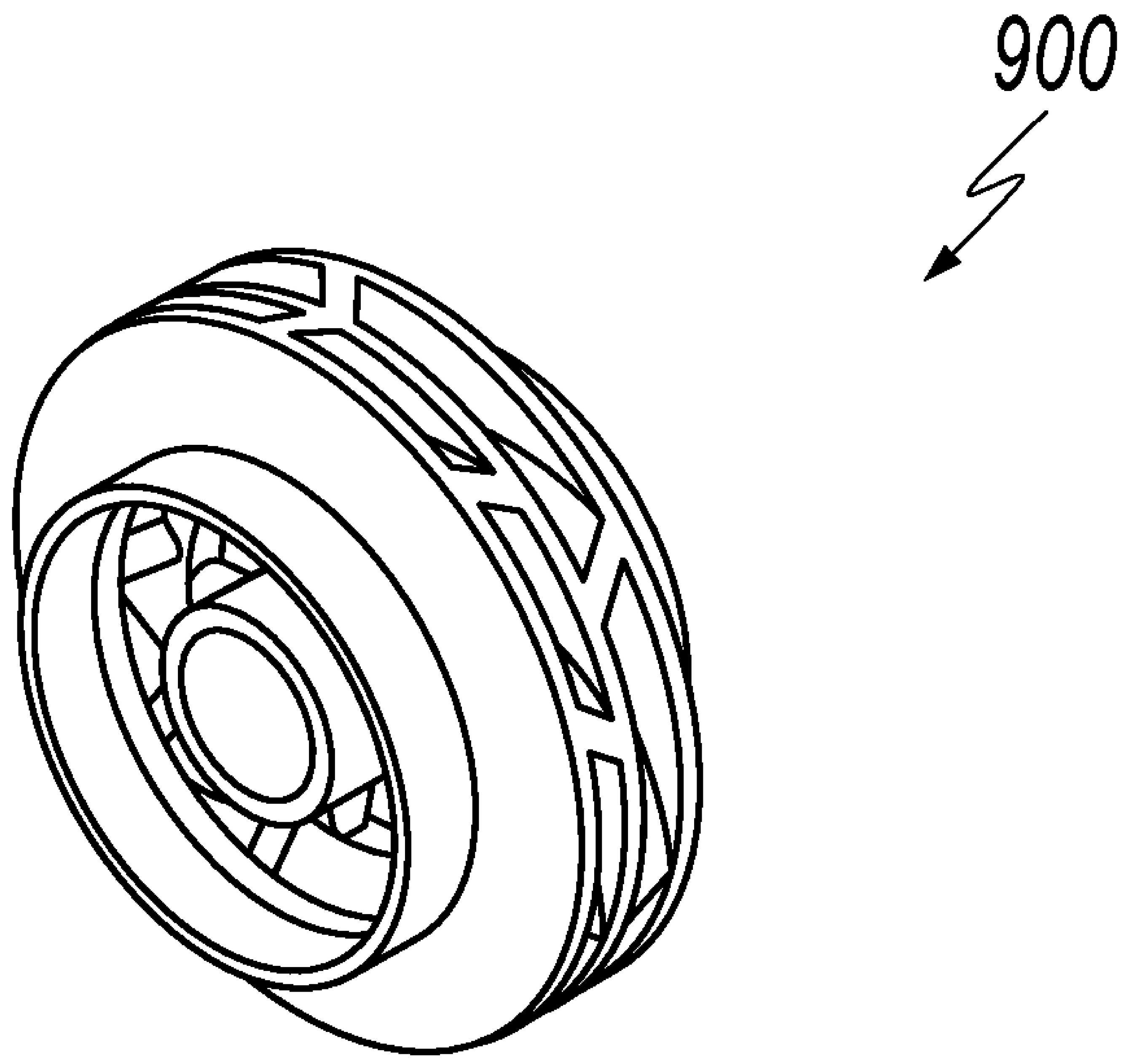


FIG. 11B

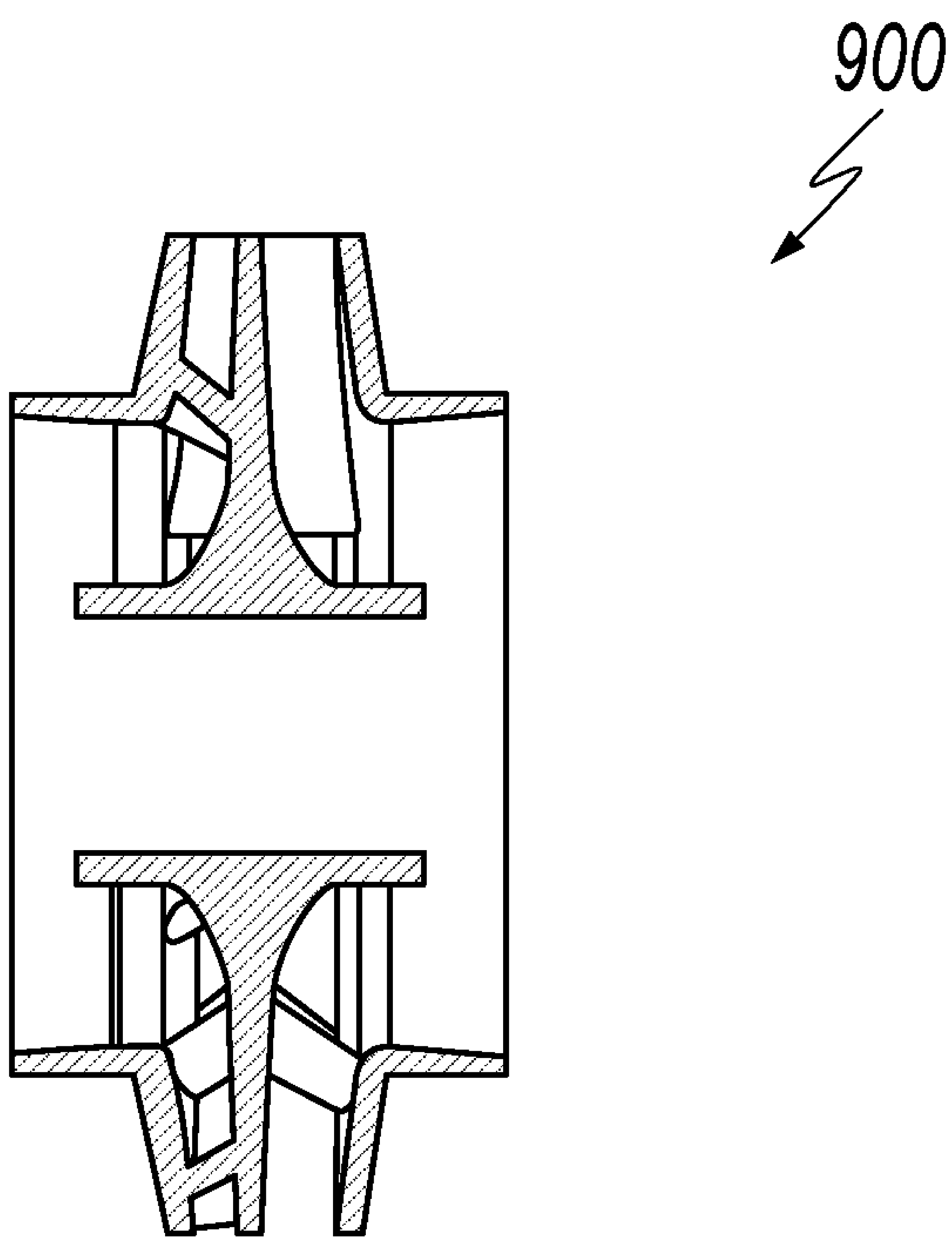


FIG. 11C

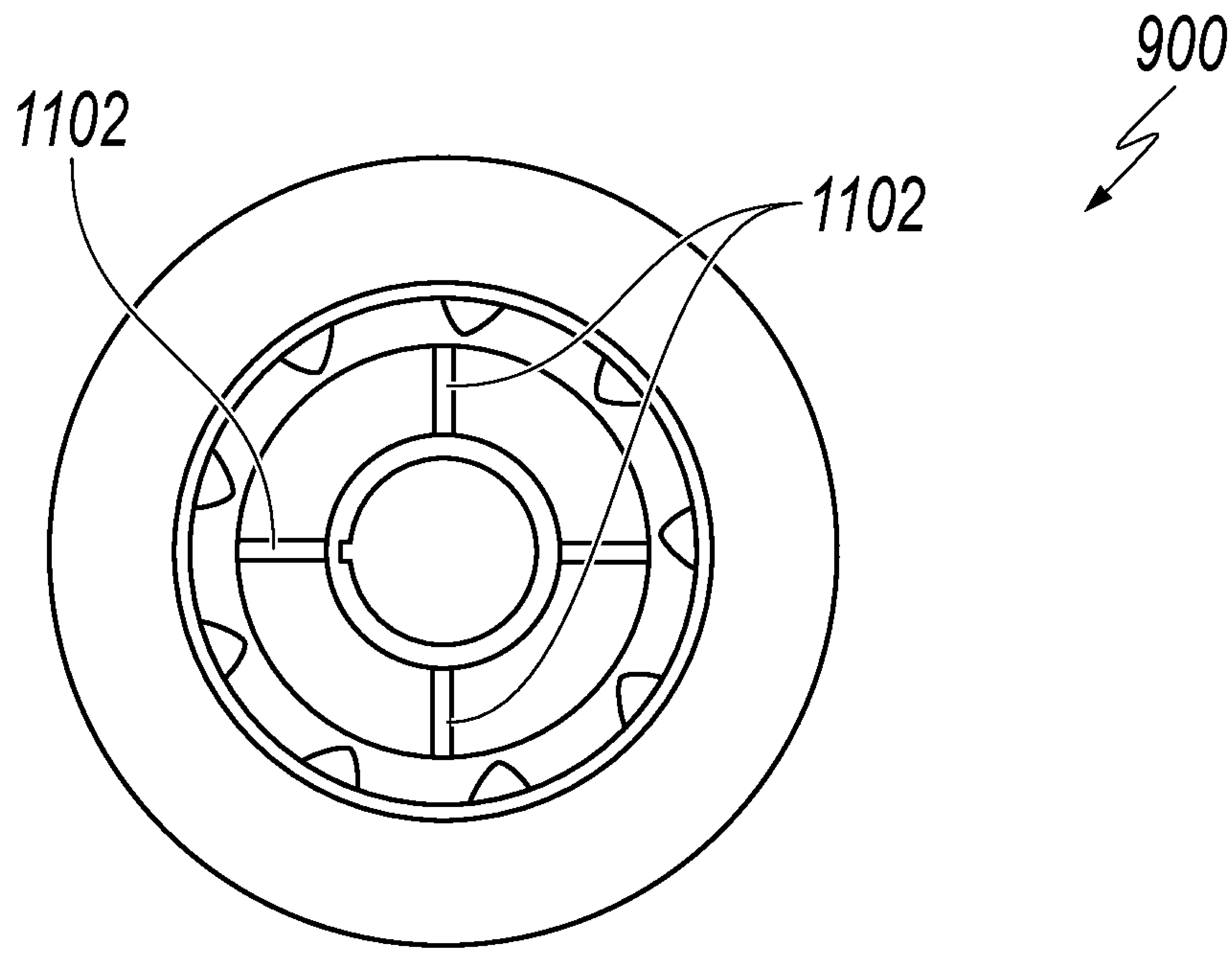


FIG. 11D

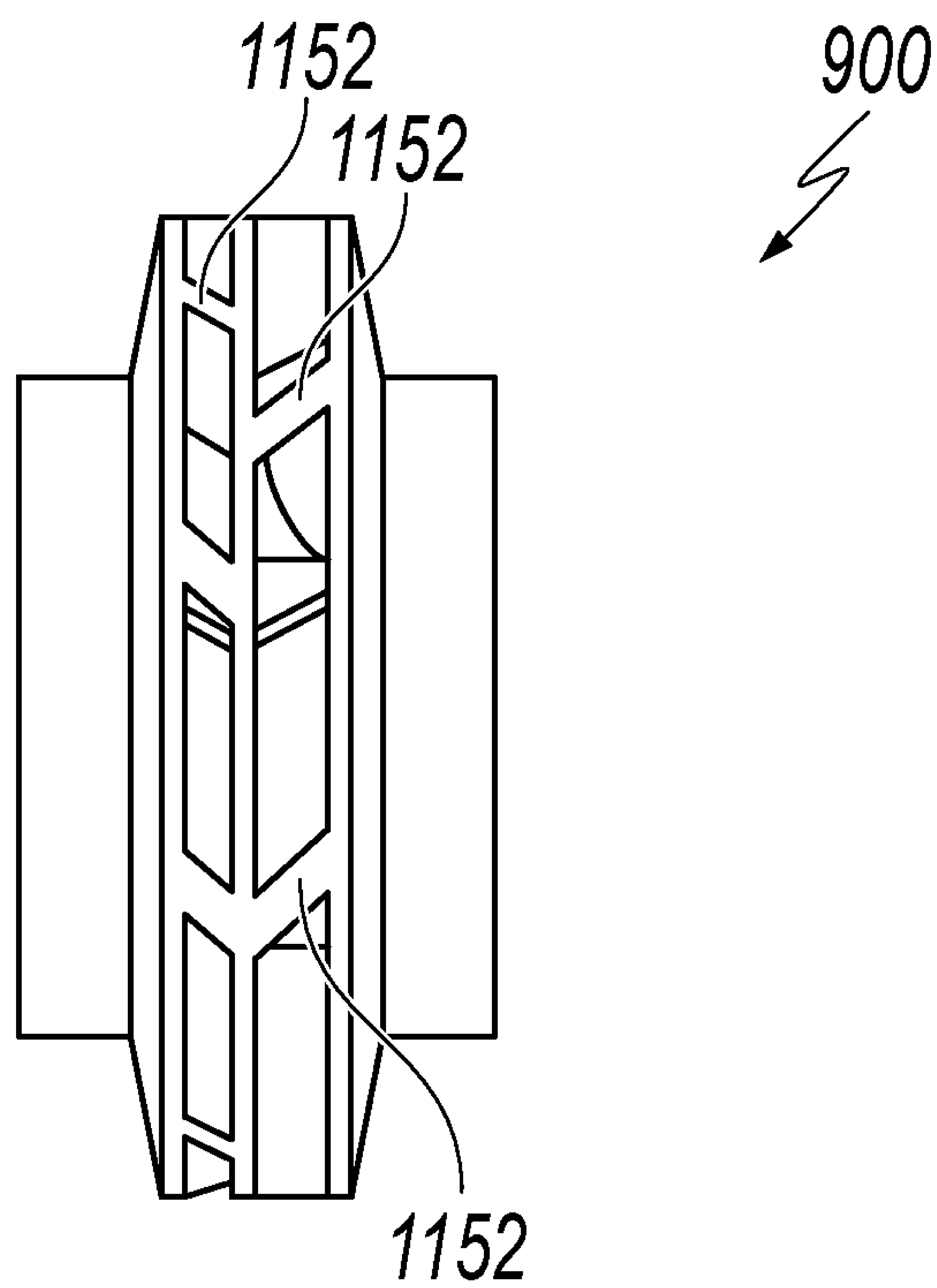


