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**Conrad**

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(54) **EXTRUDER**

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patent is extended or adjusted under 35  
U.S.C. 154(b) by 276 days.

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(51) **Int. Cl.**  
**B29C 48/92** (2019.01)  
**B29C 48/395** (2019.01)  
(Continued)

(52) **U.S. Cl.**  
CPC ..... **B29C 48/92** (2019.02); **B29C 45/18**  
(2013.01); **B29C 45/2669** (2013.01);  
(Continued)

(58) **Field of Classification Search**  
CPC ..... **B29C 45/77**; **B29C 45/76**; **B29C 45/47**;  
**B29C 45/58**; **B29C 45/18**; **B29C 45/73**;  
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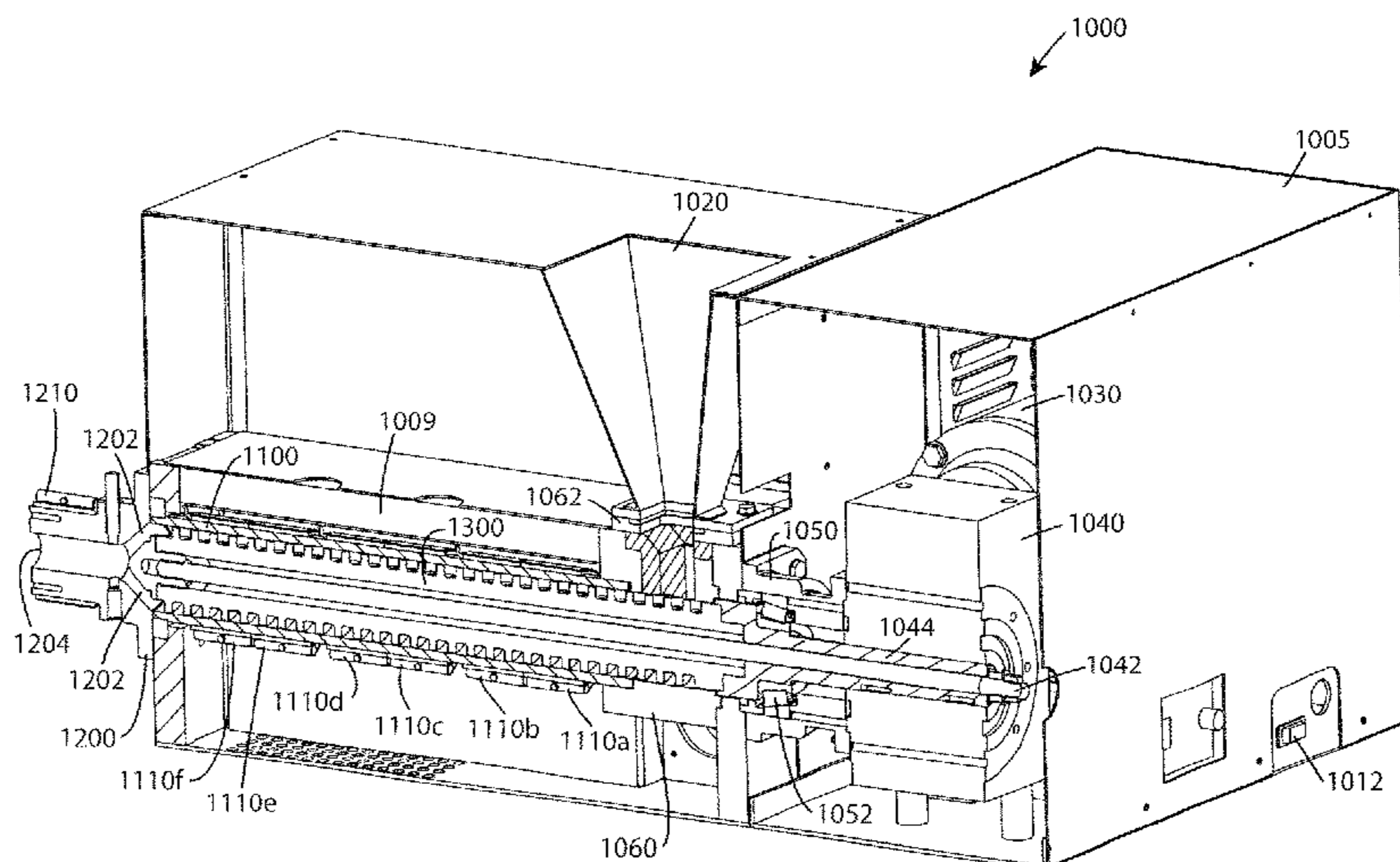
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(57) **ABSTRACT**

An extruder has a barrel extending from a feed inlet end to  
an extruder outlet end. The barrel has an inner surface, an  
outer surface, and a wall thickness between the inner and  
outer surfaces. The extruder also has at least one heating  
member positioned provided on the barrel; a screw drive  
motor drivingly connected to a rotatably mounted screw  
positioned within the barrel, whereby the screw is rotatable  
at various revolutions per minute (RPM); and a controller is  
operably connected to the screw drive motor to adjust the  
RPM of the screw based upon a temperature of material  
passing through and/or being extruded from the barrel.  
Methods for operating an extruder filling a mold are also  
provided.

**22 Claims, 51 Drawing Sheets**



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	<i>B29C 48/681</i> (2019.02); <i>B29C 48/6803</i>			
	(2019.02); <i>B29C 48/832</i> (2019.02); <i>B29C</i>			
	<i>48/865</i> (2019.02); <i>B29C 49/78</i> (2013.01);			
	<i>B29C 48/02</i> (2019.02); <i>B29C 48/03</i> (2019.02);			
	<i>B29C 48/509</i> (2019.02); <i>B29C 48/53</i>			
	(2019.02); <i>B29C 48/60</i> (2019.02); <i>B29C</i>			
	<i>48/6801</i> (2019.02); <i>B29C 2948/924</i> (2019.02);			
	<i>B29C 2948/9238</i> (2019.02); <i>B29C 2948/9259</i>			
	(2019.02); <i>B29C 2948/92209</i> (2019.02); <i>B29C</i>			
	<i>2948/92447</i> (2019.02); <i>B29C 2948/92885</i>			
	(2019.02); <i>B29C 2948/92952</i> (2019.02); <i>B29K</i>			
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(58) **Field of Classification Search**  
 CPC .....

B29C 45/57; B29C 45/00; B29C 48/00;  
 B29C 48/14; B29C 48/25; B29C 48/92;  
 B29B 13/00

See application file for complete search history.

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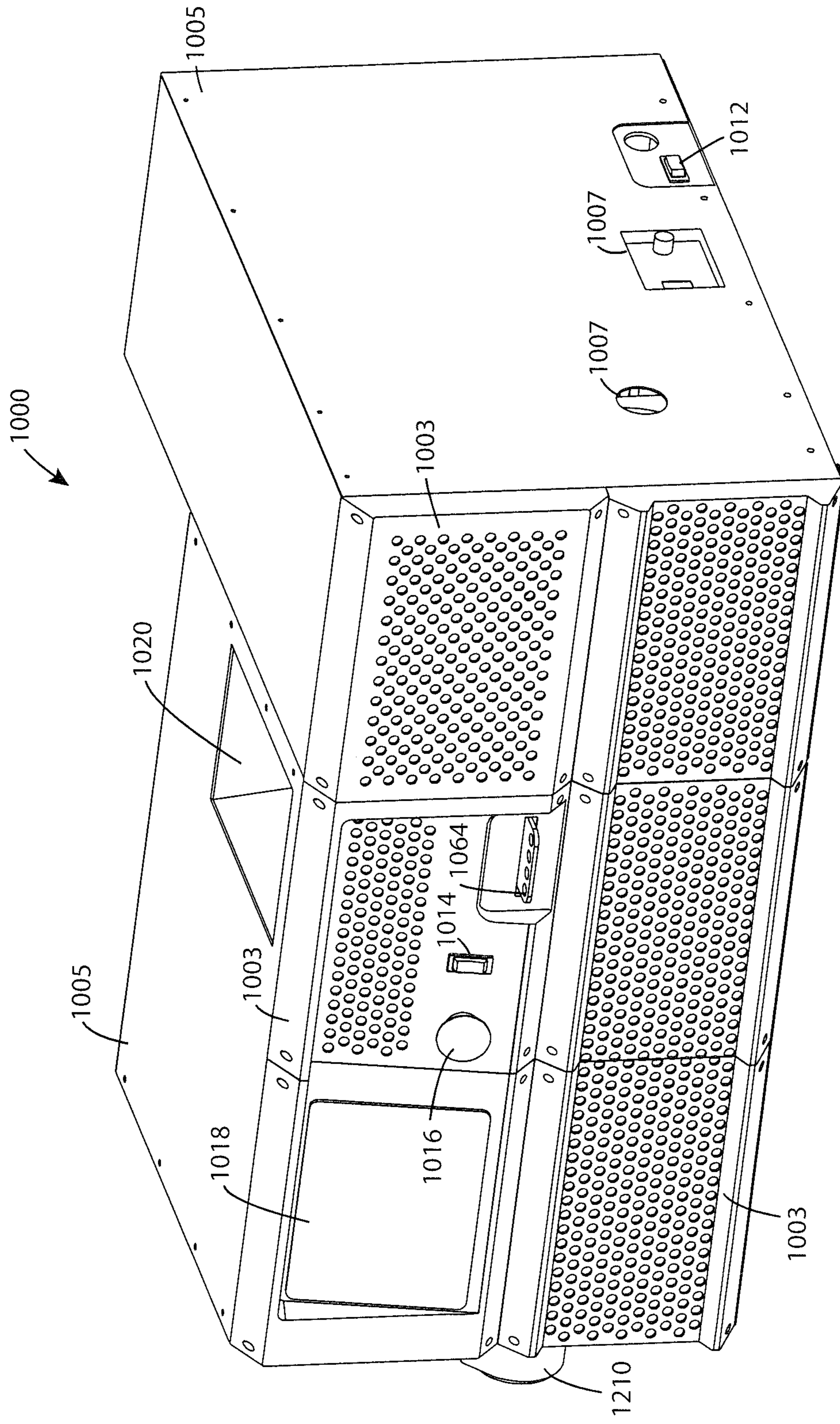