FIG. 11E

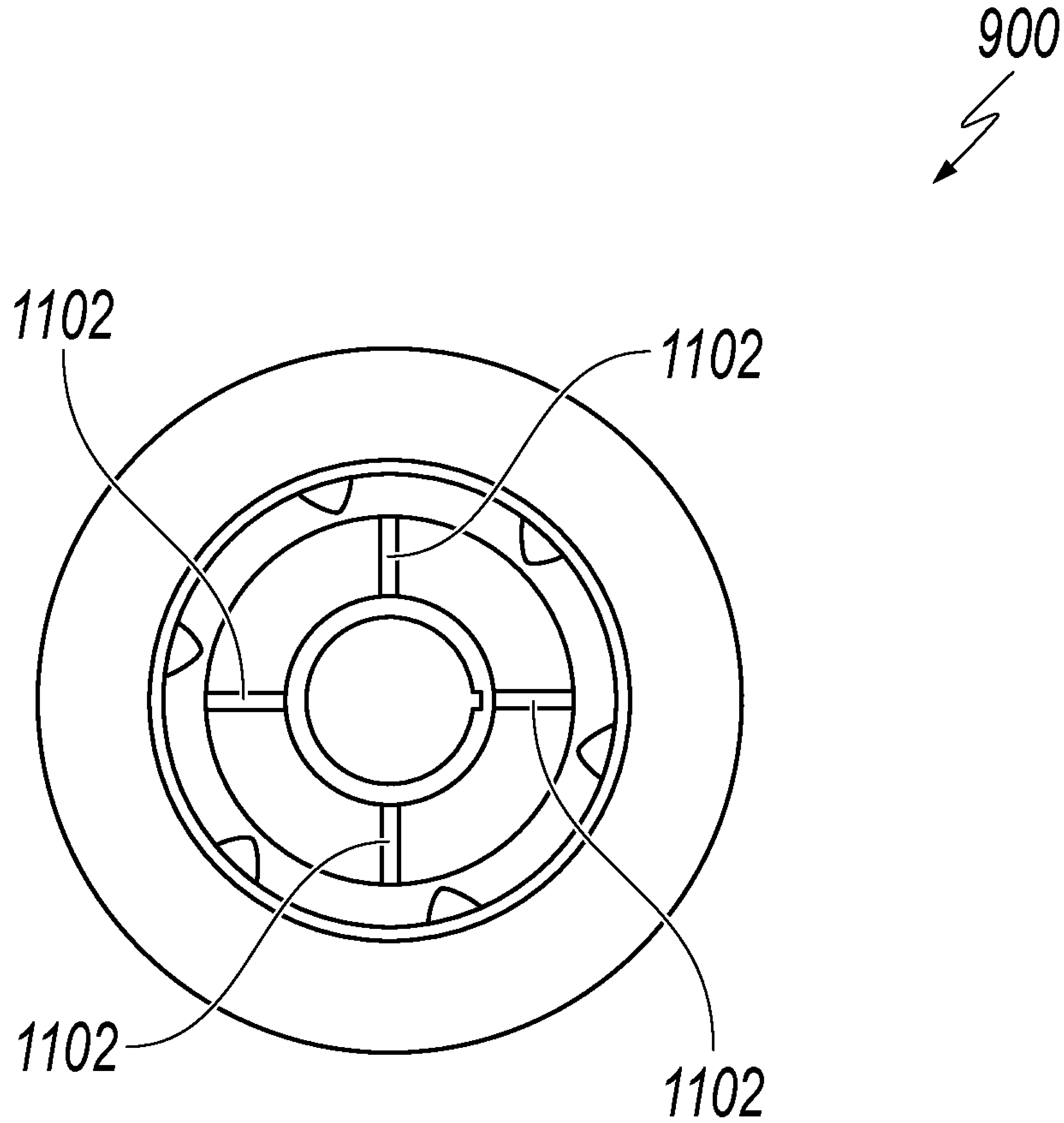


FIG. 11F

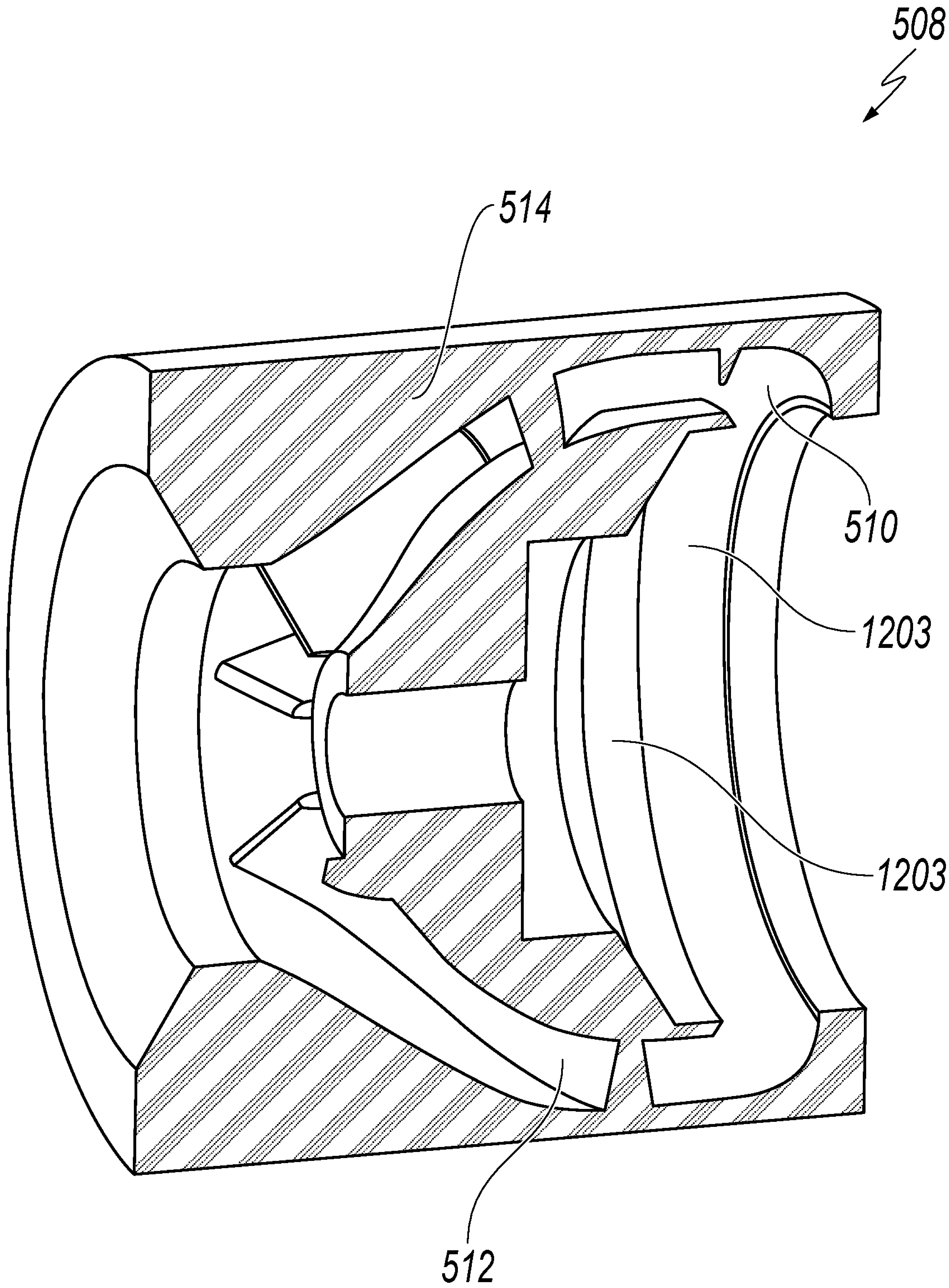


FIG. 12

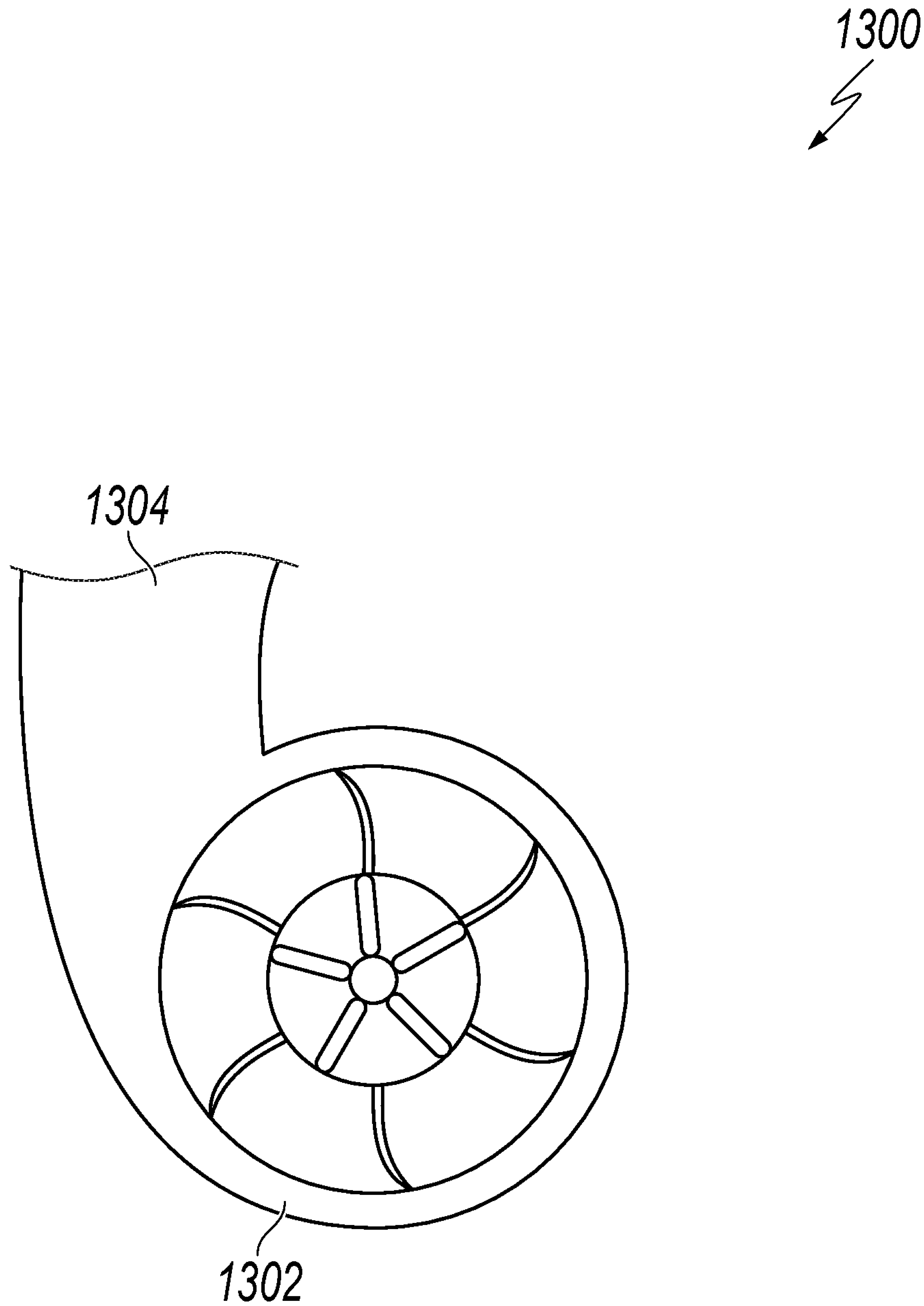


FIG. 13A

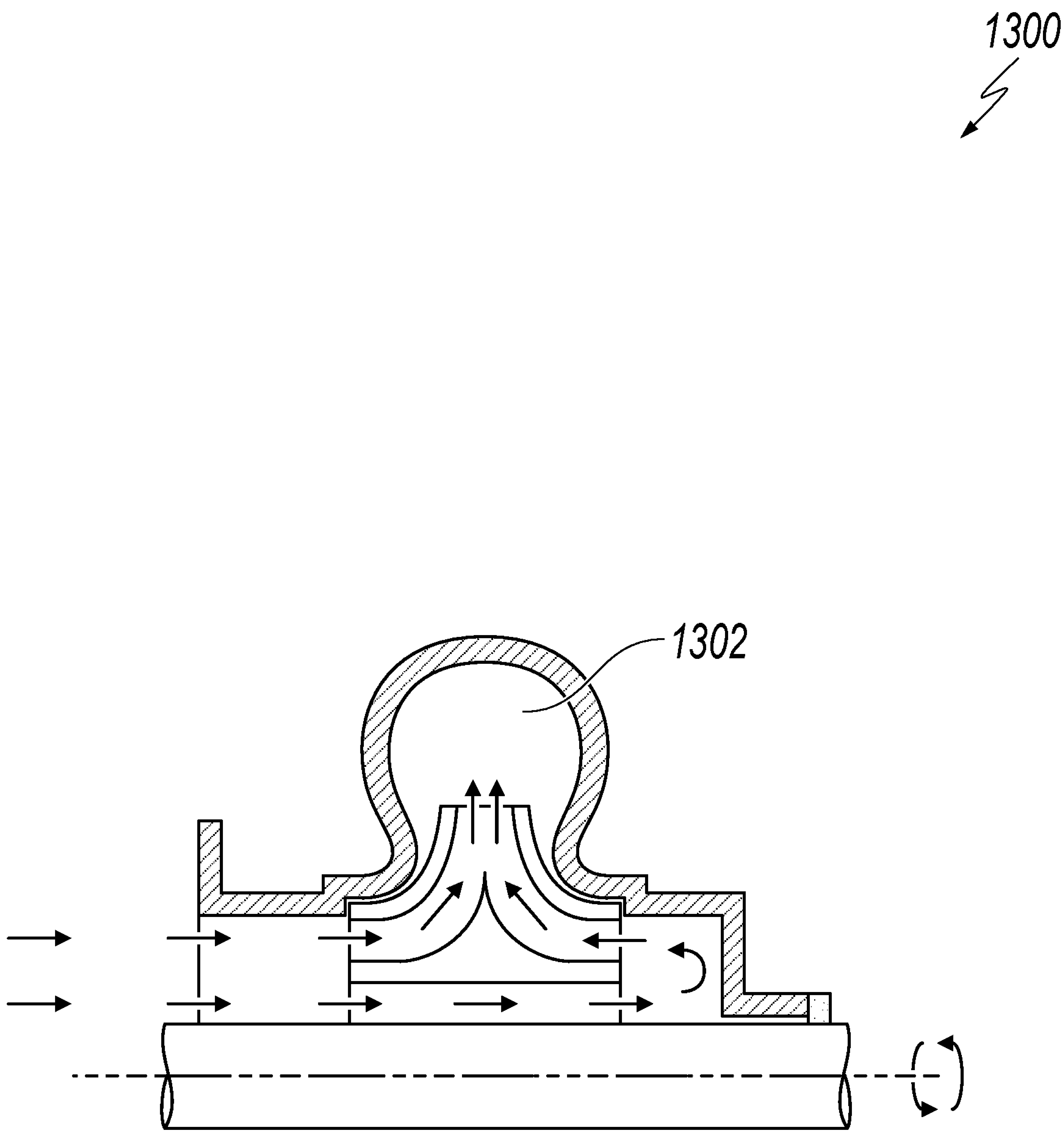


FIG. 13B

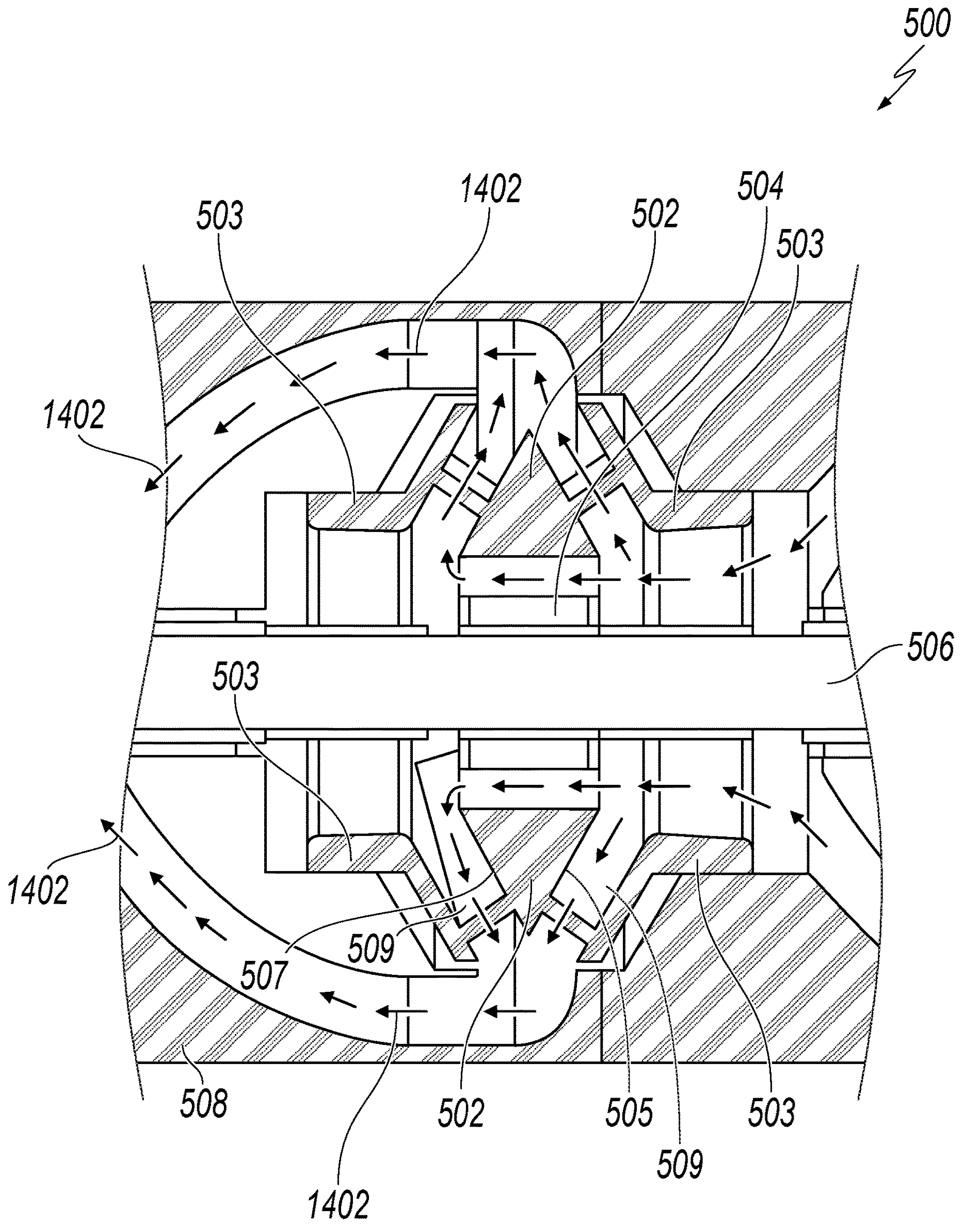

500
1402
503
502
504
503
1402
506
503
1402
509
507
508
1402
502
505
509
503

FIG. 14A

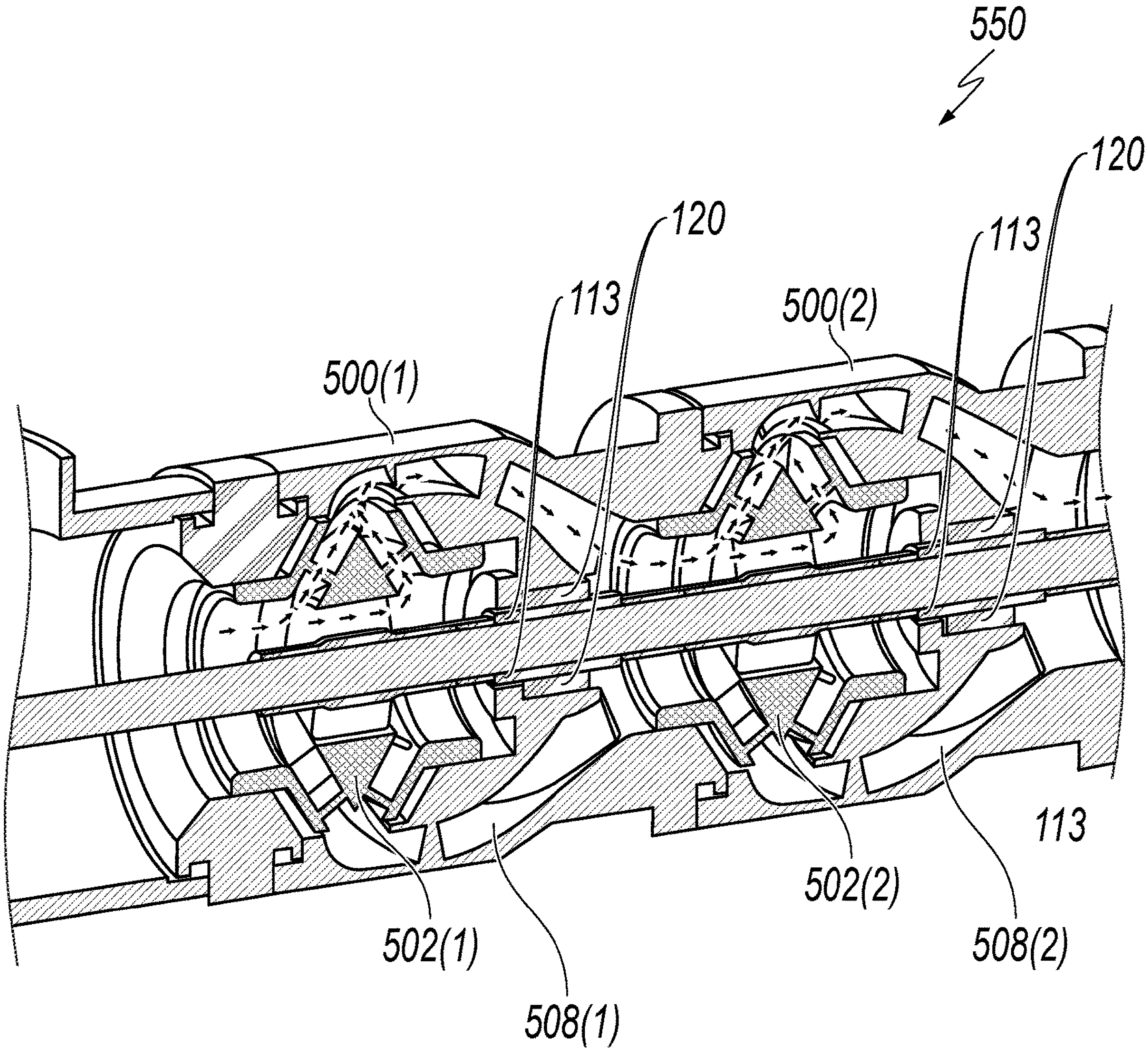


FIG. 14B