FIG. 1A

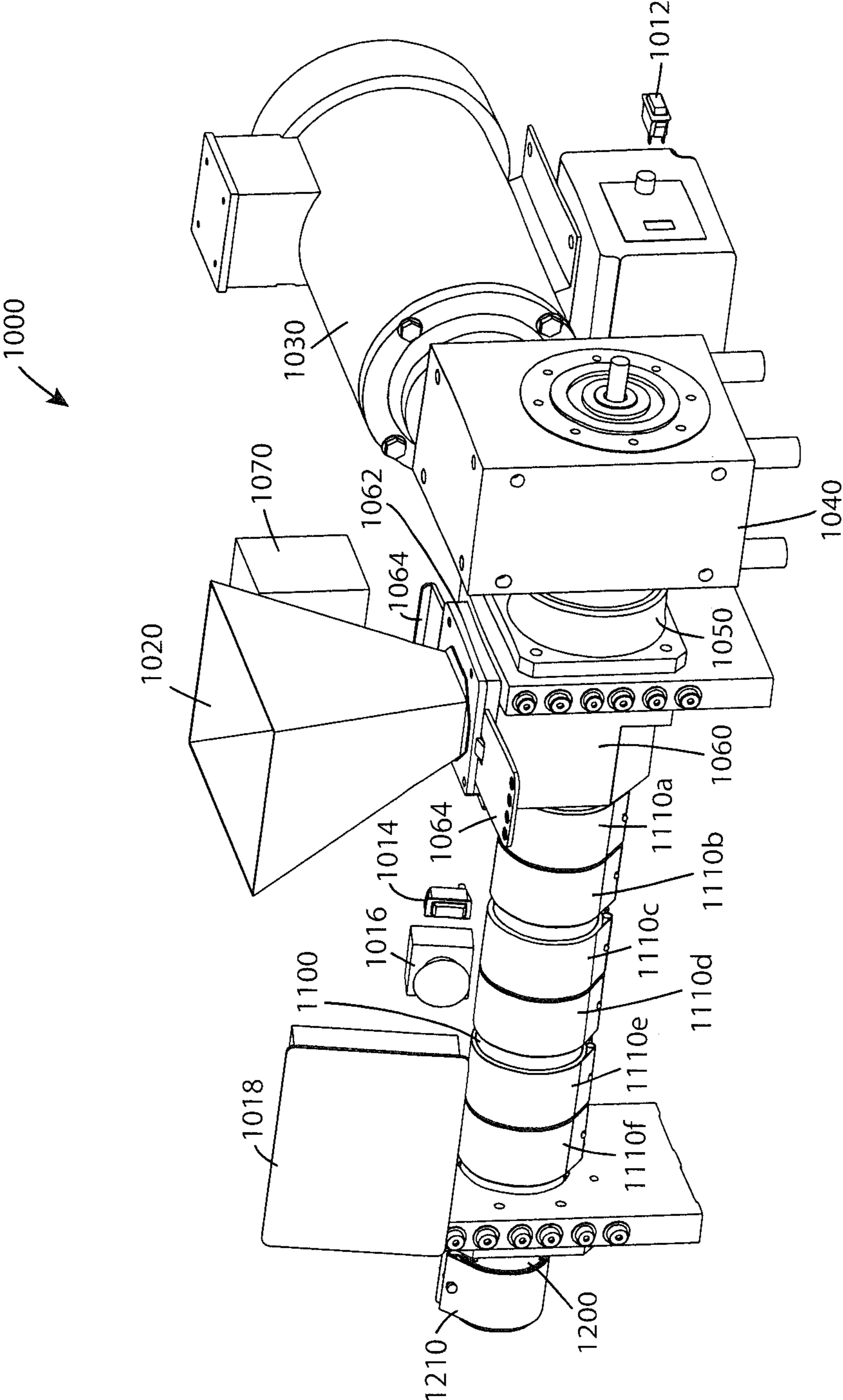


FIG. 1B

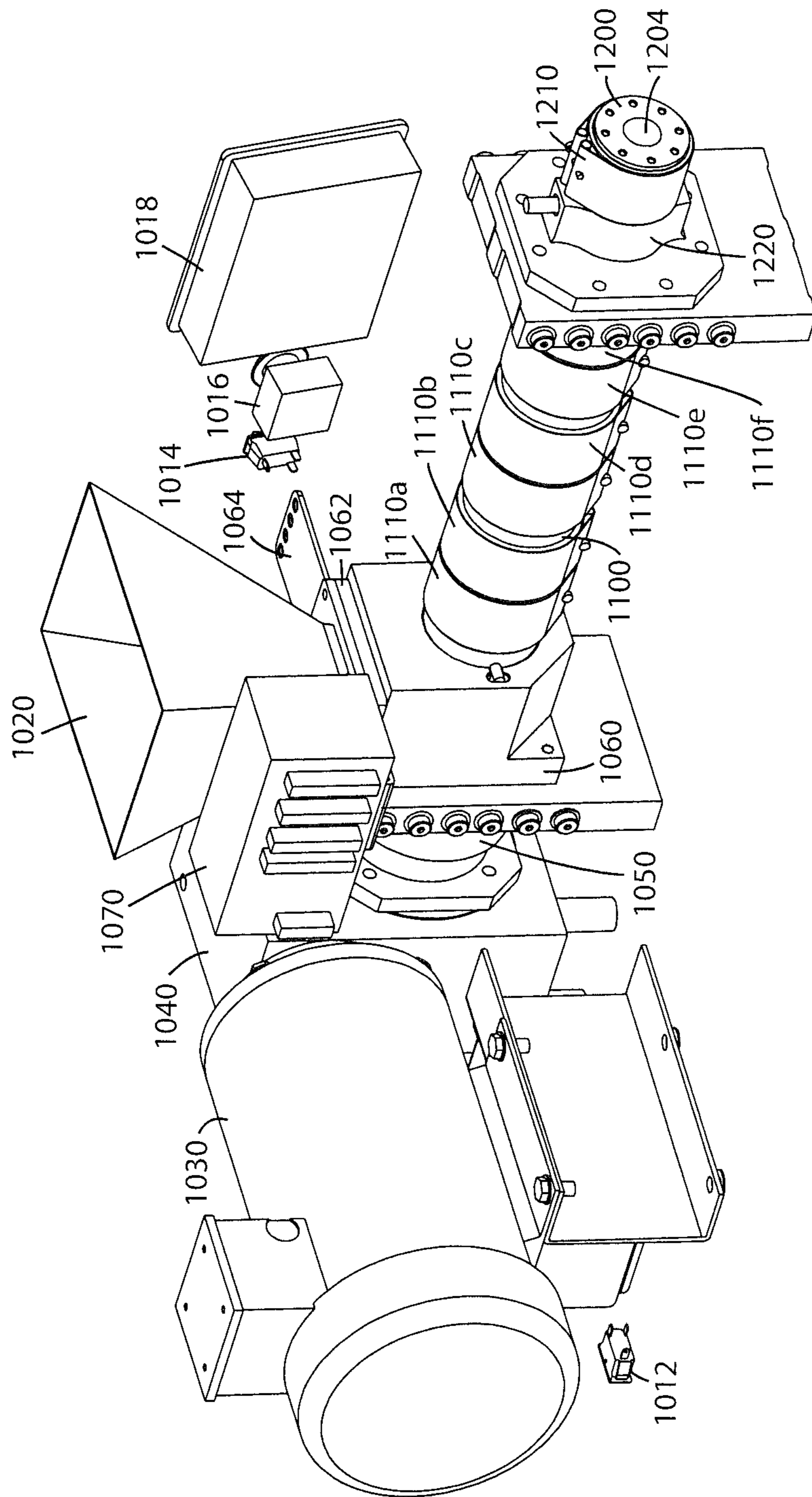


FIG. 2

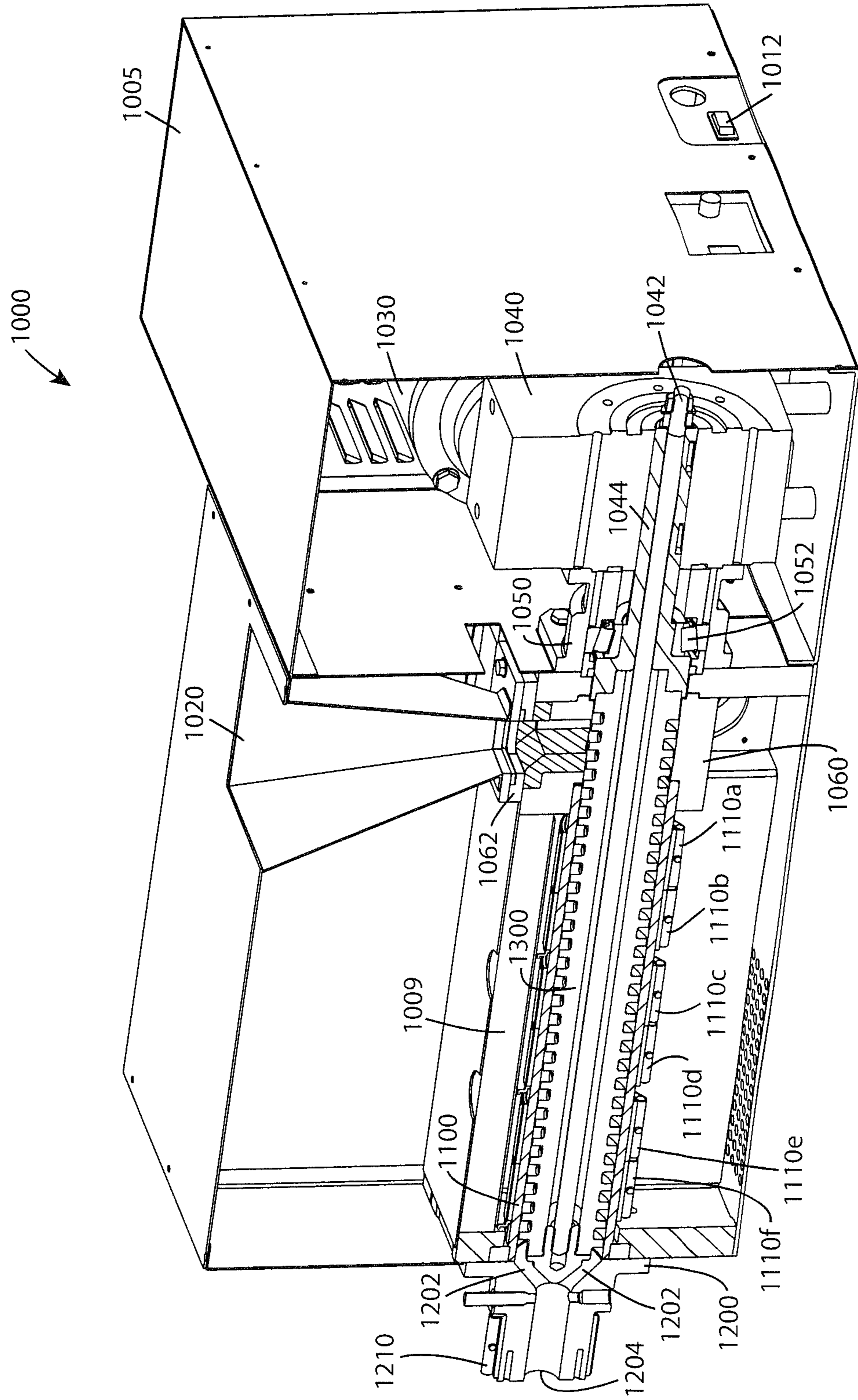


FIG. 3

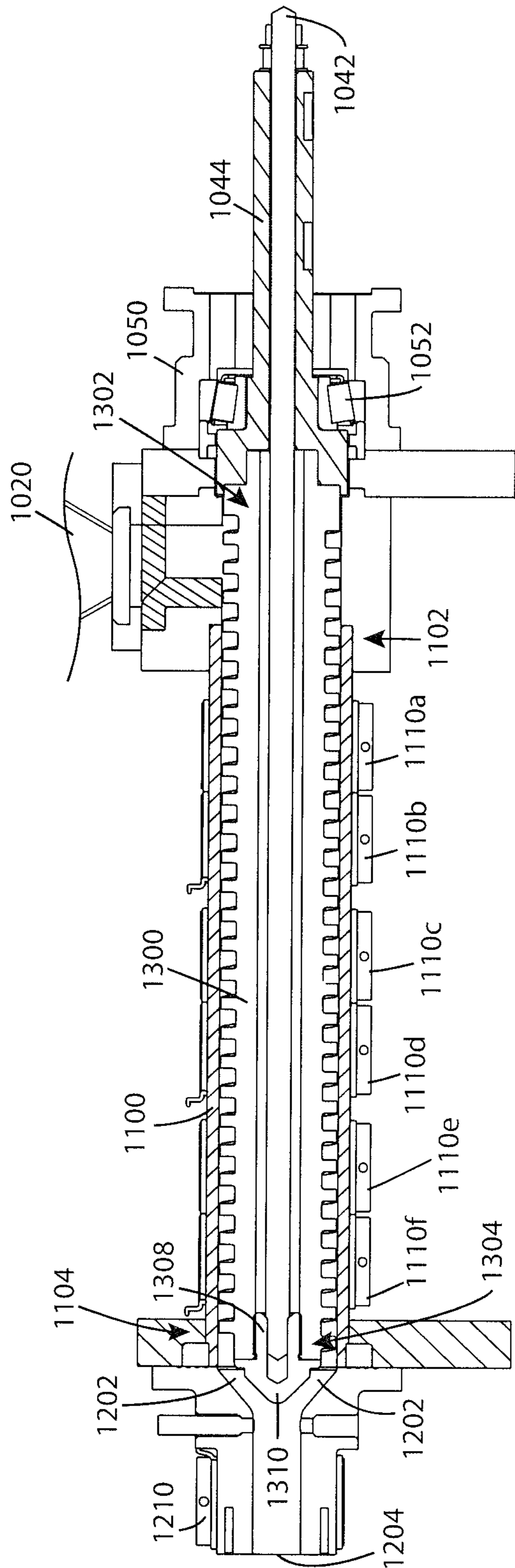