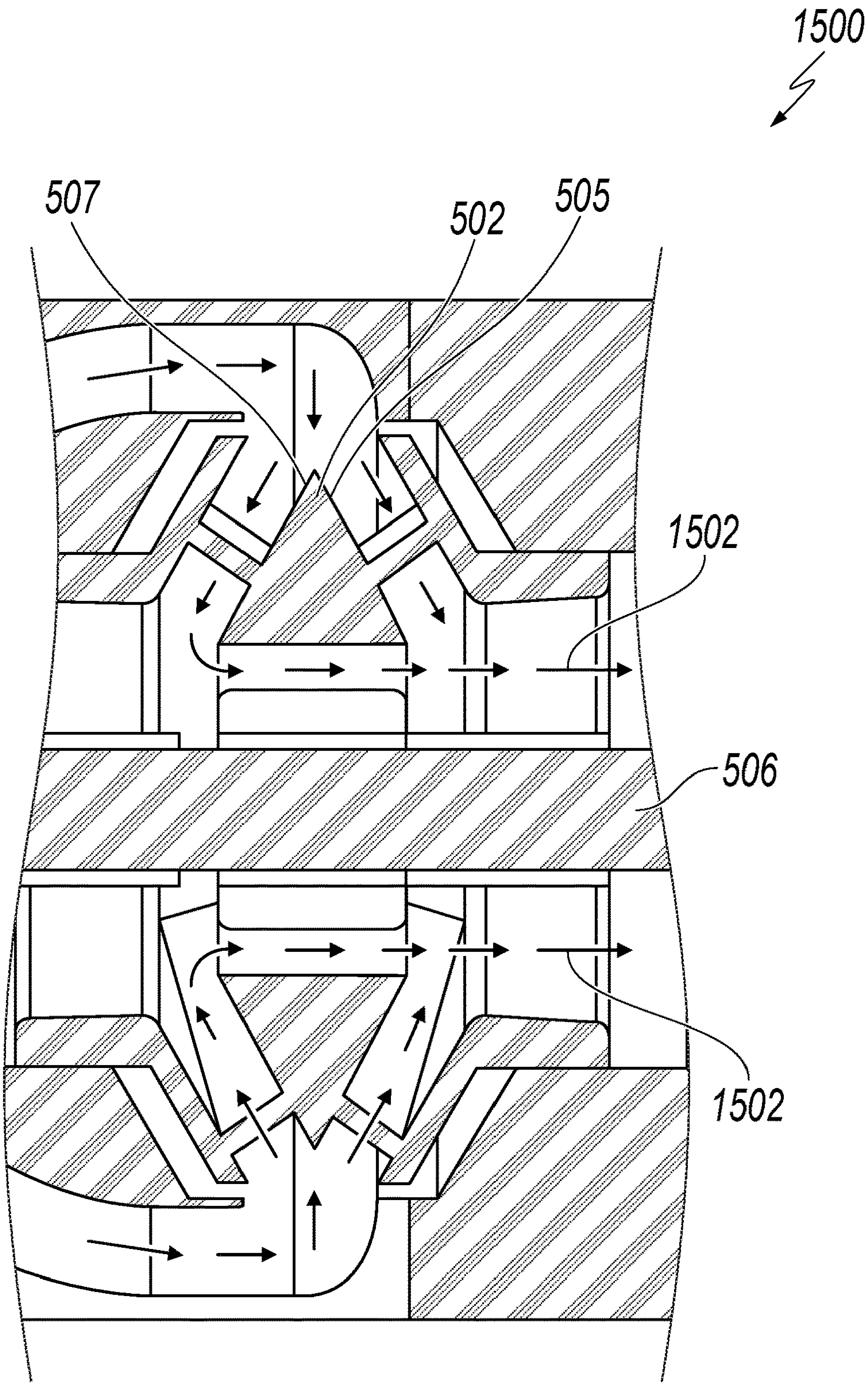
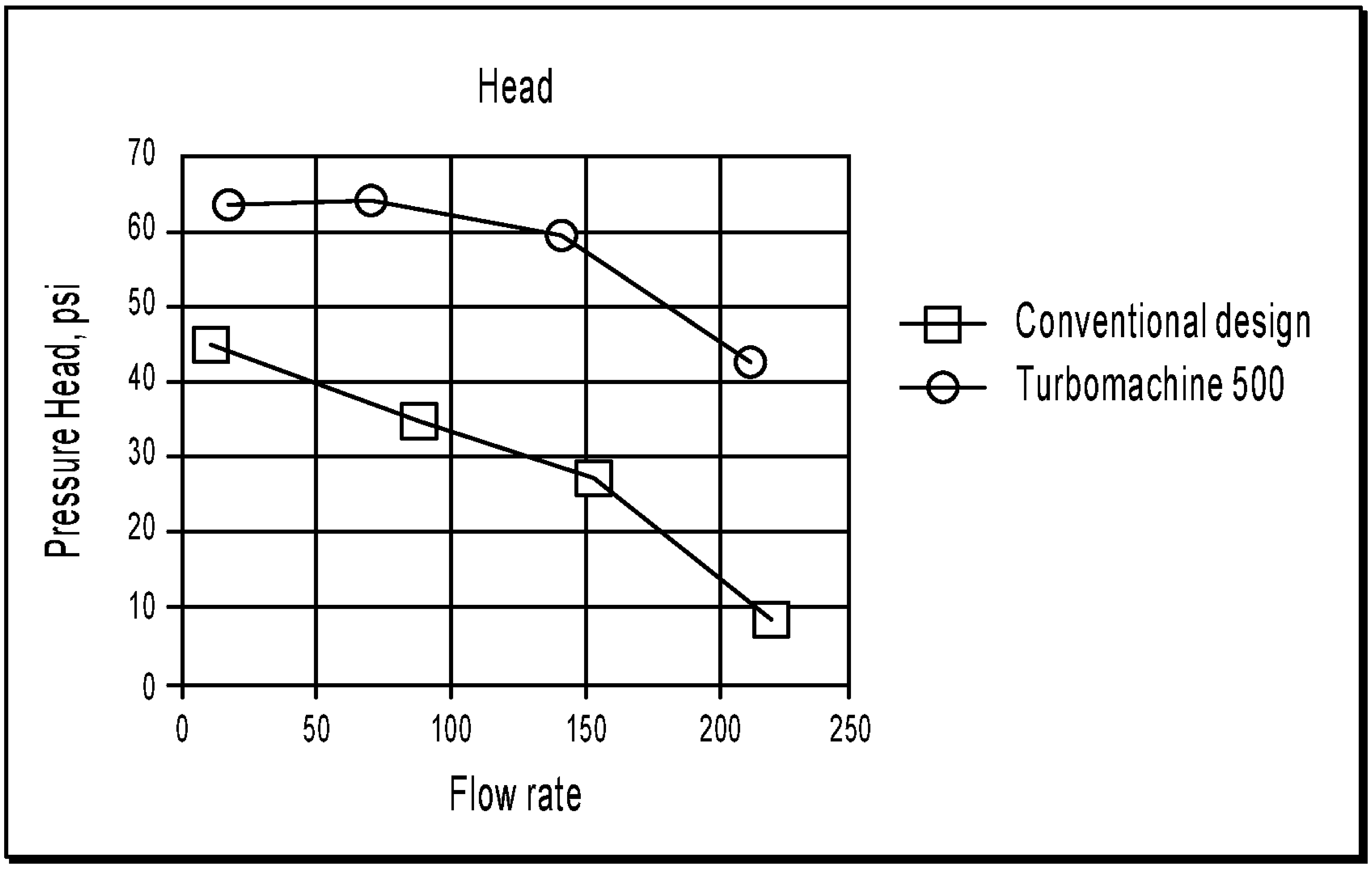


FIG. 15



Head
70
60
50
40
30
20
10
0
0
50
100
150
200
250
Flow rate
Pressure Head, psi
Conventional design
Turbomachine 500