FIG. 4

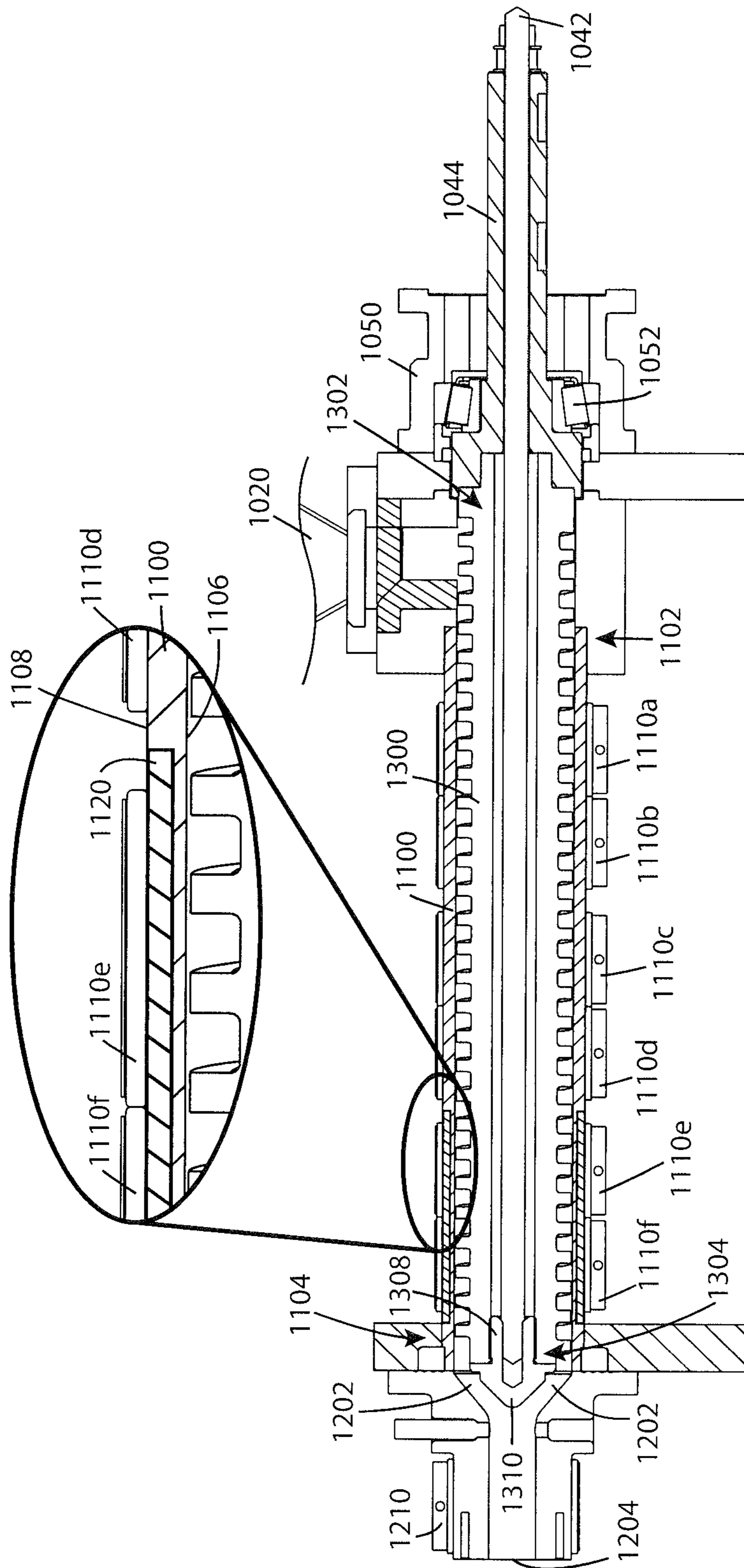


FIG. 5



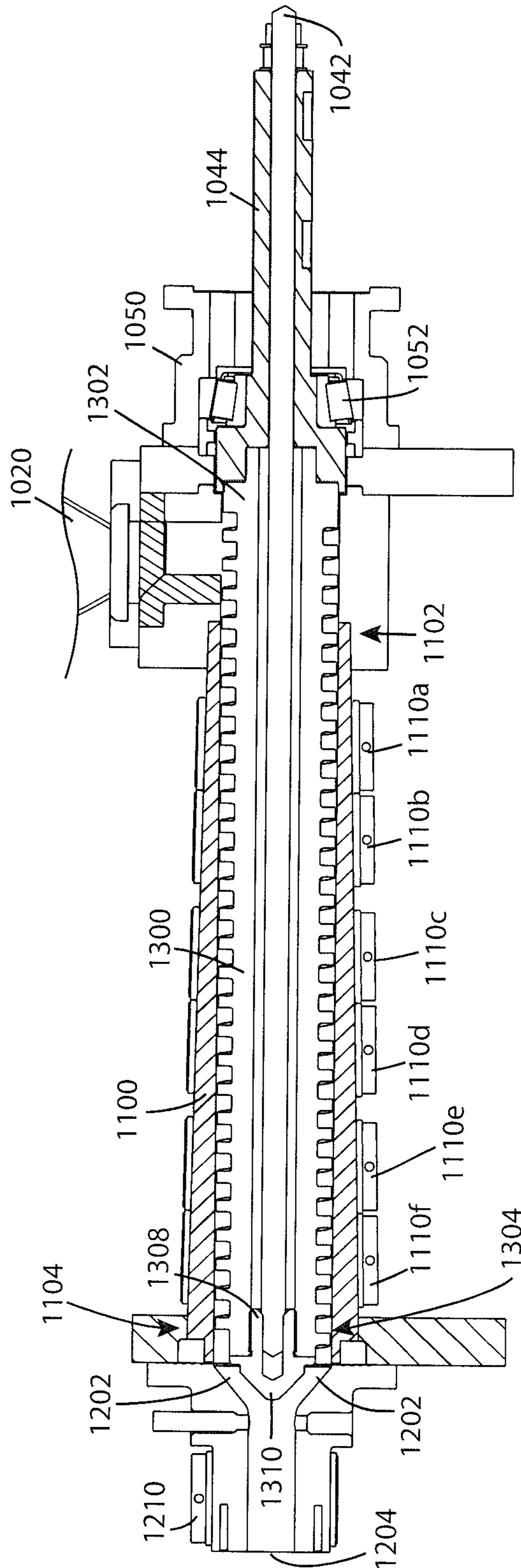


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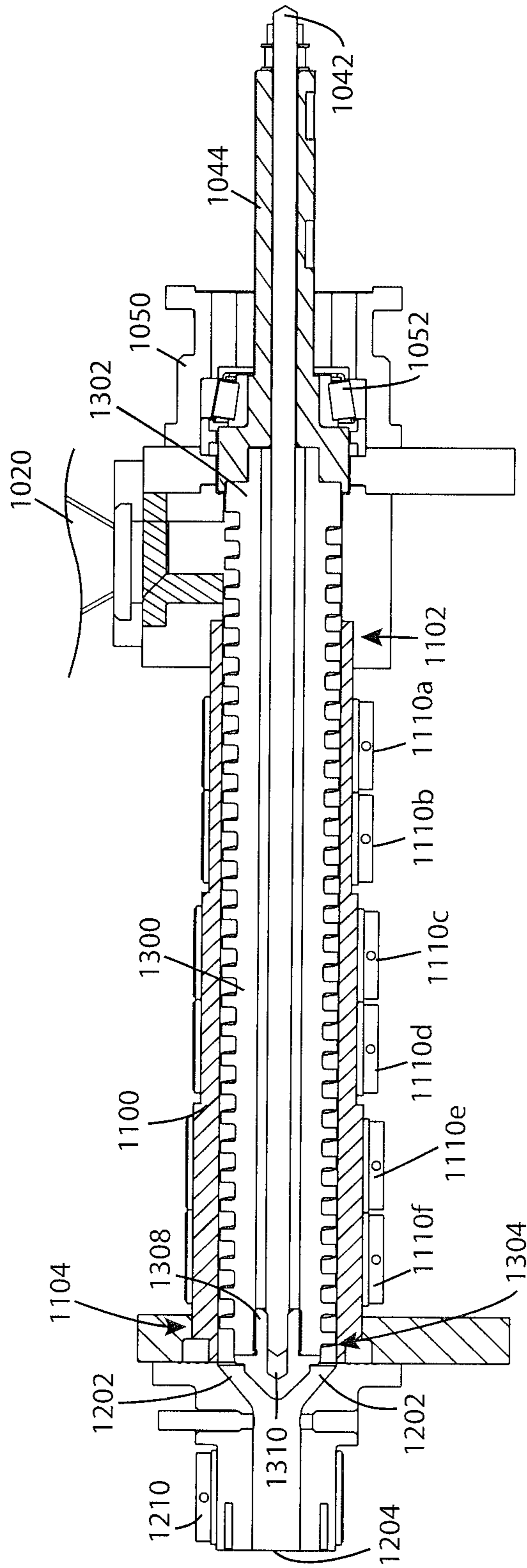


FIG. 7

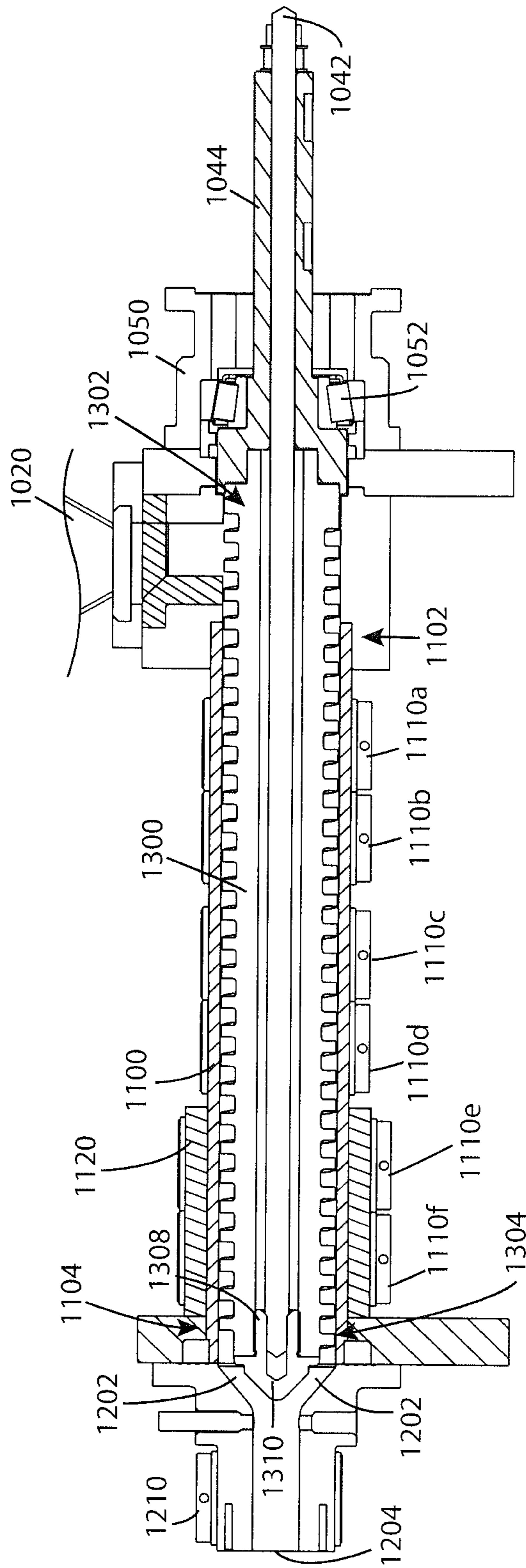


FIG. 8

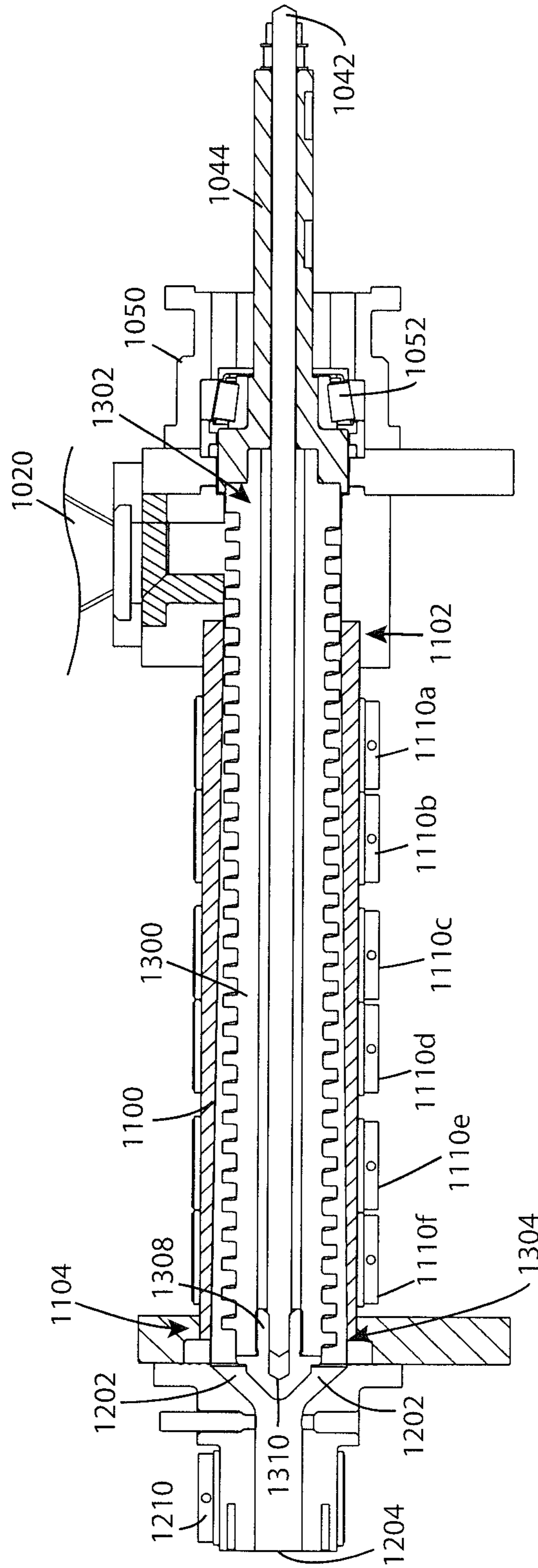


FIG. 9

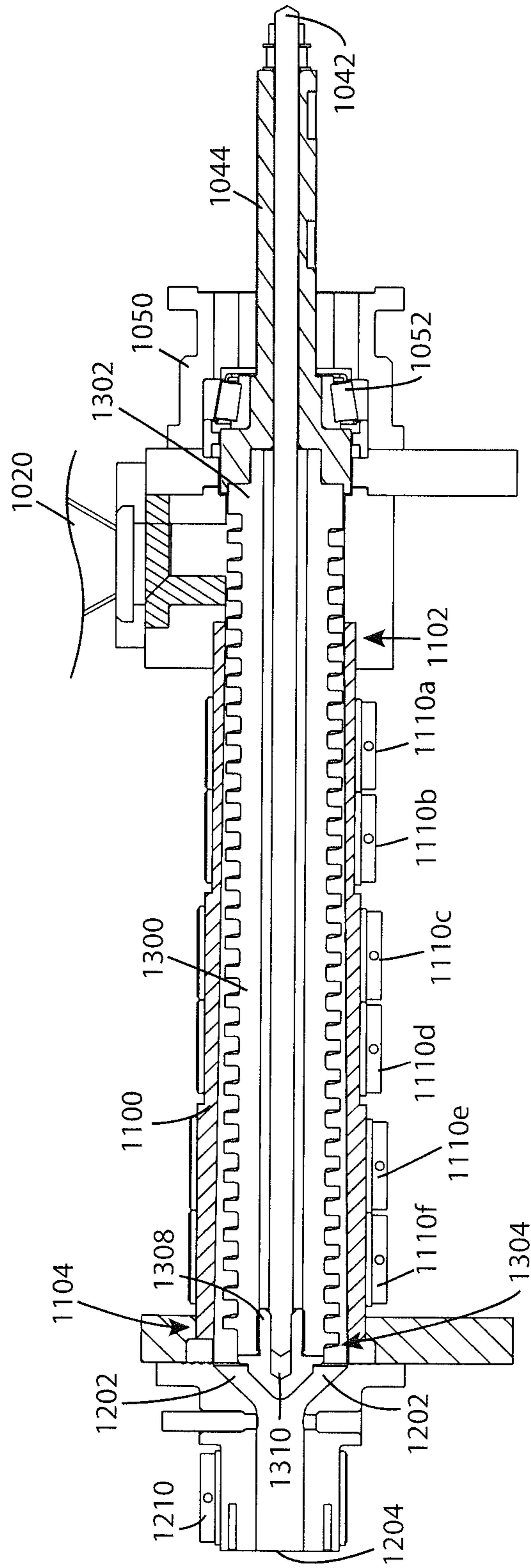


FIG. 10

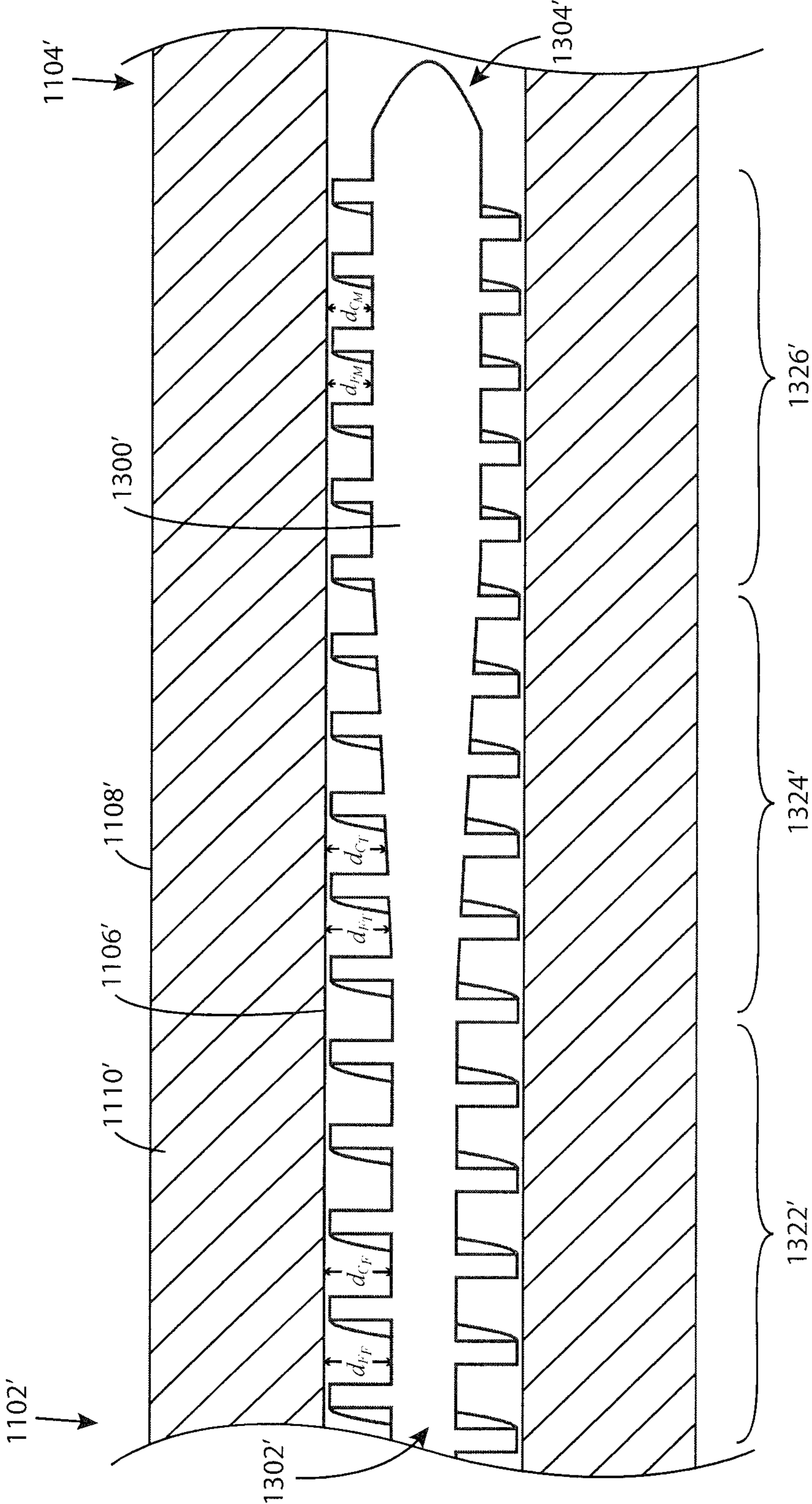


FIG. 11 - Prior Art

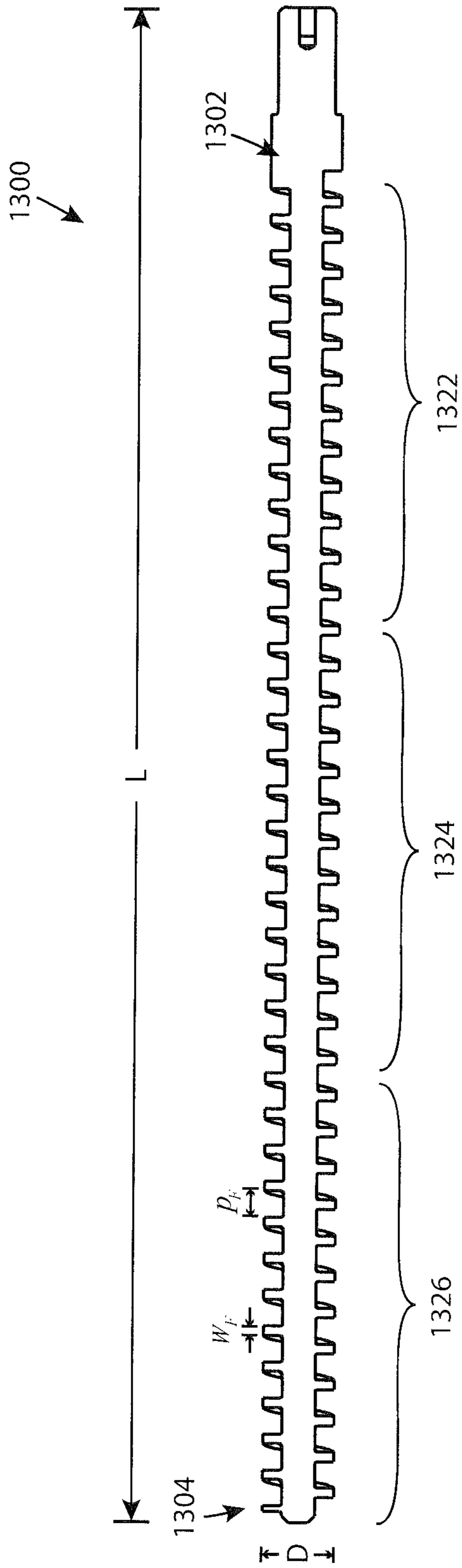


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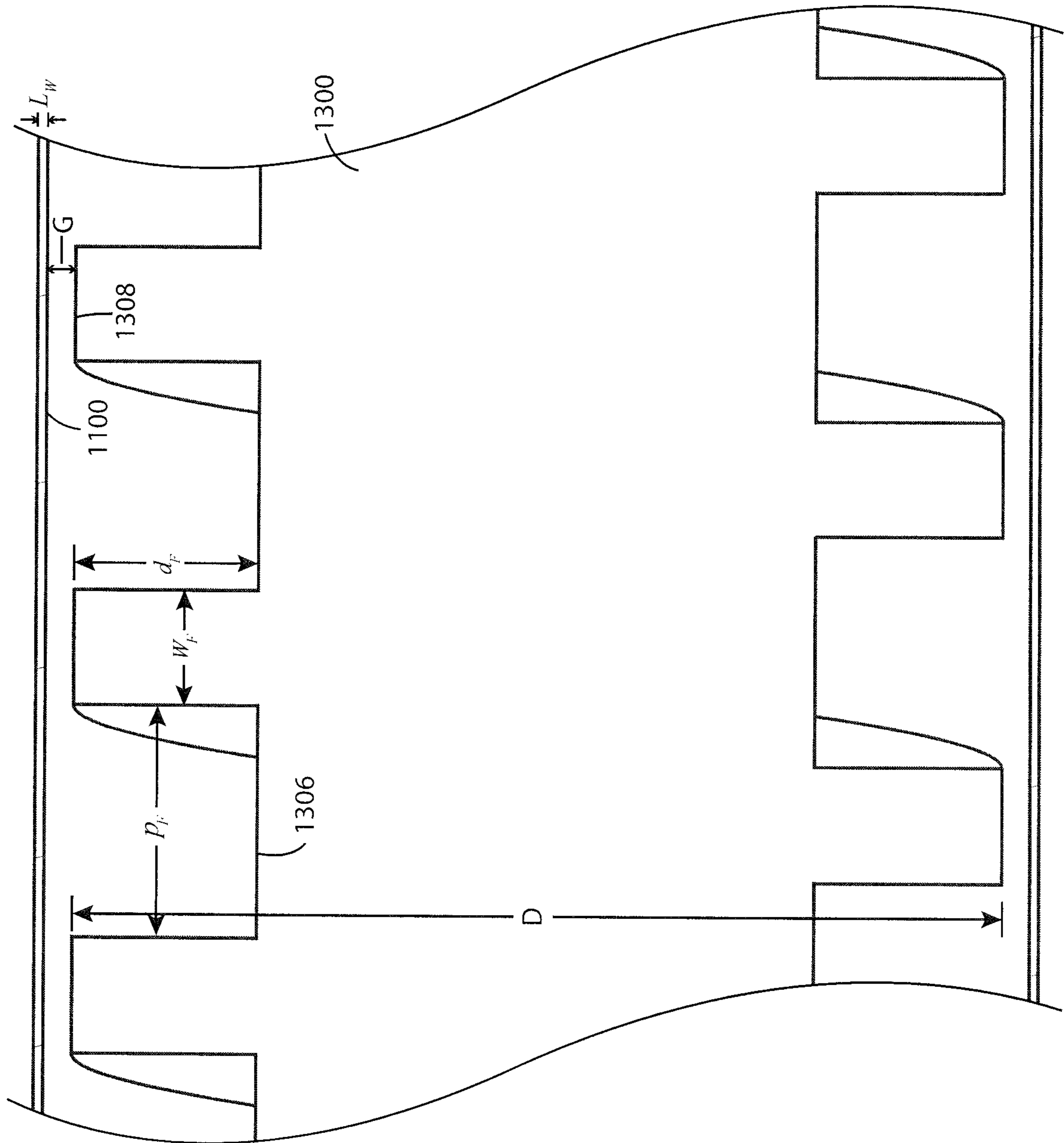