FIG. 16

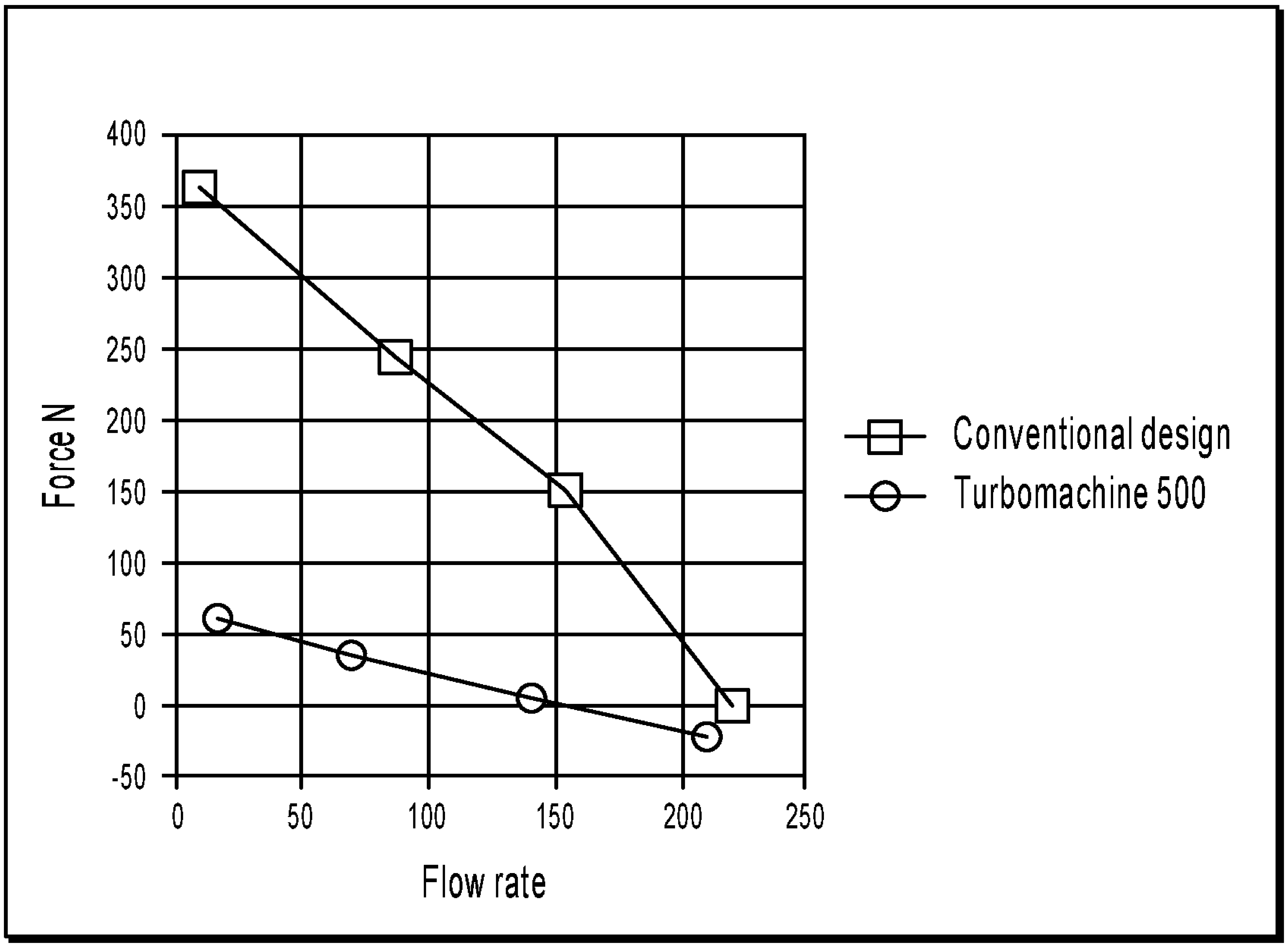
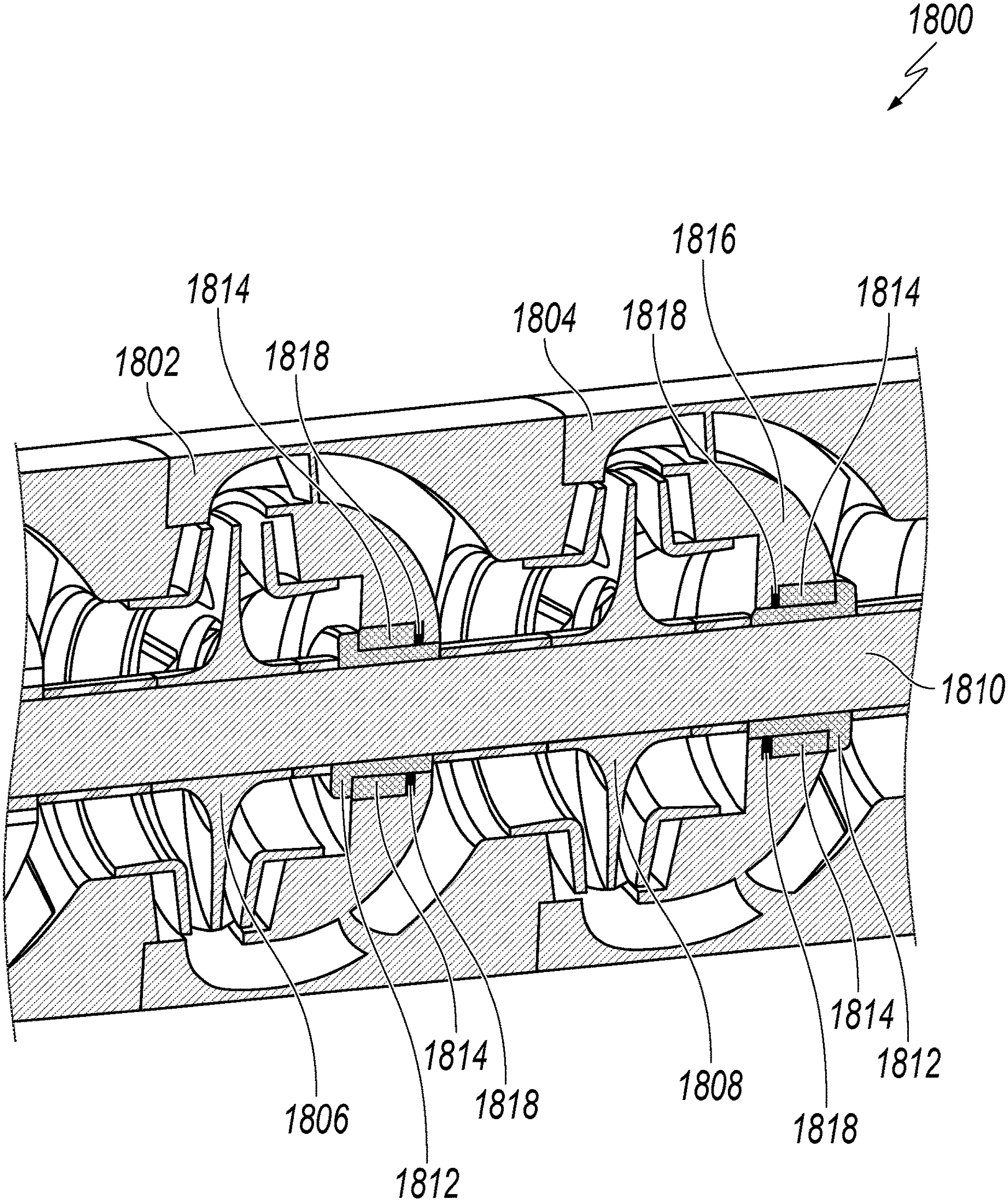

400
350
300
250
200
150
100
50
0
-50
Force N
0
50
100
150
200
250
Flow rate
Conventional design
Turbomachine 500

FIG. 17


1800
1816
1814
1804
1818
1814
1802
1818
1810
1814
1812
1814
1818
1808
1806
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1812
1818
1812
1814

FIG. 18

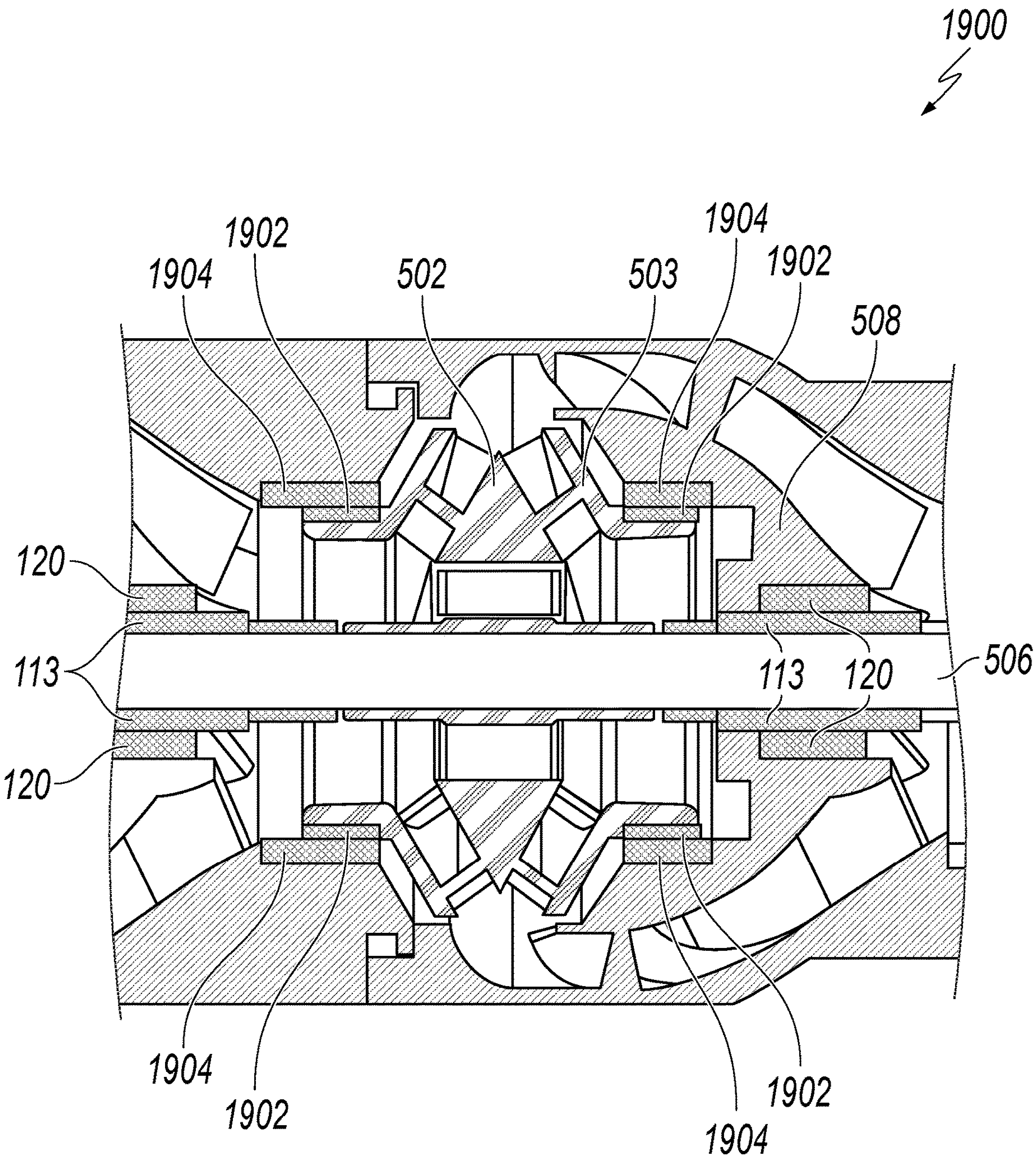
1900
1904
1902
502
503
1904
1902
508
120
113
120
506
113
120
1904
1902
1904
1902