FIG. 13



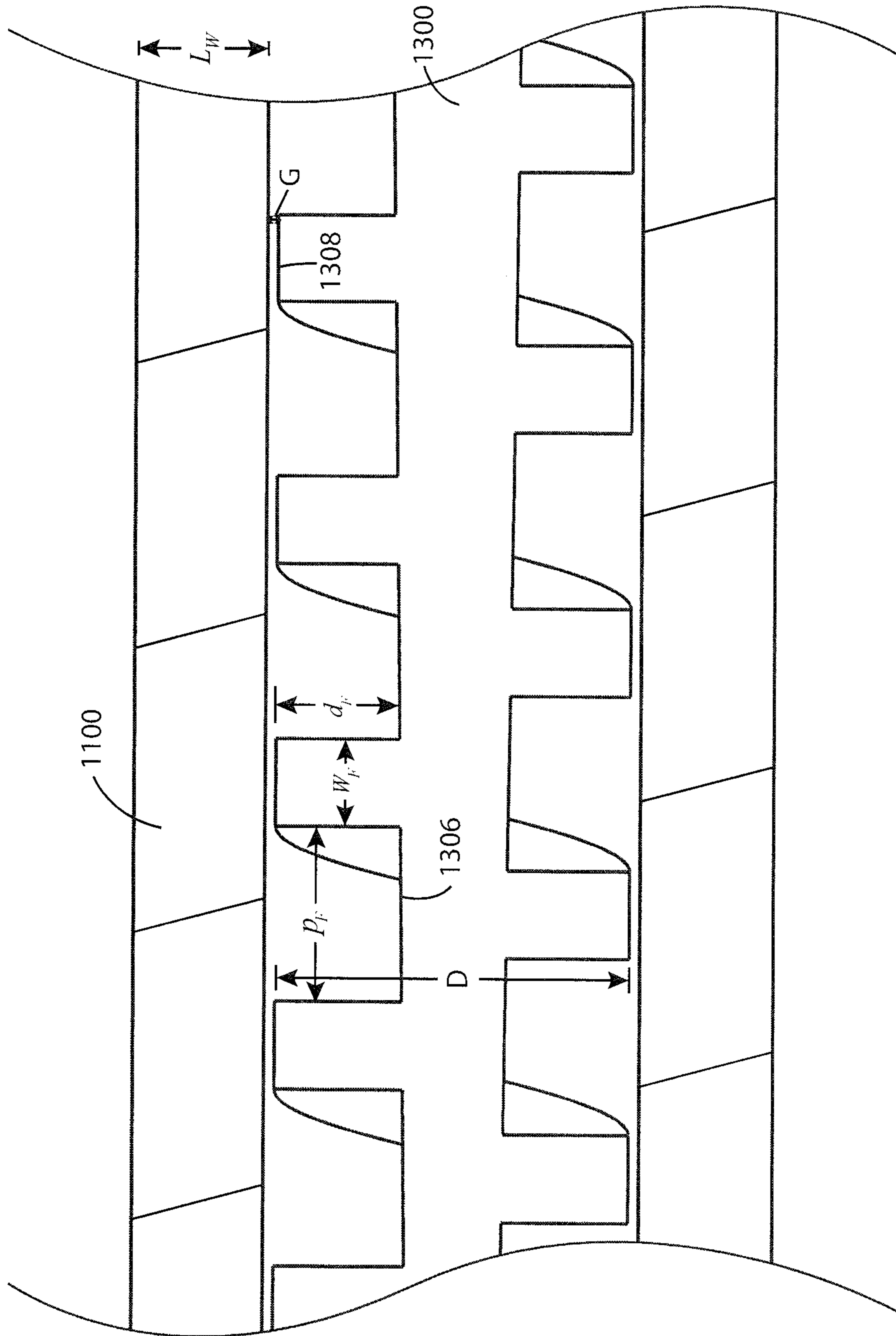


FIG. 14

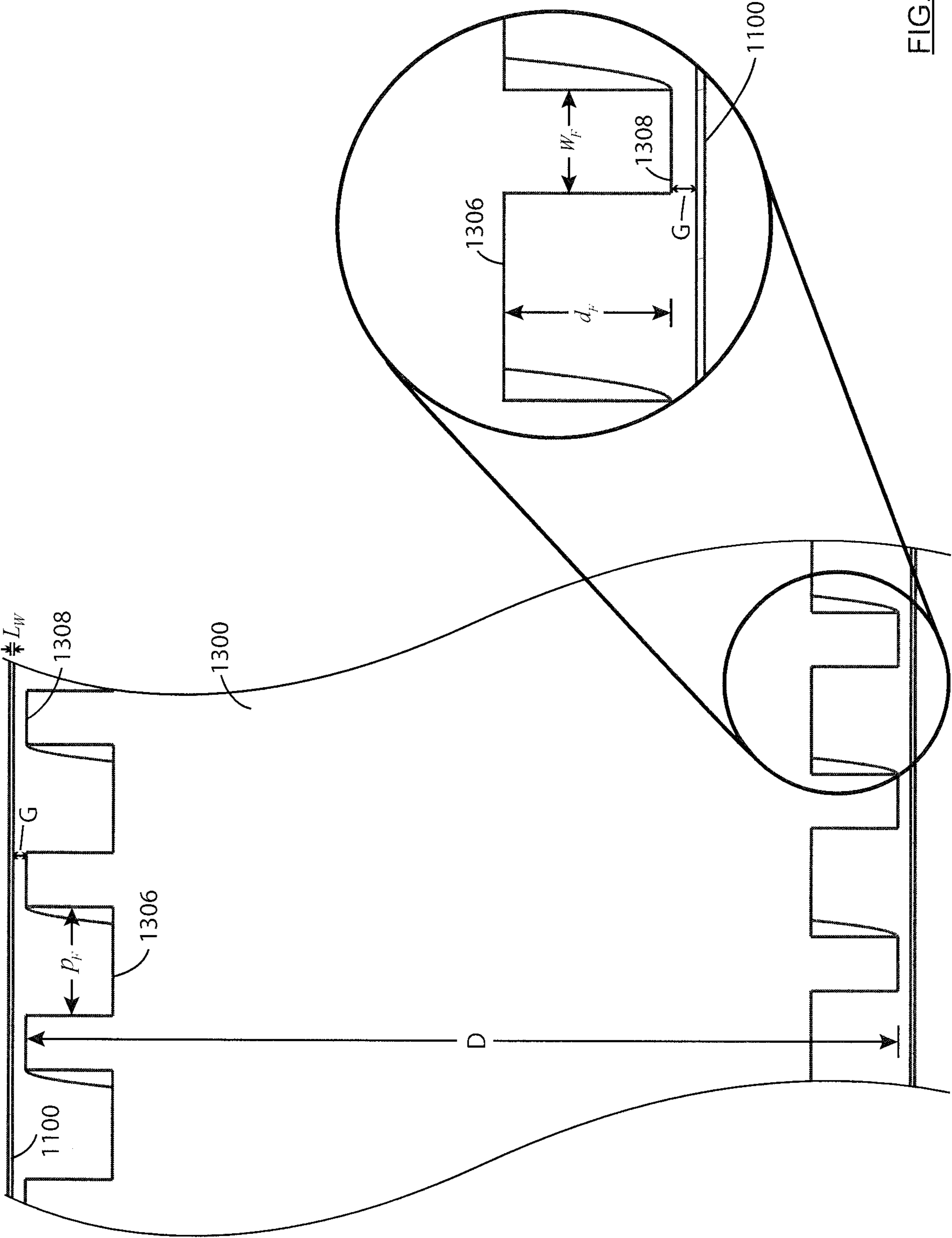


FIG. 15

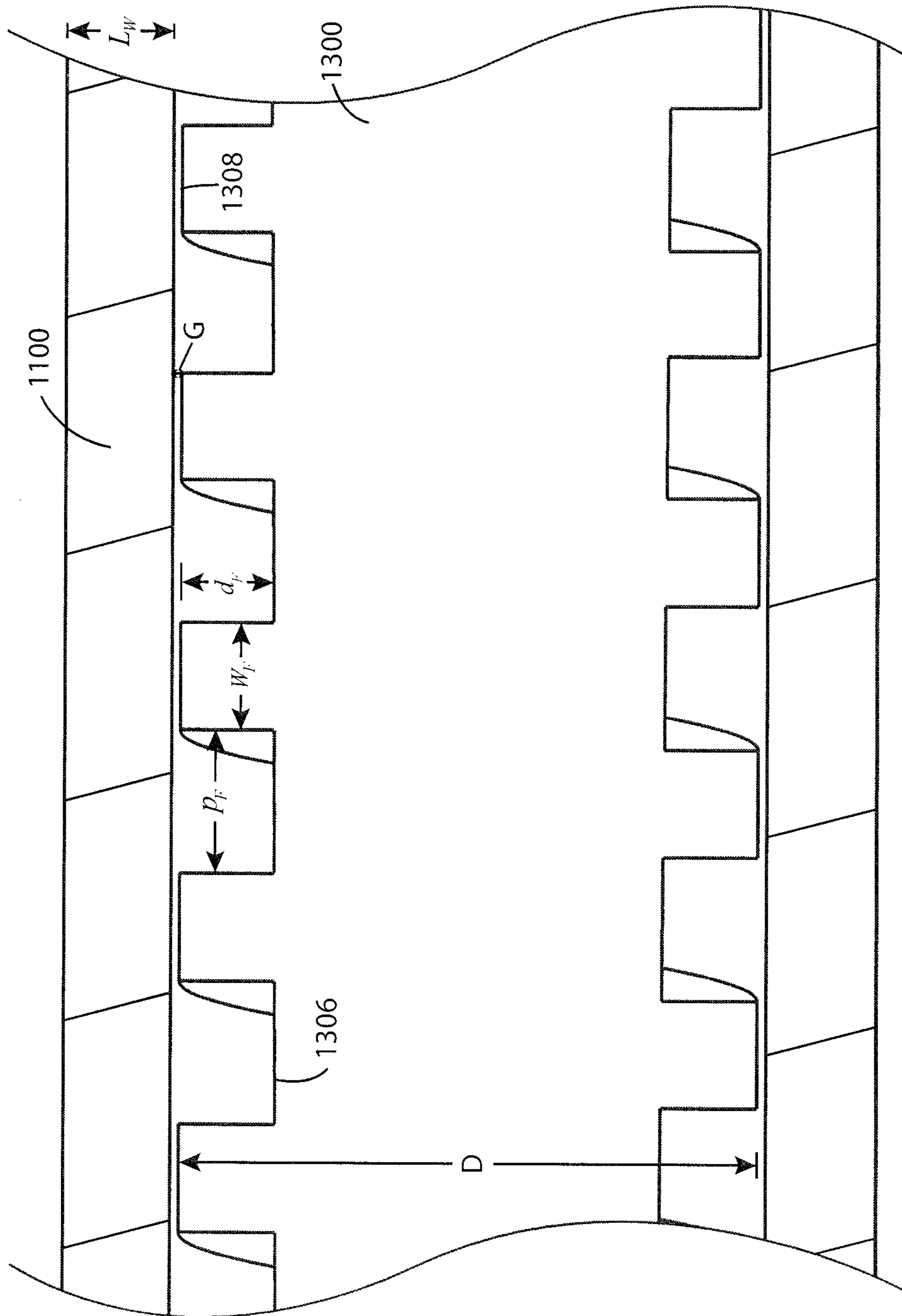


FIG. 16

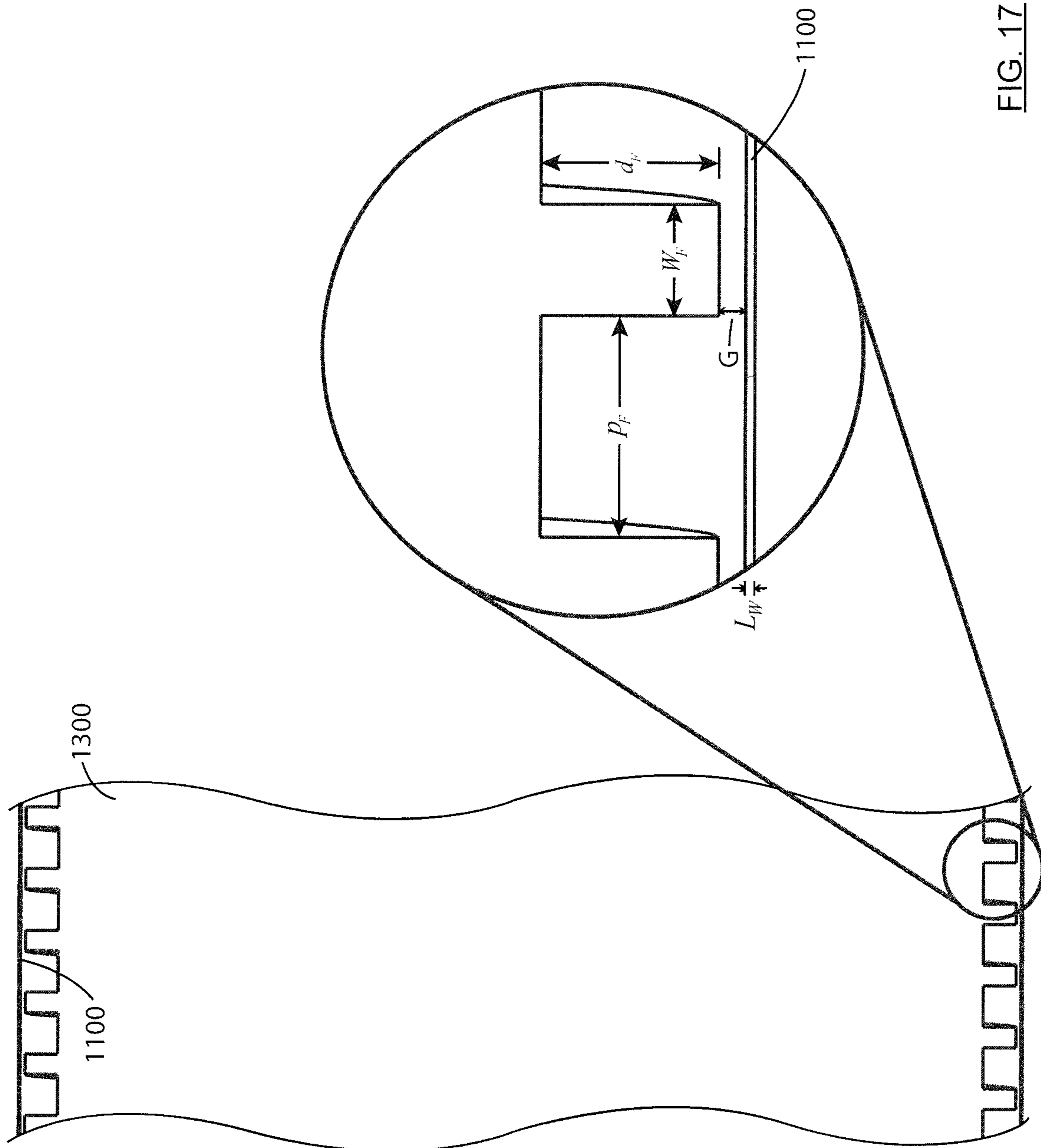


FIG. 17

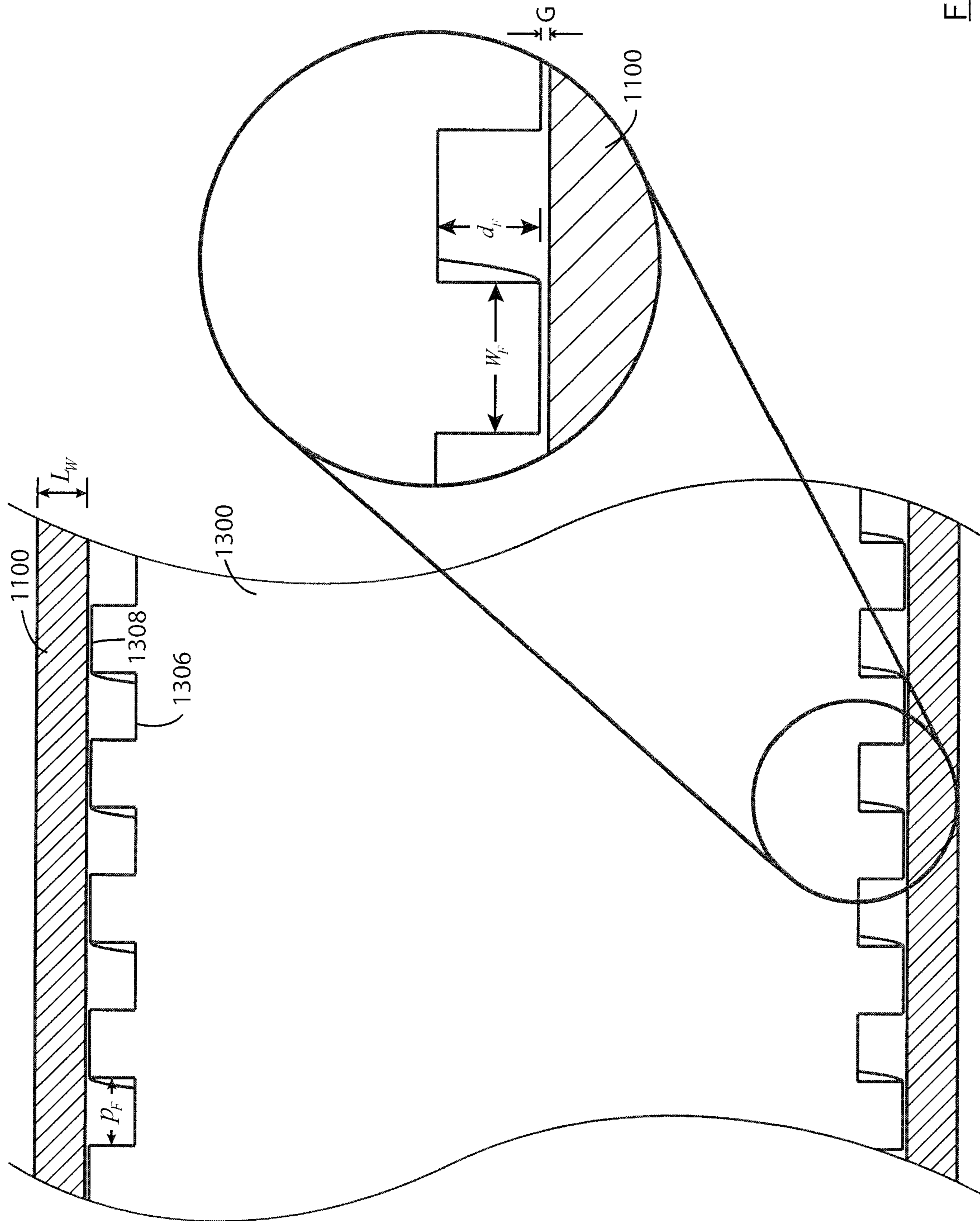


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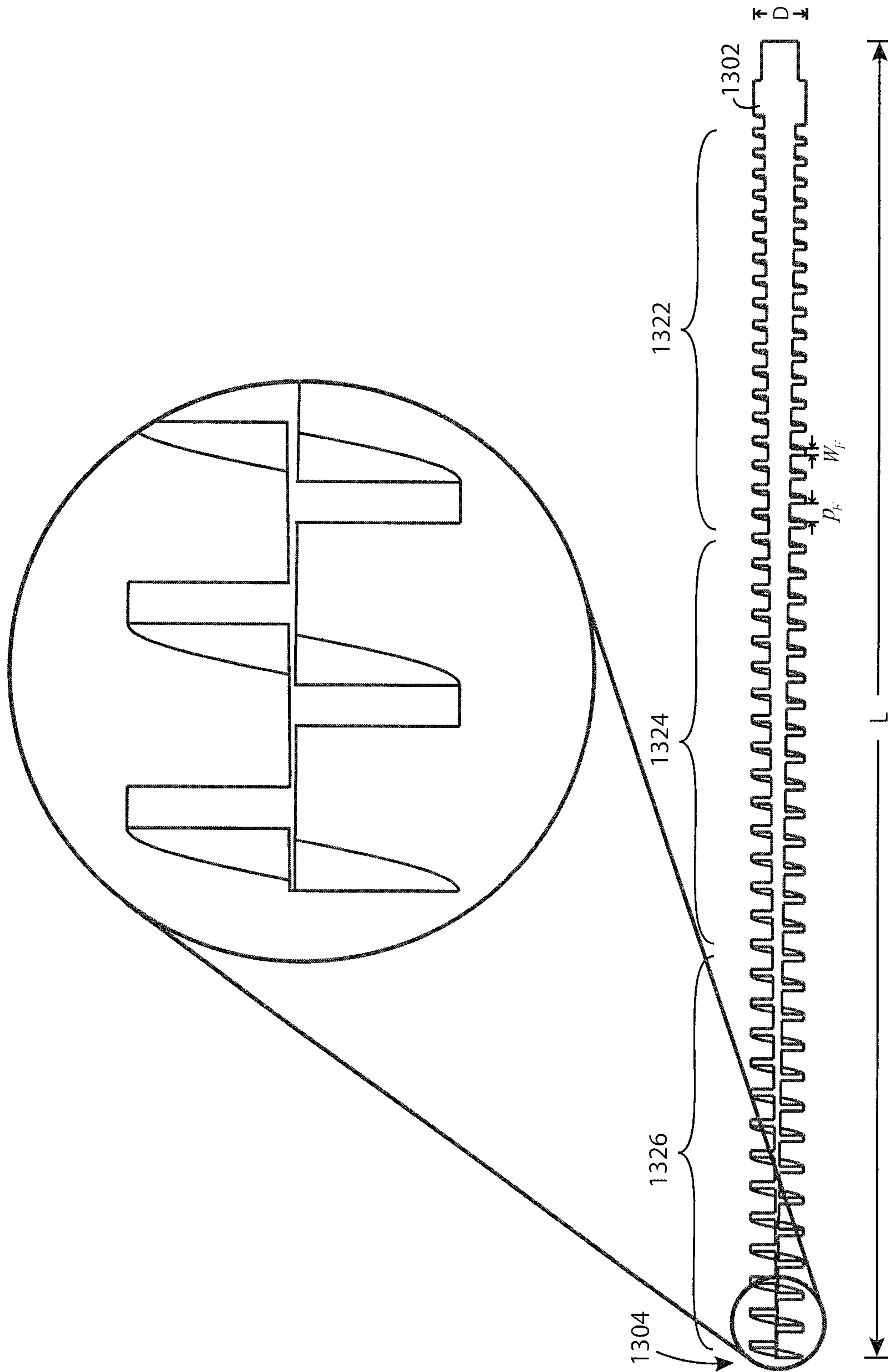