FIG. 19

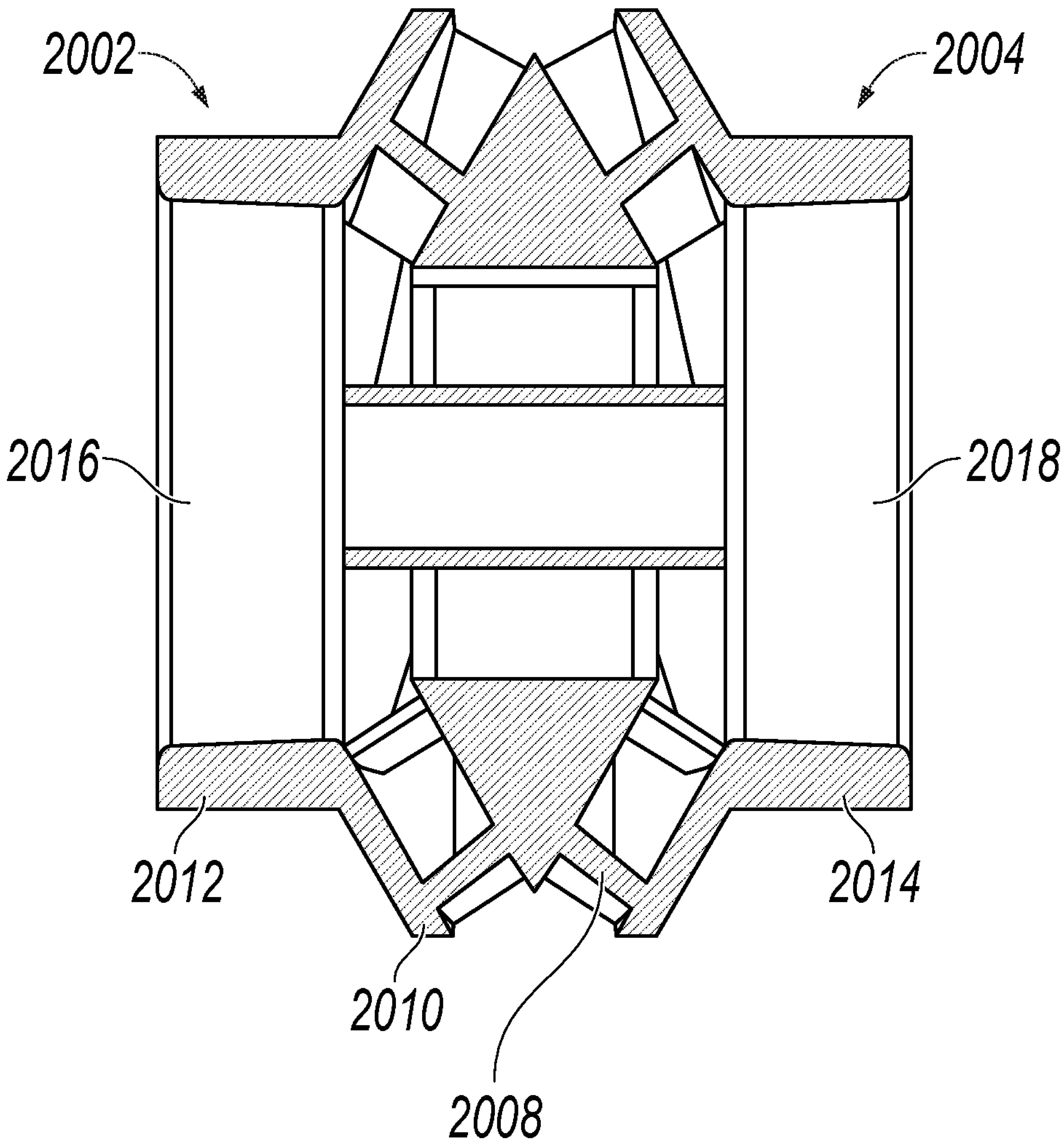

FIG. 20

HIGH ENERGY DENSITY TURBOMACHINES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to, and incorporates by reference the entire disclosure of, U.S. Provisional Patent Application No. 62/723,185 filed on Aug. 27, 2018.

BACKGROUND

This section provides background information to facilitate a better understanding of the various aspects of the disclosure. It should be understood that the statements in this section of this document are to be read in this light, and not as admissions of prior art.

Turbomachinery is a term used to describe mechanical devices that transfer energy between a rotor and a fluid. Turbomachines may be power-absorbing devices, such as pumps and compressors, or may be power-producing devices such as turbines. Power-absorbing turbomachines typically transfer energy from a rotor to a fluid while power-producing turbomachines typically transfer energy from a fluid to a rotor.

SUMMARY

Various aspects of the disclosure relate to a turbomachine. The turbomachine includes a housing having an inlet and an outlet. A shaft is rotationally disposed in the housing. The shaft is rotatable about a longitudinal axis. An impeller is coupled to the shaft between the inlet and the outlet and rotates with the shaft. The impeller includes a single impeller inlet and an impeller outlet, a first set of vanes disposed on a first side of the impeller, and a second set of vanes disposed on a second side of the impeller. A passage is formed through a thickness of the impeller. The passage facilitates transmission of fluid from the first side of the impeller to the second side of the impeller such that fluid is supplied to the first set of vanes and the second set of vanes via the single impeller inlet. Transmission of fluid through the impeller reduces net axial thrust imparted to at least one of the impeller and the shaft.

Various aspects of the disclosure relate to an impeller for use in a turbomachine. The impeller includes a first side having a first set of vanes disposed thereon and a second side having a second set of vanes disposed thereon. The second side is arranged opposite the first side. The impeller includes a single fluid inlet and a fluid outlet. A passage is formed through a thickness of the impeller. The passage facilitates transmission of fluid from the first side of the impeller to the second side of the impeller such that fluid is supplied to the first set of vanes and the second set of vanes via the single impeller inlet.

Various aspects of the disclosure relate to a method of reducing axial thrust on an impeller shaft. The method includes directing a fluid onto a first side of an impeller and a second side of an impeller via a single impeller inlet. The method also includes transmitting the fluid through a passage formed through a thickness of the impeller between the first side of the impeller and the second side of the impeller. The fluid is expelled from the impeller via an impeller outlet. Various aspects of the disclosure relate a method of assembling an impeller in a single-stage or multistage turbomachine so as to allow radial and axial position adjustment of the impeller during operation.

This summary is provided to introduce a selection of concepts that are further described below in the detailed description. This summary is not intended to identify key or essential features of the claimed subject matter, nor is it intended to be used as an aid in limiting the scope of claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present disclosure and for further objects and advantages thereof, reference may now be had to the following description taken in conjunction with the accompanying drawings in which:

FIG. **1** is a cross-sectional view of a single suction multi-stage electrical submersible pump;

FIG. **2** is a diagram illustrating stage clearances and pressure contour for the single suction multi-stage electrical submersible pump of FIG. **1**;

FIG. **3** is a graph illustrating thrust change with rotational speed for a single suction multi-stage electrical submersible pump;

FIG. **4**A is a cross sectional view of a single-suction impeller design;

FIG. **4**B is a cross sectional view of a double-suction impeller design;

FIG. **5** is a cross-sectional view of a turbomachine having an impeller with an annular passage according to aspects of the disclosure;

FIG. **6** is a cross sectional view of an impeller with an annular passage utilized with the turbomachine of FIG. **5** according to aspects of the disclosure;

FIG. **7**A is a perspective view of an unshrouded impeller utilized with the turbomachine of FIG. **5** according to aspects of the disclosure;

FIG. **7**B is a cross-sectional view of the turbomachine of FIG. **5** illustrating a shrouded impeller;

FIG. **8** is an exploded view of a turbomachine shaft assembly according to aspects of the disclosure;

FIG. **9**A is a perspective view of an exemplary unshrouded impeller for a compressor according to aspects of the disclosure;

FIG. **9**B is a perspective view of an exemplary shrouded impeller for use with a compressor;

FIG. **9**C is a plan view of the shrouded impeller of FIG. **9**B;

FIG. **9**D is a side view of the shrouded impeller of FIG. **9**B;

FIG. **9**E is a cross-sectional view of the shrouded impeller of FIG. **9**B;

FIG. **9**F is perspective view of the shrouded impeller of FIG. **9**B;

FIG. **10** is a plan view of an impeller utilizing balance holes according to aspects of the disclosure;

FIG. **11**A is a plan view of a split blade impeller according to aspects of the disclosure;

FIGS. **11**B-**11**F illustrate an impeller having differing vane geometry on opposite sides thereof according to aspects of the disclosure;

FIG. **12** is a cross-sectional view of a diffuser according to aspects of the disclosure;

FIG. **13**A is a plan view of a volute according to aspects of the disclosure;

FIG. **13**B is a cross sectional view of the volute of FIG. **13**A;

FIG. **14**A is a cross-sectional view of the turbomachine of FIG. **5** illustrating fluid flow therethrough according to aspects of the disclosure;

FIG. **14**B is a cross-sectional view of the turbomachine of FIG. **14**A illustrating multiple stages.

FIG. **15** is a cross sectional view of a hydraulic turbine illustrating fluid flow therethrough according to aspects of the disclosures;

FIG. **16** is a graph relating pressure head to flow rate for turbomachine according to aspects of the disclosure.

FIG. **17** is a graph relating thrust to flow rate for a turbomachine according to aspects of the disclosure;

FIG. **18** is a cross-sectional view of a turbomachine illustrating interstage bearing supports;

FIG. **19** is a cross-sectional view of a turbomachine illustrating impeller-mounted bearing supports; and

FIG. **20** is a cross-sectional view of an exemplary impeller having different diffuser skirt diameters.

DETAILED DESCRIPTION

Various embodiments will now be described more fully with reference to the accompanying drawings. The disclosure may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein.

Turbomachines such as pumps and compressors are power absorbing devices used to add energy to fluids such as, for example, gases, liquids, or multiphase fluids that include at least one of gases, solids, and liquids. Turbomachines such as hydraulic and pneumatic turbines are power-producing devices used to generate mechanical or electrical power from hydraulic or pneumatic energy. A factor affecting reliability and feasibility of employing multistage turbomachines is the turbomachine's ability to handle reactive forces such as axial thrusts and radial loads. Hydraulic design of the impeller includes a shape of the impeller vanes and an ability of the impeller to tolerate axial and radial loading during operation. The axial thrust and radial loads limit rotational speed and operational spans of the turbomachine. In various embodiments, a turbomachine includes an impeller having an annular passage formed therein to balance thrust forces acting on the impeller shaft at elevated rotational speeds. Shrouded impeller designs allow axial and radial repositioning during assembly and operation. Such a turbomachine lowers axial thrust values and handles radial loads effectively compared to traditional turbomachine designs thereby increasing a threshold speed limit and dynamic stability of the turbomachine.

FIG. **1** is a cross-sectional view of a single suction multi-stage electrical submersible pump **100**. The electrical submersible pump **100** includes rotating elements such as an impeller **102** driven by a shaft **104** and a journal **113** on the shaft **104**. The impeller **102** includes a hub **110** and at least one vane **108** that is mounted to the hub **110**. An impeller shroud **112** is disposed on an upstream side of the impeller **102** and conceals the at least one vane **108**. In various embodiments, however, the impeller shroud **112** could be omitted. The rotating elements are supported by a stationary bushing **120** installed in a diffuser **106**. The diffuser **106** includes at least one diffuser vane **114** that is mounted on a diffuser hub **116**. A diffuser shroud **118** is positioned downstream of the at least one vane **114** and conceals the at least one vane **114**. The diffuser **106** is stationary and redirects the fluid flow to an inlet of the next stage impeller. During operation, the electrical submersible pump **100** causes a pressure differential between an input (i.e. suction) side and an output (i.e. discharge) side. Such a pressure differential causes significant axial loading on the shaft **104**, the journal **113**, and the stationary bushing **120**. Over time, the axial loading can result in premature wear and failure of components of the electrical submersible pump **100** leading to costly repairs and component replacement.

FIG. **2** is a diagram illustrating stage clearances and pressure contour for the single suction multi-stage electrical submersible pump **100**. Due to rotation of the impeller **102**, fluid pressure is boosted at an output side and causes a pressure differential between an input pressure and an output pressure. Due to the difference between inlet and outlet pressure, axial thrust is exerted on the impeller **102** as shown in FIG. **2**. The axial thrust is transmitted to a thrust bearing via the shaft **104**.

FIG. **3** is a graph illustrating variation in axial thrust with rotational speed for the single suction multi-stage electrical submersible pump **100**. Line **302** illustrates variation of flow rate with thrust at 4,200 rpm. Line **304** illustrates variation of flow rate with thrust at 3,600 rpm. To boost production or maintain a desired fluid flow rate, a rotational speed of the impeller **102** is increased. Such an increase in rotational speed of the impeller **102** increases an output pressure head. Consequently, as shown in FIG. **3**, the axial thrust values are increased. Axial thrust values on the shaft **104** limit the operational span of the single suction multi-stage electrical submersible pump **100** at higher rotational speeds.