FIG. 19

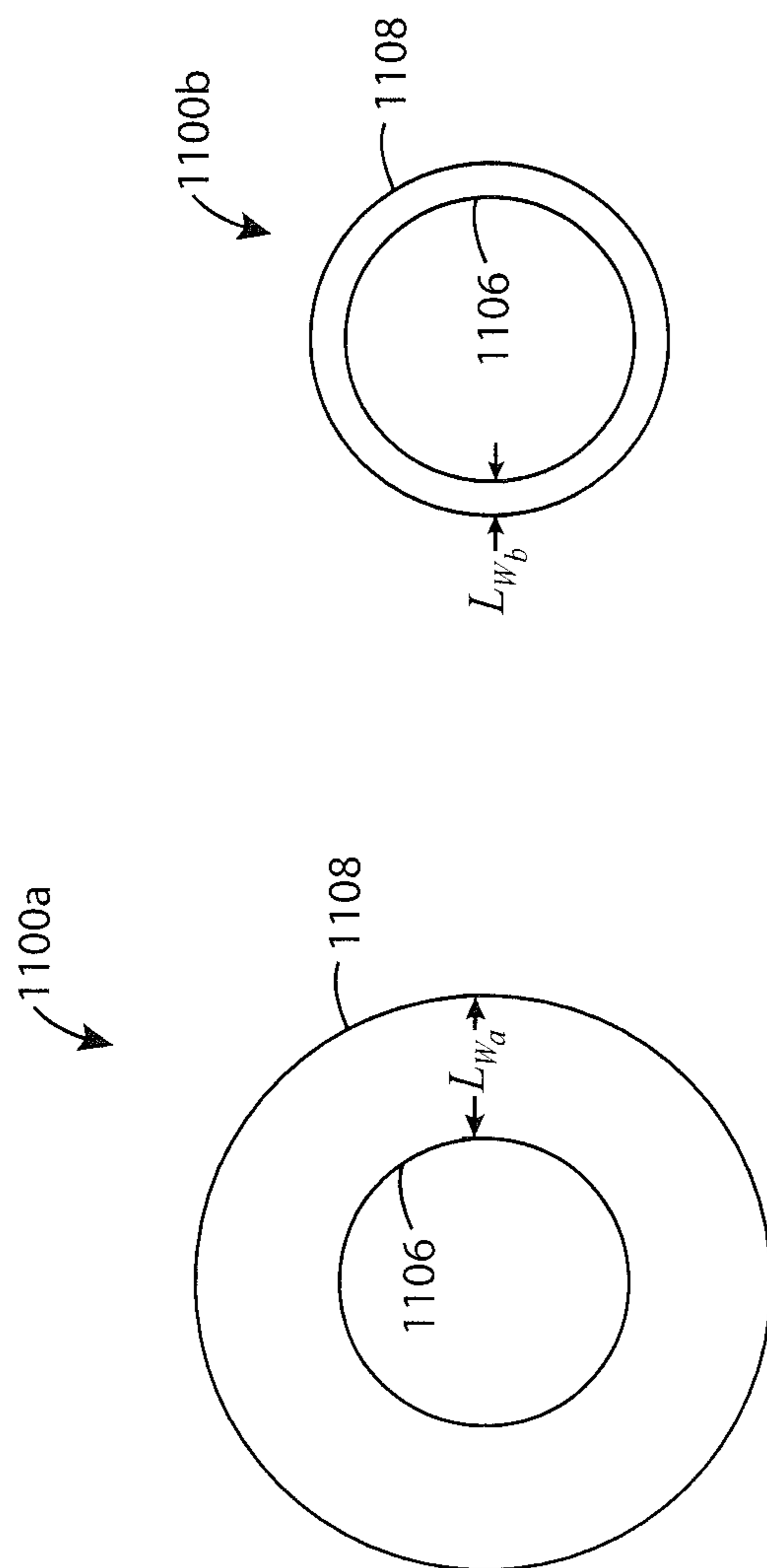


FIG. 20

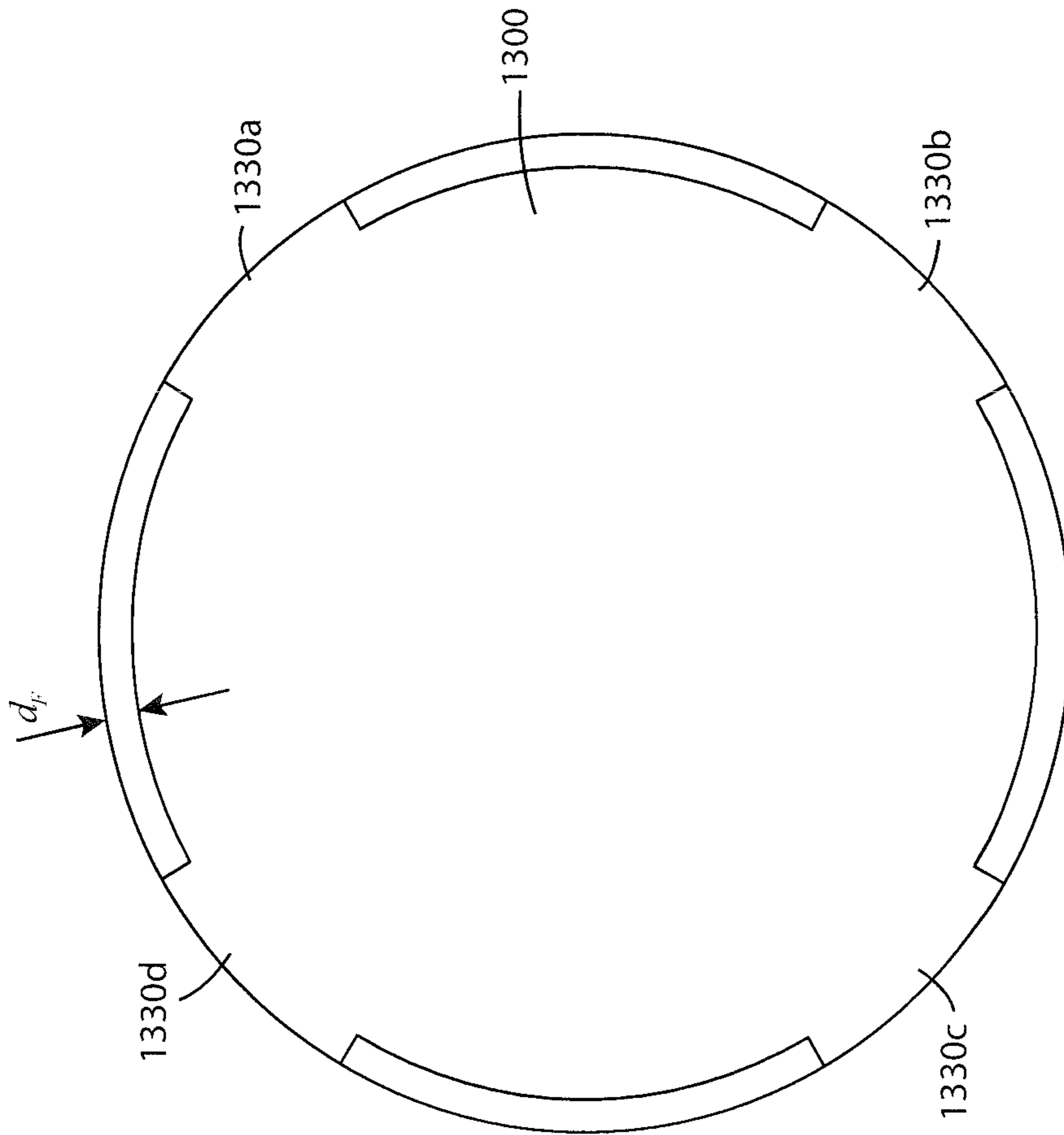


FIG. 21



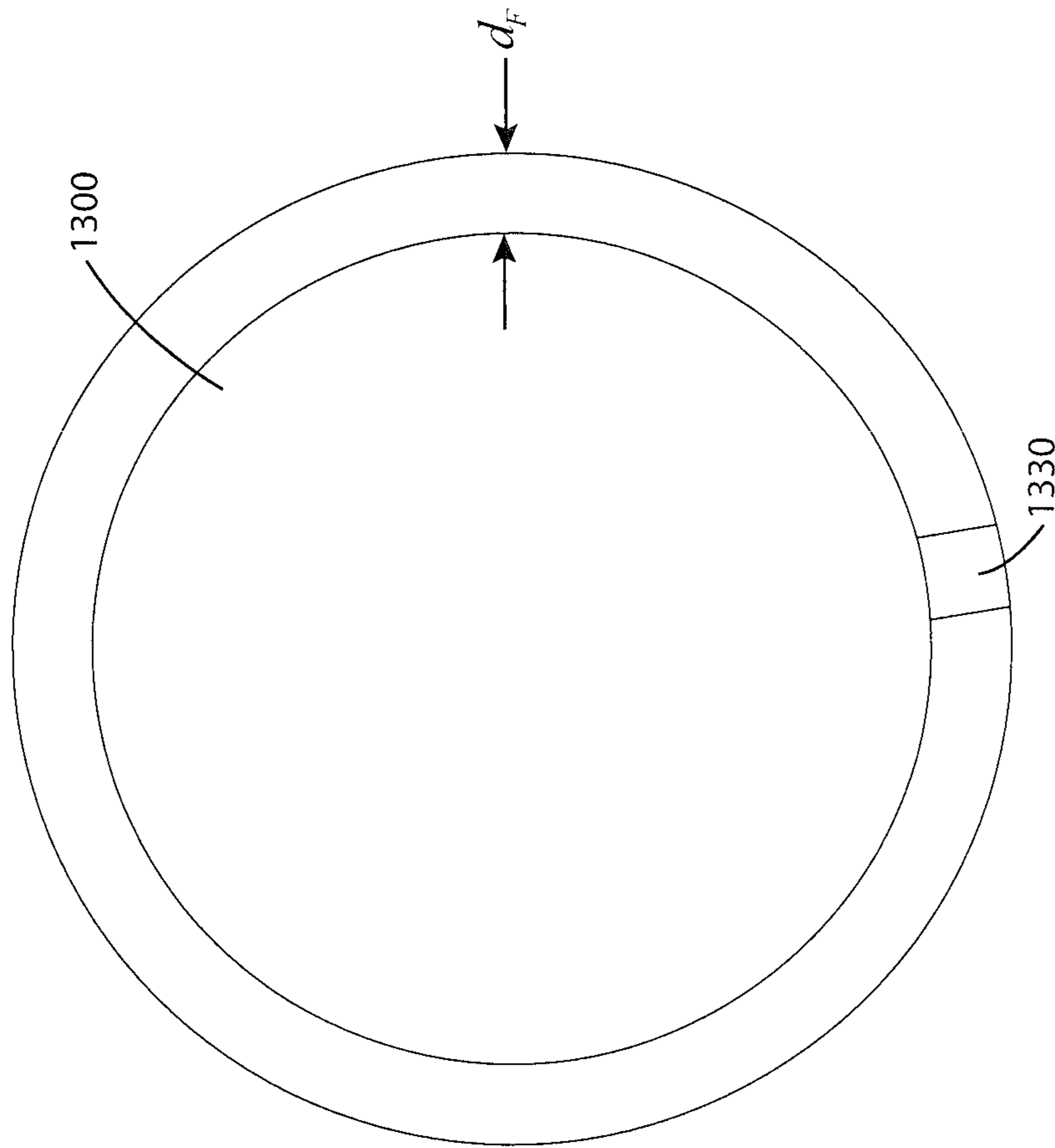


FIG. 22

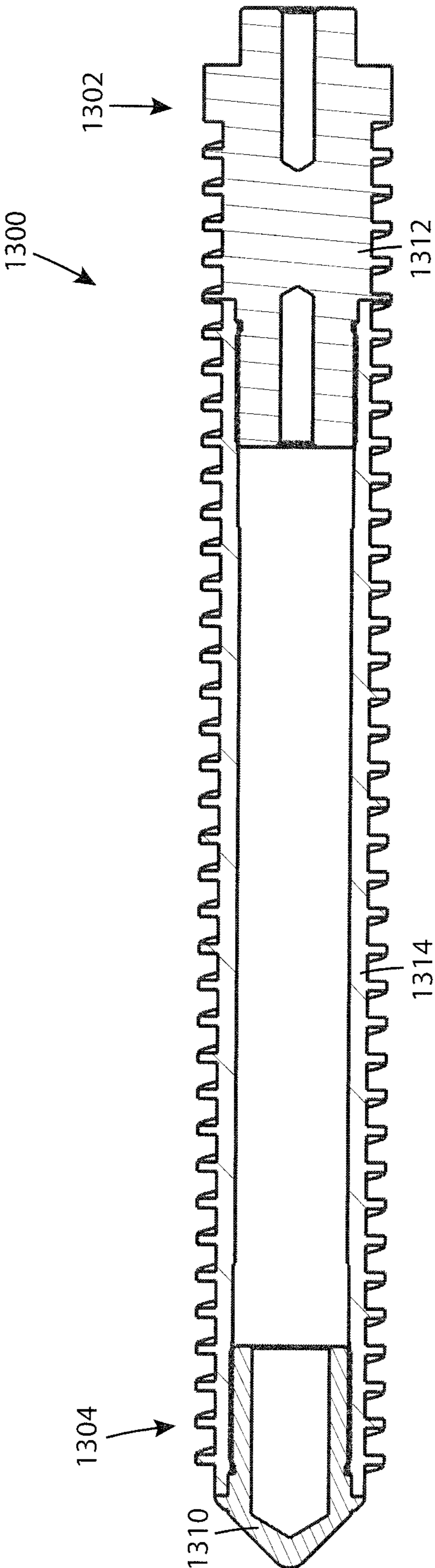


FIG. 23A

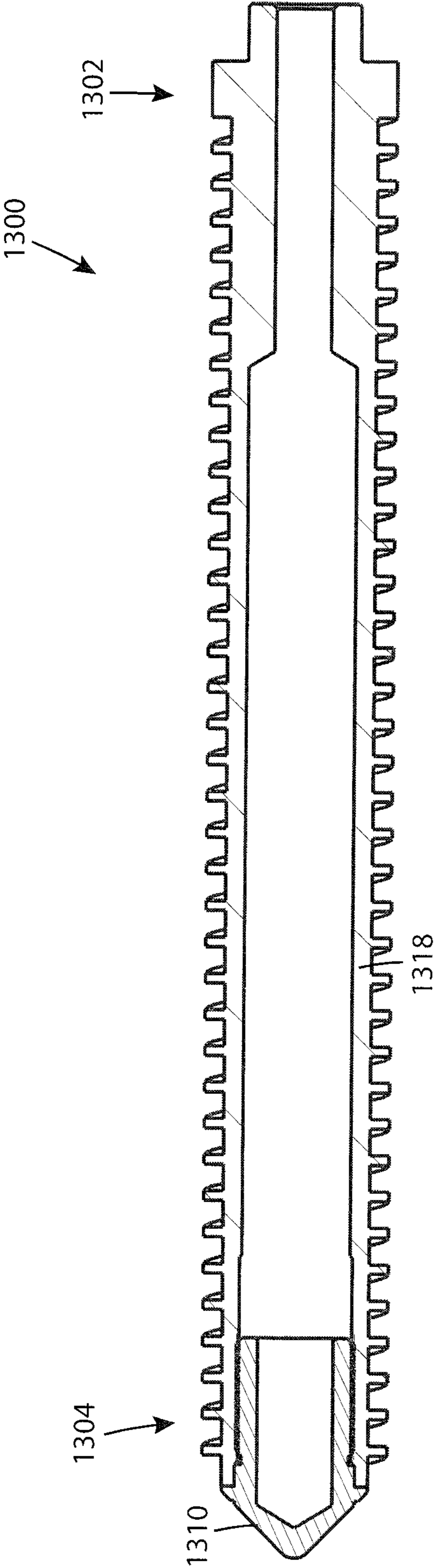


FIG. 23B



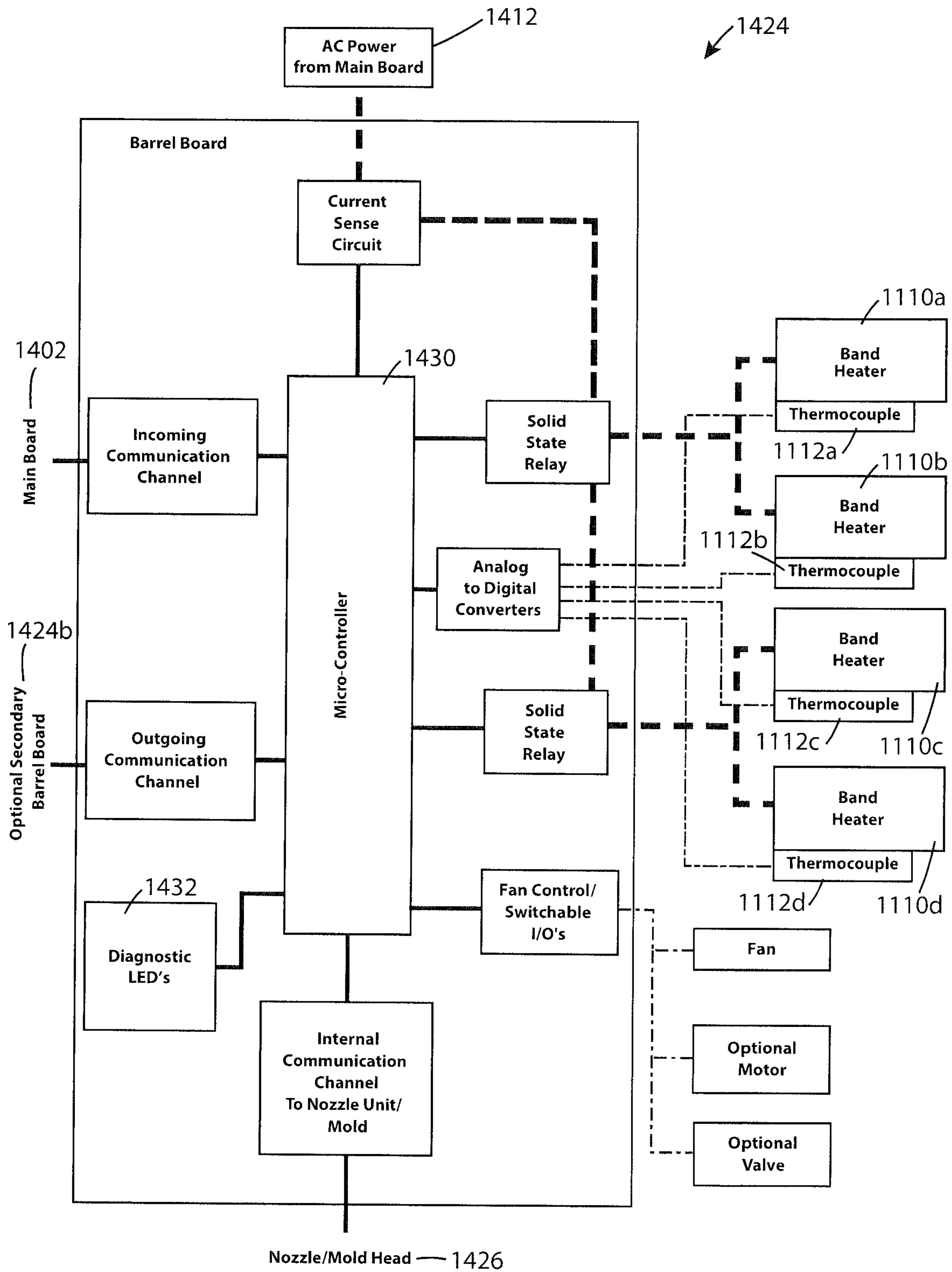


FIG. 25A

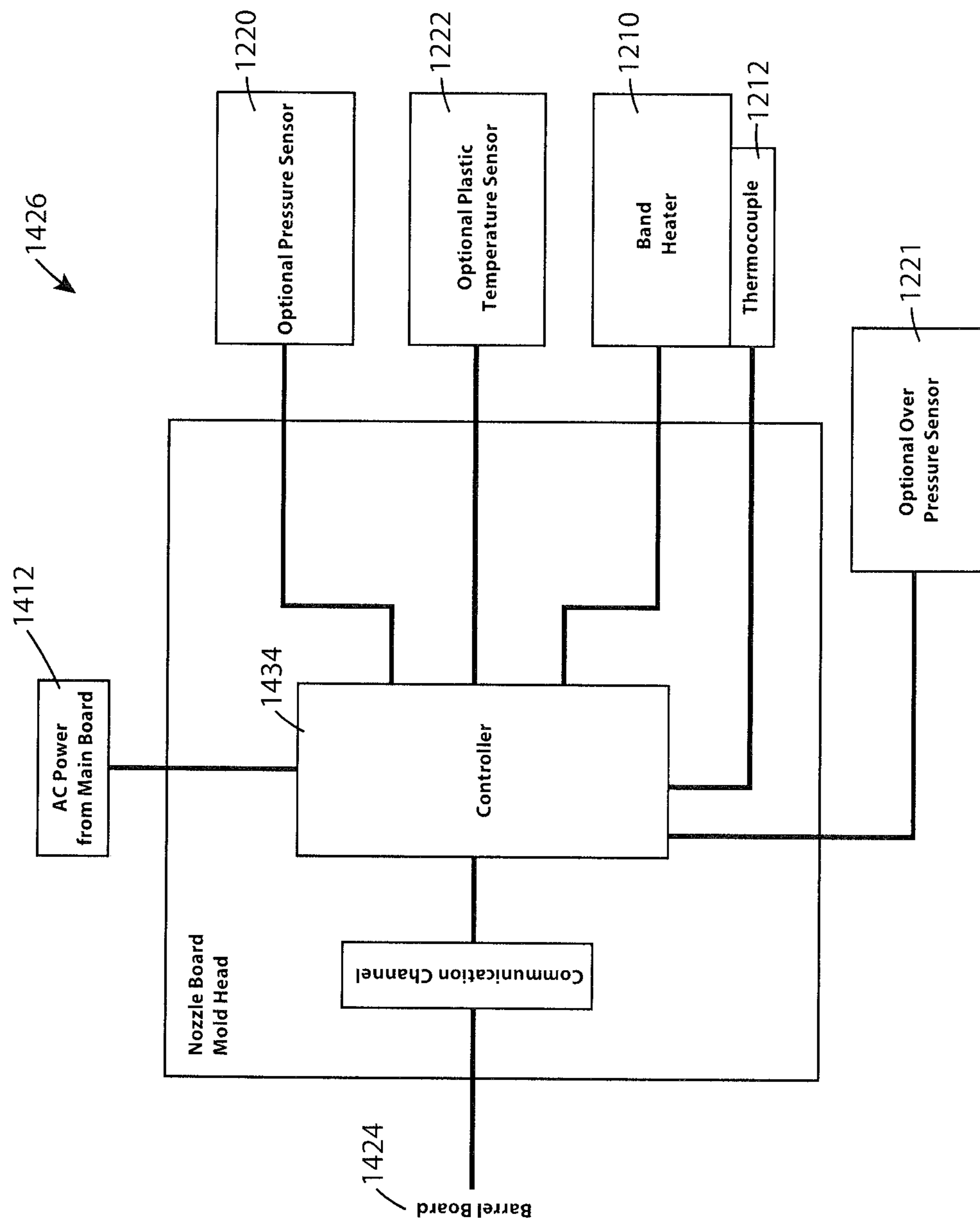


FIG. 25B

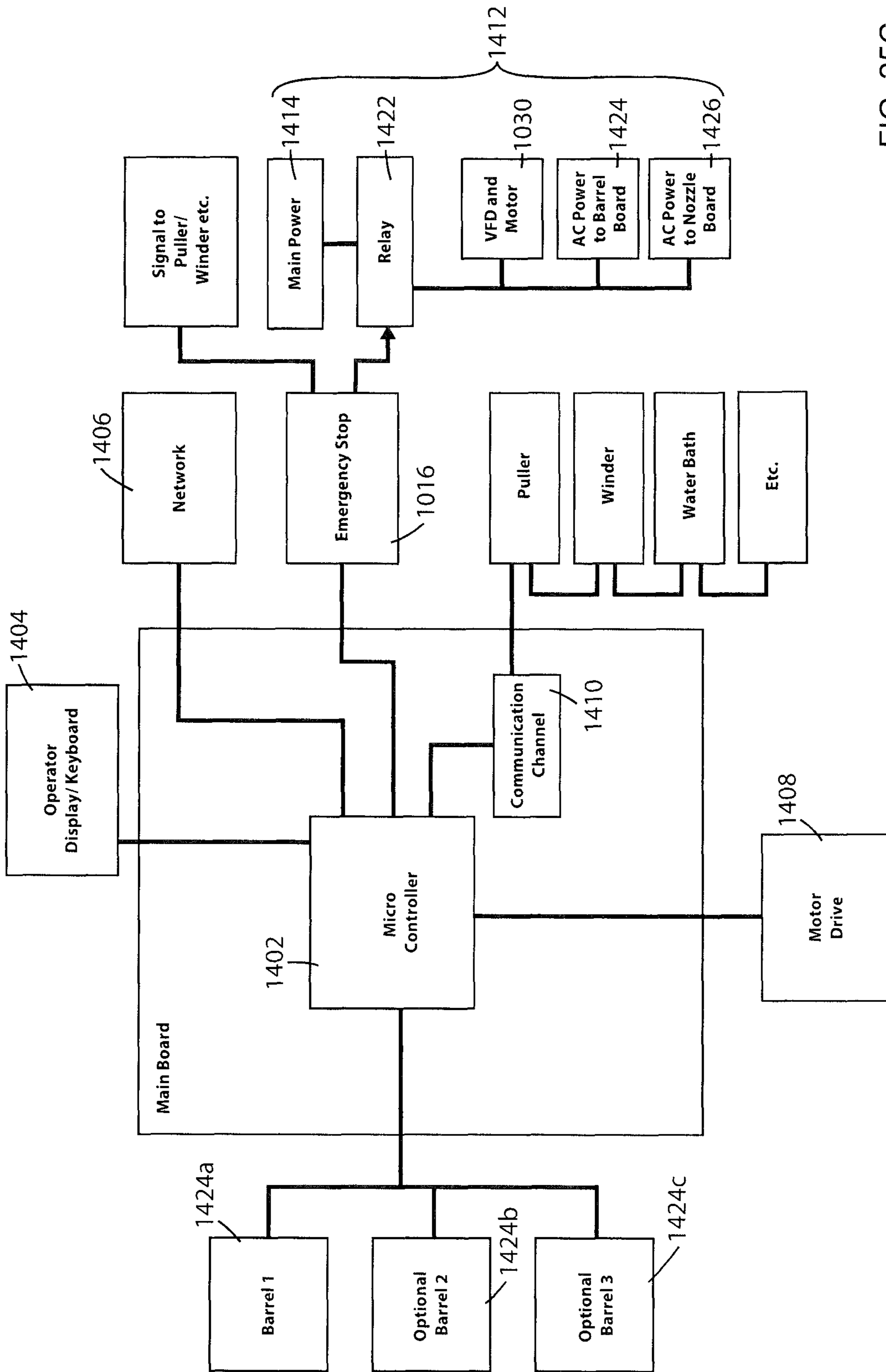
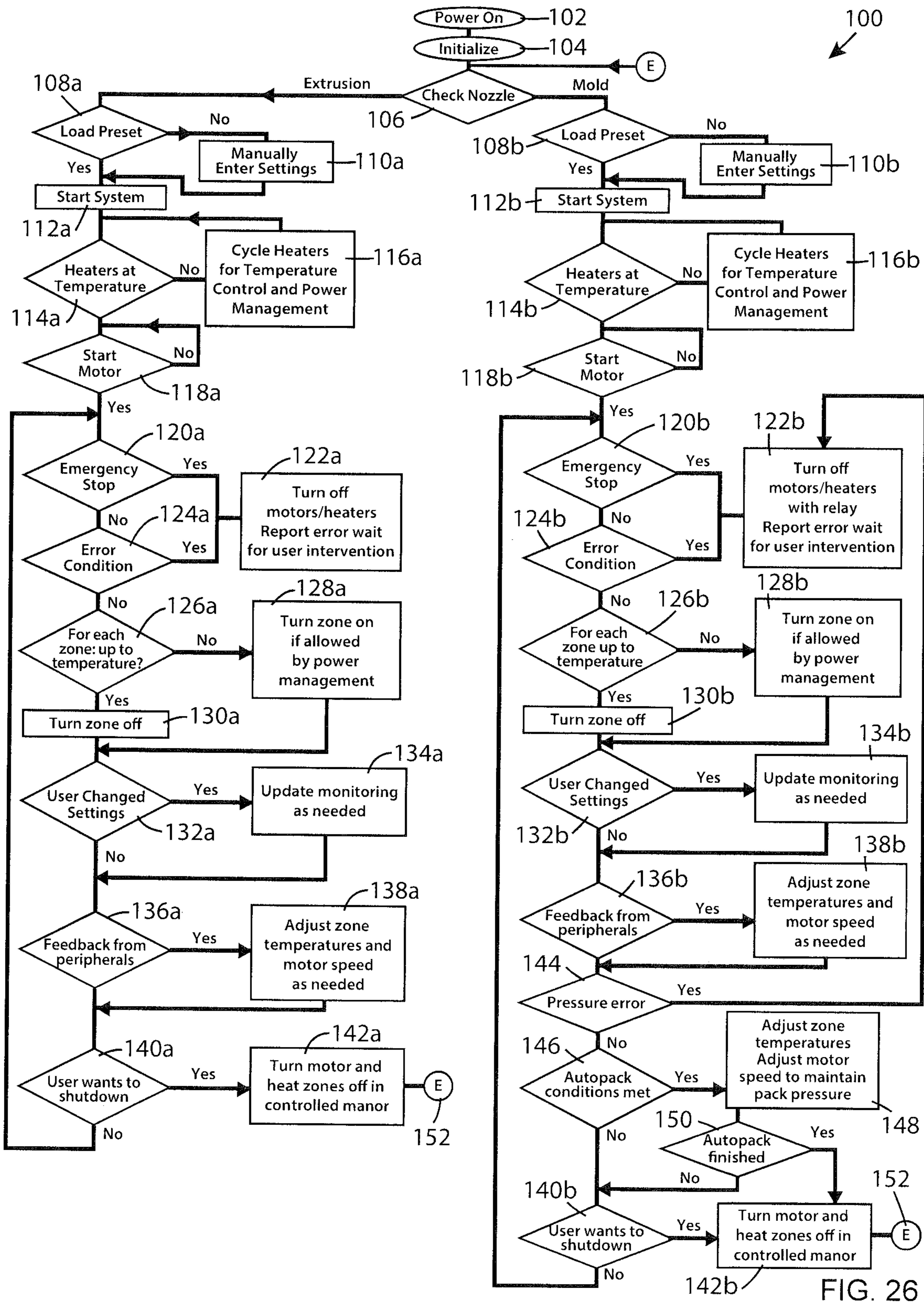