FIG. **4**A illustrates a single suction impeller **402** where fluid is drawn from one side of the impeller **402**. In contrast, FIG. **4**B illustrates a double suction impeller **404** designed to draw fluid flow from a first side **406** and a second side **408** of the impeller **404**. Thus, the double suction impeller **404** has a first inlet **410**, a second inlet **412** and one outlet **414**. The double suction impeller **404** reduces axial thrust on the shaft **104**, while also allowing higher flows than the single suction impeller **402**. However, the double suction impeller **404** is not feasible for downhole multistage pumps or compressors since it requires the first inlet **410** and the second inlet **412** on opposite sides, which increases a size of a housing.

FIG. **5** is a cross-sectional view of a turbomachine **500** having an impeller **502** with an annular passage **504**. FIG. **6** is a cross sectional view of the impeller **502** with the annular passage **504** utilized with the turbomachine **500**. Referring to FIGS. **5-6**, the turbomachine **500** draws fluid from one direction. Pumping is accomplished from both the sides of an impeller **502**. The turbomachine **500** balances the thrust forces acting on the shaft **506**. A shrouded design of the impeller **502** facilitates an axial positioning clearance, which allows use of the turbomachine **500** as a downhole multi-stage pump. A shrouded design of the impeller **502** forms a seal between stationary and rotating parts and acts as a radial load support on the impeller **502**. The turbomachine **500** increases the threshold rotational speed and improves stability.

The turbomachine **500** includes an impeller **502** and a diffuser **508**. The impeller **502** is designed in such a way that flow is drawn from one side; however, the impeller **502** allows flow to be divided and passed through both sides of the impeller **502**, thereby allowing the axial thrust forces acting on the shaft **506** to be balanced in a manner similar to the double suction impeller **404**. In various embodiments, the impeller **502** includes an impeller shroud **503**; however, in other embodiments, the impeller shroud **503** may be omitted and the impeller **502** may be unshrouded. An example of an unshrouded impeller **550** is illustrated in FIG. **7**A. In various embodiments, the impeller shroud **503** mechanically supports a vane **514** and isolates a higher pressure region **510** of the turbomachine **500** from a lower pressure region **512** of the turbomachine **500**. In this manner, the impeller shroud **503** reduces a leakage flow rate of fluid passing through the turbomachine **500**, thereby increasing an efficiency of the turbomachine **500**. Further, an impeller shroud skirt **516** acts as a bearing support by supporting the impeller **502** using the diffuser **508** surface against the radial loads or side loads. During use, unshrouded impellers carry a risk of the impeller **502** contacting the housing and generating sparks. This risk generally makes unshrouded impellers best suited for handling water and other non-volatile fluids. In contrast, use of the impeller shroud **503** facilitates better handling of volatile fluids than unshrouded impellers due to the fact that it is the shroud **503** that will contact the housing if the shaft **506** displaces from center-line. Because of this, impellers **502** having the shroud **503** are often utilized, for example, in oil and gas production and other applications involving volatile fluids.

FIG. **7**B illustrates a cross sectional view of an impeller **502** having an impeller shroud **503**. Impellers **502** having the shroud **503** are less sensitive to axial positioning and can compensate for thermal expansion of the shaft **506**. In various embodiments, a clearance space **511** is defined on either side of the impeller **502** between the impeller hub **110** and the journal **113**. The clearance space **511** allows the impeller **502** to float axially on the shaft **506** in response to changes in axial force. The impeller **502** has means for fluid transmission formed therein which facilitates transmission of fluid through the clearance formed between the impeller **502** and the diffuser **508**. In various embodiments, the means for transmission include an annular passage **504** formed through a thickness of the impeller **502** in order to facilitate passage of fluids from a first side of the impeller **502** to a second side of the impeller **502**. Passage of liquids through the impeller **502** facilitates fluid flow on both sides of the impeller **502** and balances thrust forces acting on the shaft **506**. While the impeller **502** is described and shown herein as being utilized in conjunction with a power-absorbing turbomachine, such as pumps and compressors, it will be recognized that an impeller of a similar design could also be utilized in conjunction with power-producing turbomachines such as, for example, turbines. In various embodiments, the impeller **502** may be operated in single phase or multi-phase flow conditions having mixtures of liquids, gases, solids, and combinations thereof.

FIG. **8** is an exploded view of the shaft **506**. The shaft **506** includes ribs **704** formed thereon. A first impeller side **706** is received onto the shaft **506** and a second impeller side **708** is received onto the shaft **506**. The first impeller side **706** and the second impeller side **708** are coupled to each other to form the impeller **502** and are coupled to the shaft **506** via the ribs **704**. In various embodiments, the ribs **704** may have an aero foil shape. The first impeller side **706** and the second impeller side **708** may be shrouded or unshrouded. In various embodiments, vanes of the first impeller side **706** may include vanes with a shape, pitch, angle, and profile that is either the same or different from the vanes of the second impeller side **708**. In various embodiments, the first impeller side **706** and the second impeller side **708** include vanes **711** extend radially from the shaft **506**. In various embodiments, the vanes **711** are arranged at an angle other than 90 degrees relative to the shaft **506**. Arrangement of the vanes **711** relative to the shaft **506** at non-90-degree angles imparts several benefits to the turbomachine **500**. First, arrangement of the vanes **711** at non-90-degree angles facilitates better handling of multiphase fluid flow than vanes that are arranged at 90-degree angles. Additionally, arrangement of the vanes **711** at non-90-degree angles allows the turbomachine **500** to handle concentrations of solid particulates, such as for example, sand, which may be entrained in the fluid. Also, arrangement of the vanes **711** at non-90-degree angles facilitates better pressure loading on the vanes **711**. In this regard, pressure gradually increases on the vane **711** unlike 90-degree vanes, which can exhibit areas of pressure concentration. These features of non-90-degree arrangement of the vanes **711** facilitate better reliability and longer service life than impellers having vanes arranged at 90-degree angles under multiphase flow conditions.

FIG. **9**A is a perspective view of an unshrouded impeller **900** (also referred to as an "open impeller") for a compressor. The impeller **900** as shown in the FIG. **9** is unshrouded; however, in other embodiments, the impeller **900** may be shrouded (also referred to as a "closed impeller") or unshrouded. FIG. **9**B is a perspective view of a shrouded impeller **950** for use with a compressor. FIG. **9**C is a plan view of the shrouded impeller **950**. FIG. **9**D is a side view of the shrouded impeller **950**. FIG. **9**E is a cross-sectional view of the shrouded impeller **950**. FIG. **9**F is perspective view of the shrouded impeller **950**. In various embodiments, the minimum specific rotational speed of an unshrouded impeller is approximately 20 revolutions per minute while the minimum specific rotational speed of a shrouded impeller is approximately 2 revolutions per minute. During operation, unshrouded impellers rely on a clearance between a front edge of the vanes and the housing for maintaining efficiency. In various embodiments, the diffuser can be vanned or vaneless which will accommodate the shrouded/unshrouded impeller **900**. In the case of a multistage compressor, the diffuser **508** will direct the flow to next impeller stage similar to the turbomachine **500** illustrated in FIG. **5**. Support ribs connecting two sides can be plain (no axial thrust) or aerodynamic design such as, for example, an aero foil or helical shape that allows some energy conversion. However, aerofoil/helical design will generate some axial thrust. In various embodiments, the vane profile of the impeller **900** may be continuous or split and the impeller **900** may or may not include balance holes such as, for example, balance holes **1004** and **1104** shown in FIGS. **10**-**11**A. In various embodiments, vane inlet and exit angles on both sides of the impeller **900** can be the same or different. In various embodiments, vane profiles, shapes, and sizes can be the same or different on both sides of the impeller. In various embodiments, the vanes can be aligned or at any angle. As shown in FIGS. **11**B-**11**F, vanes **1152** having differing length, width, and thickness may be used on opposite sides of the impeller **900**. Further, the ribs **1102** that connect the shaft **104** to the impeller **900** may have any length, width, thickness, and number. In various embodiments, flow rates across the two sides of the impeller **900** may be divided equally or unequally. Furthermore, a pressure differential may be created between the first impeller side **706** and the second impeller side **708** facilitating transmission of a first fluid phase on the first impeller side **706** and transmission of a second fluid phase on a second impeller side **708**. In other embodiments, the impeller **900** employing aspects of the disclosure may be utilized in conjunction with conventional impellers in multi-stage turbomachines. In still other embodiments, turbomachines employing the impeller **900** may function as, for example, a compressor, a pump, or a turbine.

FIG. **10** is a plan view of an impeller **1002** utilizing balance holes **1004**. The impeller **1002** includes continuous vanes **1006** that extend radially in a curved fashion from a central hub **1008**. Balance holes **1004** are formed through the impeller **1002** and facilitate balance of pressure between a first side of the impeller **1002** and a second side of the impeller **1002**. The impeller **1002** includes an exit angle β_2 of less than 90 degrees, which mitigates erosion of the vanes **1006** of the impeller **1002** due to entrainment of solid particulates in the fluid.

FIG. **11**A is a plan view of a split blade impeller **1102**. The impeller **1102** includes vanes **1106** that extend radially in a curved fashion from a central hub **1108**. The vanes **1106** include an inner section **1110** and an outer section **1112**. Balance holes **1104** are formed through the impeller **1102** and facilitate balance of pressure between a first side of the impeller **1102** and a second side of the impeller **1102**.

FIG. **12** is a cross-sectional view of the diffuser **508**. In various embodiments, the diffuser **508** is used as an alternative to a diffuser for single-stage pumps and compressors. The diffuser **508** includes a fluid passage **510** having a plurality of vanes **512** formed therein. In use, the diffuser **508** receives the impeller therein. In various embodiments, the fluid passage **510** includes a diffuser shroud **514**, a hub **516**, and surfaces **1203** to accommodate the impeller and to facilitate fluid transmission.

FIG. **13**A is a plan view of a volute **1300** FIG. **13**B is a cross sectional view of the volute **1300**. The volute **1300** is typically used with a power-absorbing turbomachine such as, for example, a pump and is a casing that receives an impeller such as, for example, the impeller **502**. The volute **1300** includes a fluid passage **1302**. In various embodiments, the fluid passage **1302** has the shape of a curved funnel to facilitate fluid transmission. The fluid passage **1302** increases in cross-sectional area as it approaches a discharge port **1304**.

FIG. **14**A is a cross-sectional view of the turbomachine **500** illustrating fluid flow therethrough. In the embodiment shown in FIG. **14**A, the turbomachine **500** is a power-absorbing turbomachine such as, for example, a compressor or a pump. Fluid flow through the turbomachine **500** is illustrated by arrows **1402**. During operation, fluid enters the impeller **502** axially via an annular passage defined between the impeller shroud **503** and the shaft **506**. A first portion of the fluid is directed through the vanes **509** on a first side **505** of the impeller **502**. A second portion of the fluid is directed through the annular passage **504** to a second side **507** of the impeller **502**. The impeller vanes **509** direct the fluid on the first side **505** of the impeller **502** and the fluid on the second side **507** of the impeller **502** in a radial direction to the diffuser **508**. The fluid exits the impeller **502** radially and enters the diffuser **508**. By introducing fluid to both the first side **505** and the second side **507** of the impeller **502**, pressure is balanced on the impeller **502** thereby reducing axial thrust on the shaft **506**.

FIG. **14**B is a cross-sectional view of a turbomachine **550** illustrating multiple stages. In the embodiment shown in FIG. **14**B, the turbomachine **550** includes multiple turbomachines **500(1)-(2)** that are coupled in series such that the fluid exiting the diffuser **508(1)** of the first turbomachine **500(1)** enters the impeller **502(2)** of the second turbomachine **500(2)**. By way of example, the turbomachine **550** is illustrated in FIG. **14**B as including two stages (turbomachines **500(1)-(2)**); however, in other embodiments, the turbomachine **550** may include any number of stages as dictated by design requirements. By way of example, the turbomachine is illustrated in FIG. **14**B as a compressor or a pump such that fluid enters the impellers **502(1)-(2)** in an axial direction and exits the impellers **502(1)-(2)** in a radial direction. In other embodiments, the turbomachine **550** may operate as a turbine such that fluid enters the impellers **502(1)-(2)** in a radial direction and exits the impellers **502(1)-(2)** in an axial direction.

FIG. **15** is a cross sectional view of the turbomachine **1500** illustrating fluid flow therethrough. In the embodiment shown in FIG. **15**, the turbomachine **1500** is a power-producing turbomachine such as, for example, a hydraulic turbine. Fluid flow through the turbomachine **1500** is illustrated by arrows **1502**. The turbomachine **1500** functions similar to the turbomachine **500** (shown in FIGS. **5-7**) except that fluid enters the turbomachine **1500** radially and exits the turbomachine **1500** axially. Upon entering the impeller **502** axially, the fluid is divided onto the first side **505** and the second side **507** of the impeller **502**. By introducing fluid to both the first side **505** and the second side **507** of the impeller **502**, pressure is balanced on the impeller **502** thereby reducing axial thrust on the shaft **506**.

Simulations were performed to understand the performance as well as forces acting on the impeller. Simulations were performed for varying speeds ranging from 3,600 rpm to 30,000 rpm. The results are compared with conventional stages. FIG. **16** shows the head developed for a range of flow rates during use of the turbomachine **500**. FIG. **17** shows thrust as a function of flow rate during use of the turbomachine **500**. Data according to various embodiments is based on higher speed compared to the conventional design simulations, which is reflected in the higher pressure head values for the turbomachine **500** due to higher rotational speeds, yet the thrust values for the turbomachine **500** are significantly lower compared to the thrust values for conventional design. In various embodiments, the turbomachine **500** could have any specific speed. Specific speed is calculated according to equation 1.

$$\text{Specific speed}=\text{Rotational speed}*\sqrt{\text{flowrate}}/\text{Head}^{0.75} \quad \text{Equation 1}$$

FIG. **18** is a cross-sectional view of a turbomachine **1800** illustrating bearing supports **1814**. The turbomachine **1800** includes a first stage **1802** and a second stage **1804**. The first stage **1802** includes a first impeller **1806** and the second stage includes a second impeller **1808**. The first impeller **1806** and the second impeller **1808** are driven by a shaft **1810**. The shaft **1810** includes means for support. In various embodiments, the means for support includes a journal **1812** disposed on the shaft **1810** and that rotates with the shaft **1810**. In such embodiments, the means for support further includes a bushing **1814** that is disposed in a diffuser **1816**. During operation, rotation of the shaft **1810** causes the journal **1812** to rotate within the bushing **1814**. A thrust washer **1818** abuts the bushing **1814** and is disposed between the bushing **1814** and the diffuser **1816**. In various embodiments, the thrust washer **1818** is constructed of a material that is softer than the bearing support **1814**. In various embodiments, the bushing **1814** is constructed of a material such as, for example, tungsten carbide, silicon carbide, diamond-coated tungsten carbide, diamond-coated silicon carbide, or any other appropriate material. The thrust washer **1818** is constructed of a material such as, for example, phenolic. The bushing **1814** and the thrust washer **1818** facilitate support of radial force as well as axial force. During operation, pressure head resulting from changes in fluid flow rate can create reactive axial thrust. The thrust washer **1814** allows the turbomachine **1800** to bear this load and balances residual forces.

FIG. **19** is a cross-sectional view of a turbomachine **1900** showing bearing supports disposed on the impeller shroud **503** and the diffuser **508**. During use, the journals **113** and bushings **120** installed on the shaft **506** wear out with time. Wear of the journals **113** and bushings **120** causes the seal between the impeller shroud **503** and the diffuser **508** to act as a bearing. In an effort to mitigate wear, means for impeller support are installed on the impeller shroud **503** and the diffuser **508**. In various embodiments, the means for impeller support include a bearing support **1902** that is installed about an outer circumference of the impeller shroud **503**. The bearing support **1902** contacts and bears against a bearing support **1904** installed in an inner circumference of the diffuser **508** In various embodiments, the bearing support **1902** and the bearing support **1904** support radial loading of the impeller **502** and reduce wear on the impeller **502** and the impeller shroud **503**. In various embodiments, the bearing support **1902** and the bearing support **1904** are constructed of any appropriate material such as, for example, carbides, peek, and thermoplastics.

FIG. **20** is a cross-sectional view of an impeller **2000**. The impeller **2000** includes a first side **2002** and a second side **2004**. A plurality of vanes **2008** extend from the first side **2002** and the second side **2004**. An impeller shroud **2010** is disposed in a spaced relationship with the first side **2002** and the second side **2004** so as to cover the vanes **2008**. The impeller shroud **2010** includes a first skirt **2012** formed on the first side **2002** and a second skirt **2014** formed on the second side **2004**. The first skirt **2012** forms a first axial opening **2016**, which has a first outer diameter of Do**1** and a first inner diameter of Di**1**. The second skirt **2014** forms a second axial opening **2018**, which has a first outer diameter of Do**2** and a first inner diameter of Di**2**. In various embodiments, the first outer diameter Do**1** may differ from the second outer diameter Do**2**. Likewise, the first inner diameter Di**1** may differ from the second inner diameter Di**2**. In various embodiments, differing diameters of the first axial opening **2016** and the second axial opening **2018** facilitates control of thrust acting on the impeller **2000** during operation.

The term "substantially" is defined as largely but not necessarily wholly what is specified (and includes what is specified; e.g., substantially 90 degrees includes 90 degrees and substantially parallel includes parallel), as understood by a person of ordinary skill in the art. In any disclosed embodiment, the terms "substantially," "approximately," "generally," and "about" may be substituted with "within a percentage of" what is specified.

Depending on the embodiment, certain acts, events, or functions of any of the algorithms described herein can be performed in a different sequence, can be added, merged, or left out altogether (e.g., not all described acts or events are necessary for the practice of the algorithms). Moreover, in certain embodiments, acts or events can be performed concurrently, e.g., through multi-threaded processing, interrupt processing, or multiple processors or processor cores or on other parallel architectures, rather than sequentially. Although certain computer-implemented tasks are described as being performed by a particular entity, other embodiments are possible in which these tasks are performed by a different entity.

Conditional language used herein, such as, among others, "can," "might," "may," "e.g.," and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

While the above detailed description has shown, described, and pointed out novel features as applied to various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the devices or algorithms illustrated can be made without departing from the spirit of the disclosure. As will be recognized, the processes described herein can be embodied within a form that does not provide all of the features and benefits set forth herein, as some features can be used or practiced separately from others. The scope of protection is defined by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

What is claimed is:

1. A turbomachine, comprising:

a housing having an inlet and an outlet;

a shaft rotationally disposed in the housing, the shaft being rotatable about a longitudinal axis;

an impeller coupled to the shaft between the inlet and the outlet and rotating with the shaft, the impeller comprising an impeller shroud, a first set of vanes disposed on a first side of the impeller and configured to generate axial thrust in a first direction, and a second set of vanes disposed on a second side of the impeller and configured to generate axial thrust in a second direction that is opposite the first direction, the impeller and the impeller shroud forming a single impeller inlet and an impeller outlet;

a passage formed through a thickness of the impeller, the passage configured to facilitate transmission of a fluid from the first side of the impeller to the second side of the impeller such that the fluid is supplied to the first set of vanes and the second set of vanes via the single impeller inlet; and

wherein transmission of the fluid through the impeller reduces net axial thrust imparted to at least one of the impeller and the shaft.

2. The turbomachine of claim **1**, comprising a diffuser assembly configured to house the impeller, the diffuser assembly comprising:

a flow passage having vanes;

a diffuser shroud, wherein the diffuser shroud is configured to house the impeller and to direct flow of the fluid to at least a second stage of the turbomachine; and

a hub to facilitate fluid transmission.

3. The turbomachine of claim **2**, wherein an axial clearance is formed between the impeller shroud and the diffuser shroud so as to isolate a high pressure region of the turbomachine from a low pressure region of the turbomachine.

4. The turbomachine of claim **1**, wherein:

the turbomachine is power-absorbing;

the turbomachine is incorporated into at least one of a multistage electrical submersible pumping system and a gas compression system; and

the single impeller inlet is an axial inlet and the impeller outlet is at least one of a radial outlet.

5. The turbomachine of claim **1**, wherein the turbomachine is power producing.

6. The turbomachine of claim **5**, wherein the single impeller inlet is a radial inlet and the impeller outlet is an axial outlet.

7. The turbomachine of claim **1** comprising a volute configured to house the impeller, the volute comprising a curved funnel flow passage to facilitate fluid transmission.

8. The turbomachine of claim **1**, wherein:

a vane inlet angle of the first set of vanes on the first side of the impeller and a vane inlet angle of the second set of vanes on the second side of the impeller are equal; and

a vane exit angle of the first set of vanes on the first side of the impeller and a vane exit angle of the second set of vanes on the second side of the impeller are equal.

9. The turbomachine of claim **1**, wherein at least one of a vane profile, a vane shape, and a vane size of the first set of vanes on the first side of the impeller is different than at least one of a vane profile, a vane shape, and a vane size of the second set of vanes on the second side of the impeller.

10. An impeller for use in a turbomachine, the impeller comprising:

a first side having a first set of vanes disposed thereon, the first set of vanes configured to generate axial thrust in a first direction;

a second side having a second set of vanes disposed thereon, the second side being arranged opposite the first side, the second set of vanes configured to generate axial thrust in a second direction that is opposite the first direction;

an impeller shroud disposed around and spaced from the first side and the second side, the impeller shroud defining a single fluid inlet and a fluid outlet; and

a passage formed through a thickness of the impeller, the passage configured to facilitate transmission of fluid from the first side of the impeller to the second side of the impeller such that fluid is supplied to the first set of vanes and the second set of vanes via a single impeller inlet.

11. The impeller of claim **10**, comprising:

at least one rib disposed in the passage; and

wherein the at least one rib comprises a helical shape.

12. The impeller of claim **10**, wherein:

a vane inlet angle of the first set of vanes on the first side of the impeller and a vane inlet angle of the second set of vanes on the second side of the impeller are equal; and

a vane exit angle of the first set of vanes on the first side of the impeller and a vane exit angle of the second set of vanes on the second side of the impeller are equal.

13. The impeller of claim **10**, wherein at least one of a vane profile, a vane shape, and a vane size of the first set of vanes on the first side of the impeller is different than at least one of a vane profile, a vane shape, and a vane size of the second set of vanes on the second side of the impeller.

14. The impeller of claim **13**, wherein:

the first side of the impeller is configured to transmit a first fluid phase; and

the second side of the impeller is configured to transmit a second fluid phase distinct from the first fluid phase.

15. The impeller of claim **10**, wherein the first set of vanes on the first side of the impeller are offset from the second set of vanes on the second side of the impeller.

16. The impeller of claim **10**, wherein the single fluid inlet is an axial inlet and the fluid outlet is a radial outlet.

17. The impeller of claim **10**, wherein the single fluid inlet is a radial inlet and the fluid outlet is an axial outlet.

18. A method of reducing axial thrust on an impeller shaft, the method comprising:

directing a fluid onto a first side of an impeller having a first set of vanes and a second side of the impeller having a second set of vanes via a single impeller inlet, the single impeller inlet being defined by an impeller shroud disposed around and in a spaced relationship with the first side of the impeller and the second side of the impeller;

expelling the fluid from the impeller via an impeller outlet,

wherein the first set of vanes are configured to generate axial thrust in a first direction and the second set of vanes are configured to generate axial thrust in a second direction that is opposite the first direction; and

wherein the fluid passes through a passage formed through a thickness of the impeller prior to contacting the second set of vanes.

19. The method of claim **18**, wherein the single impeller inlet is a radial inlet and the impeller outlet is an axial outlet.

20. The method of claim **18**, wherein the single impeller inlet is an axial inlet and the impeller outlet is a radial outlet.

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