FIG. 25C





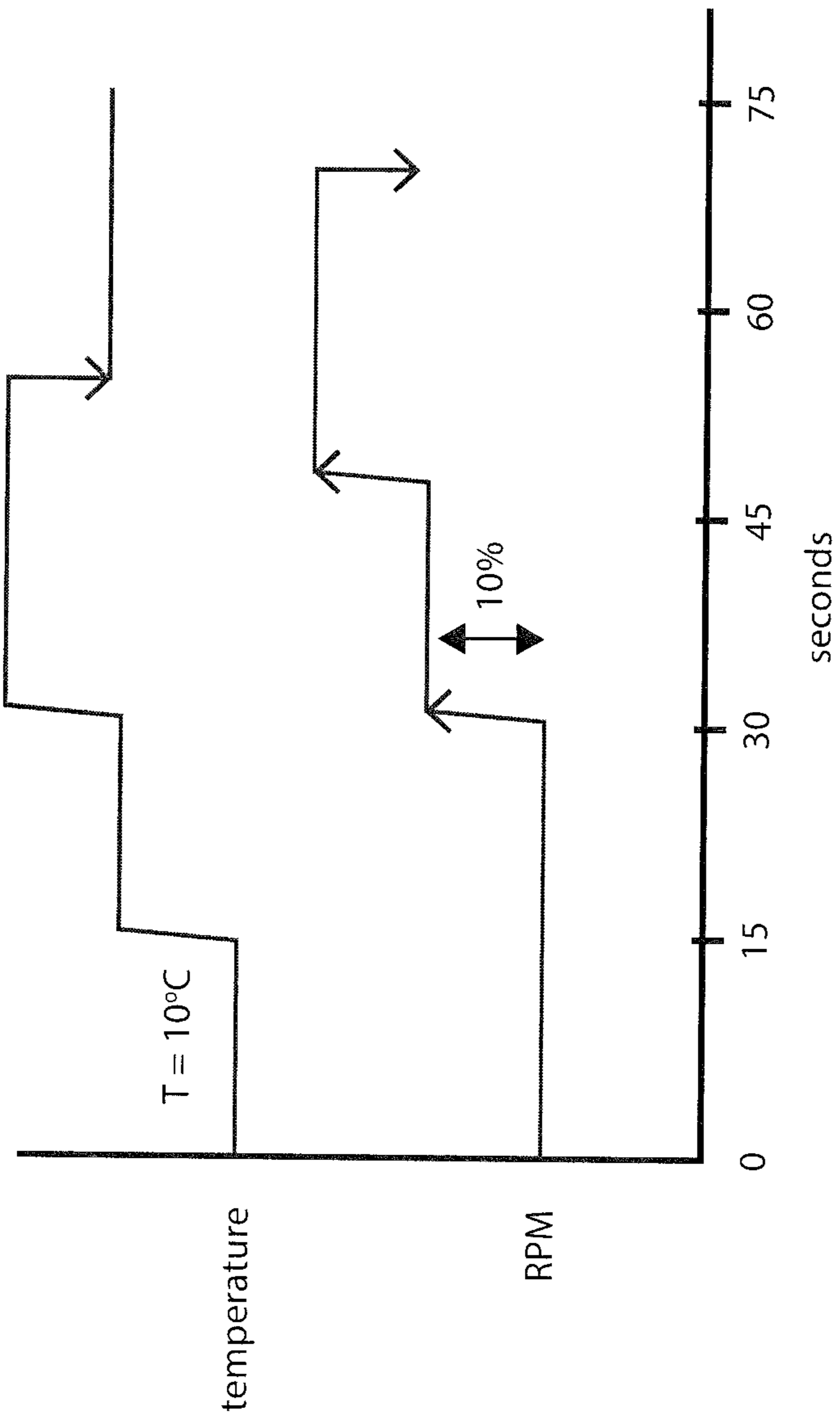


FIG. 27

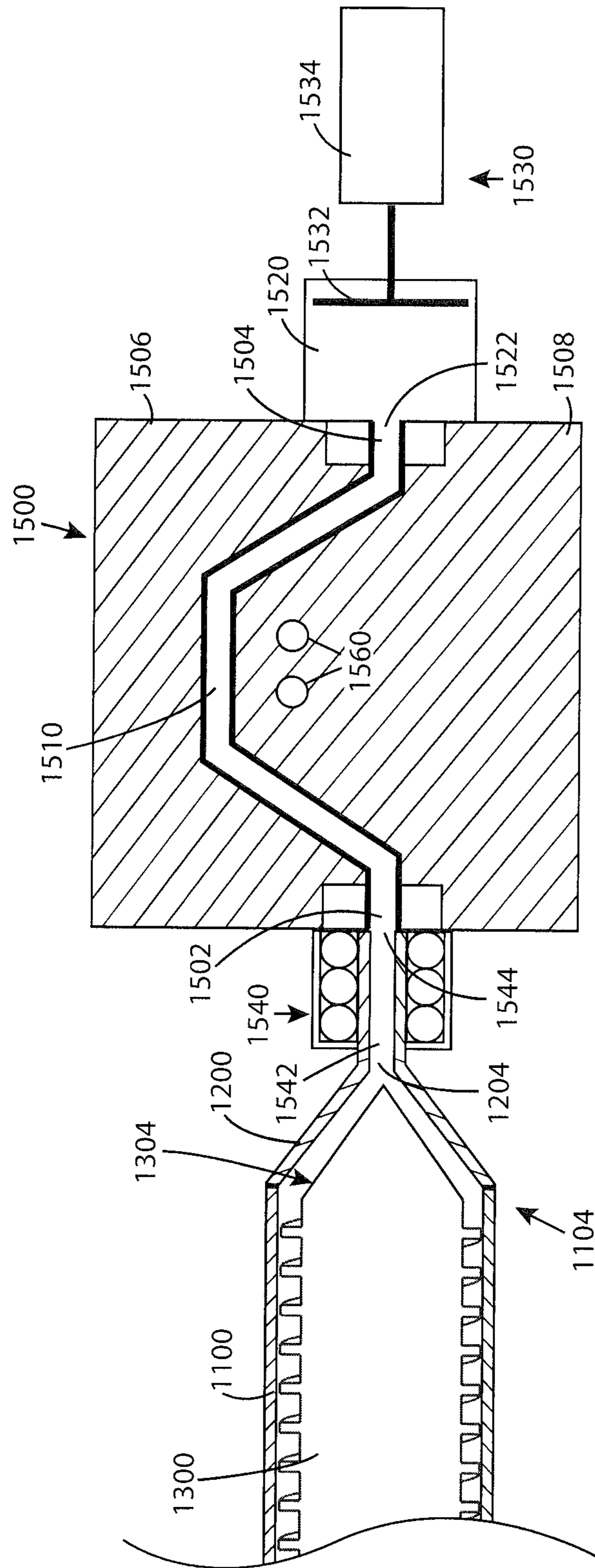


FIG. 28A

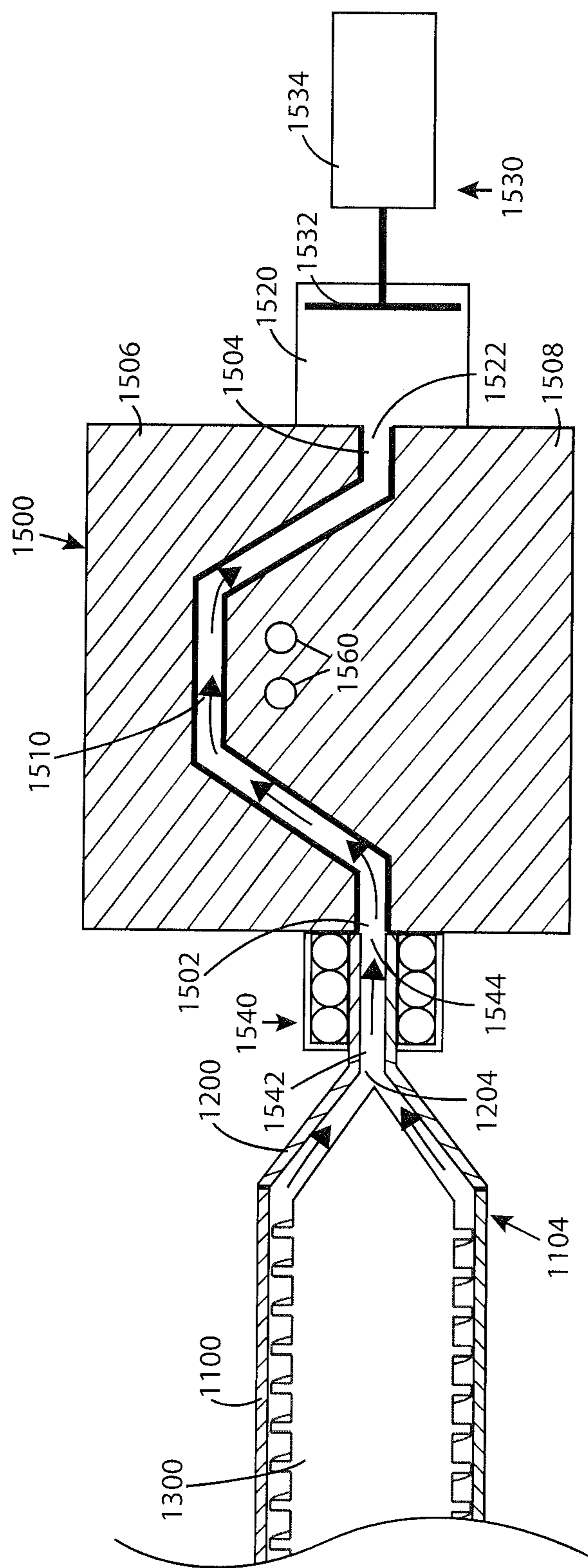


FIG. 28B

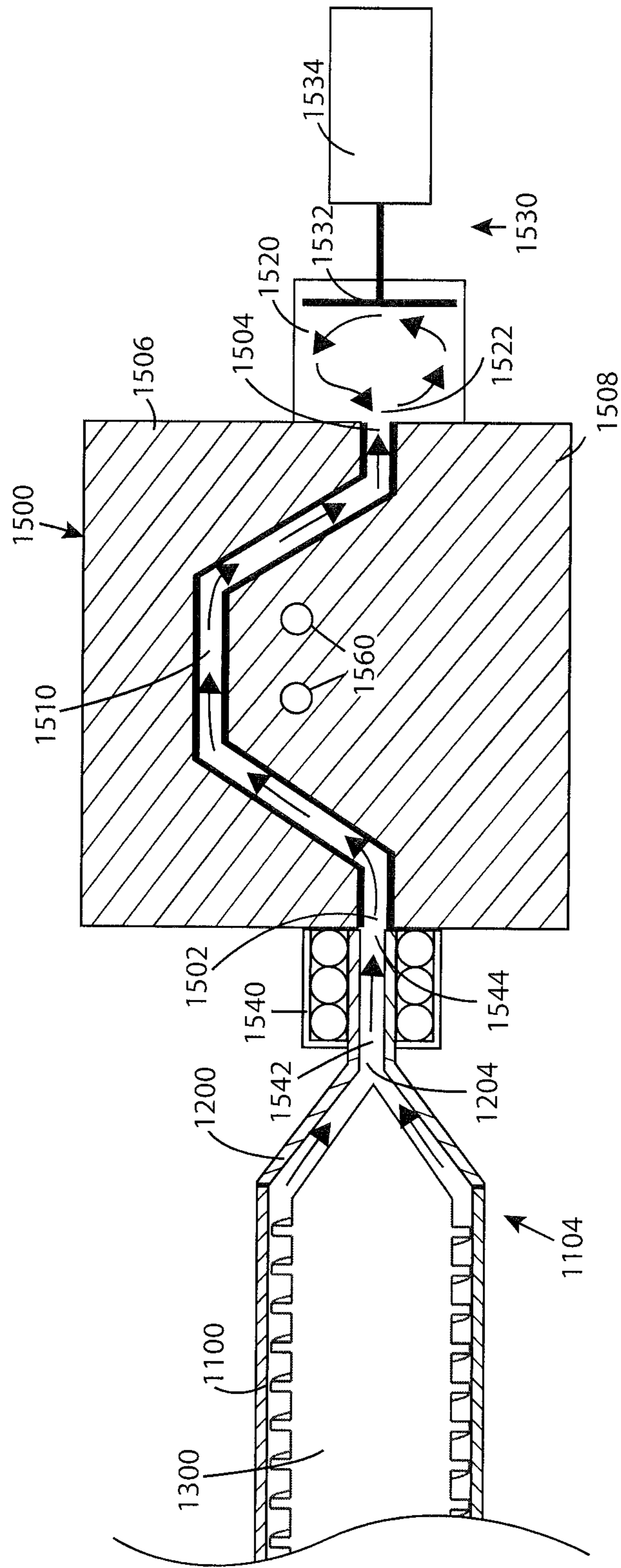


FIG. 28C

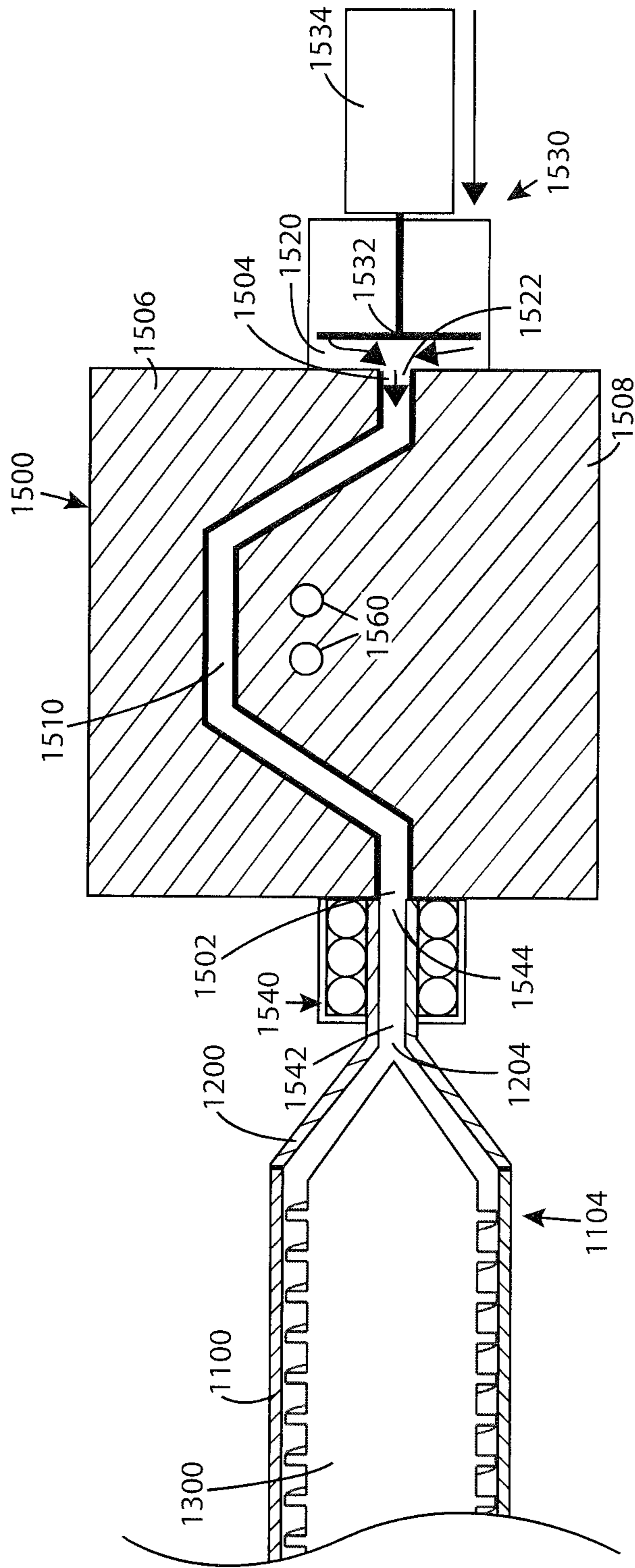


FIG. 28D

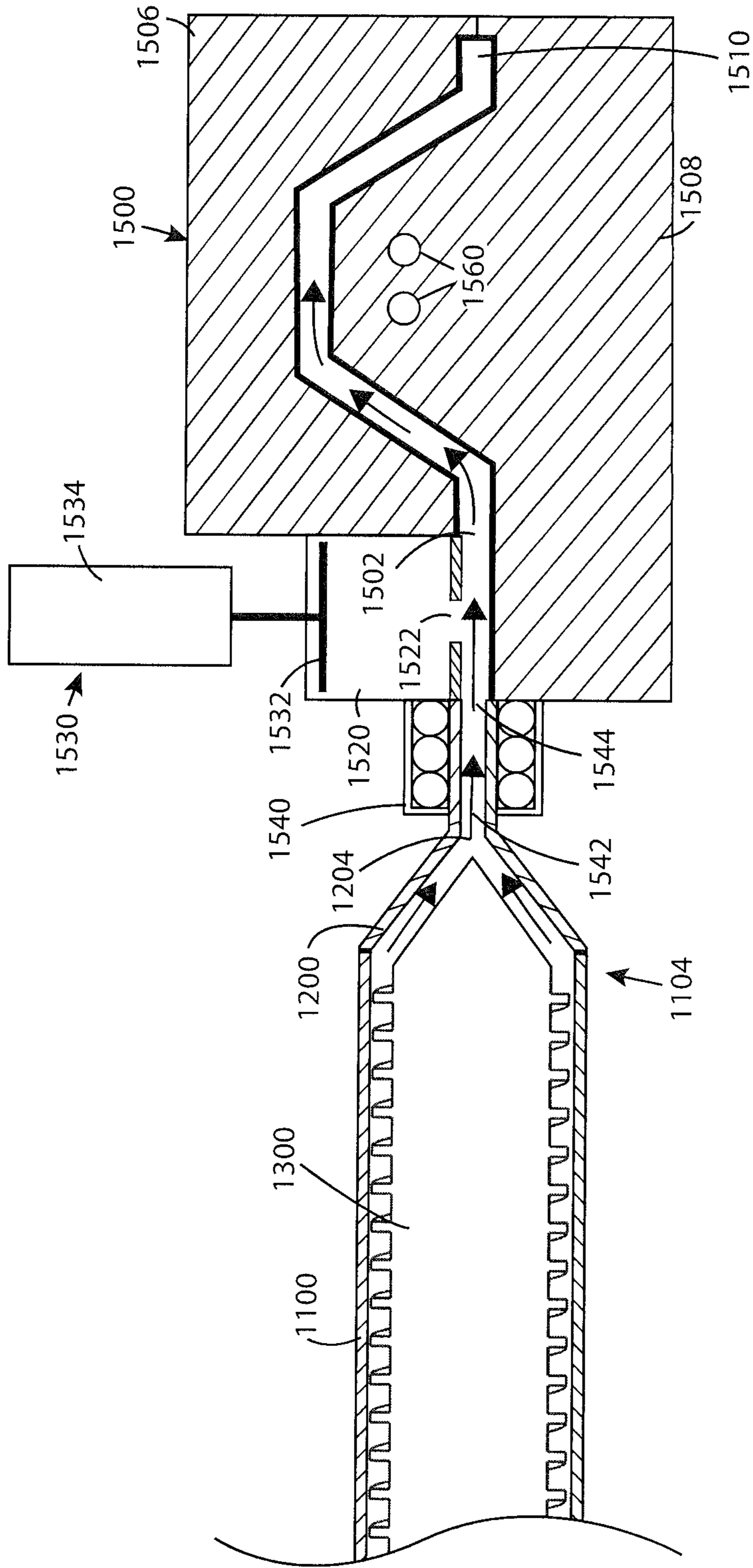


FIG. 28E

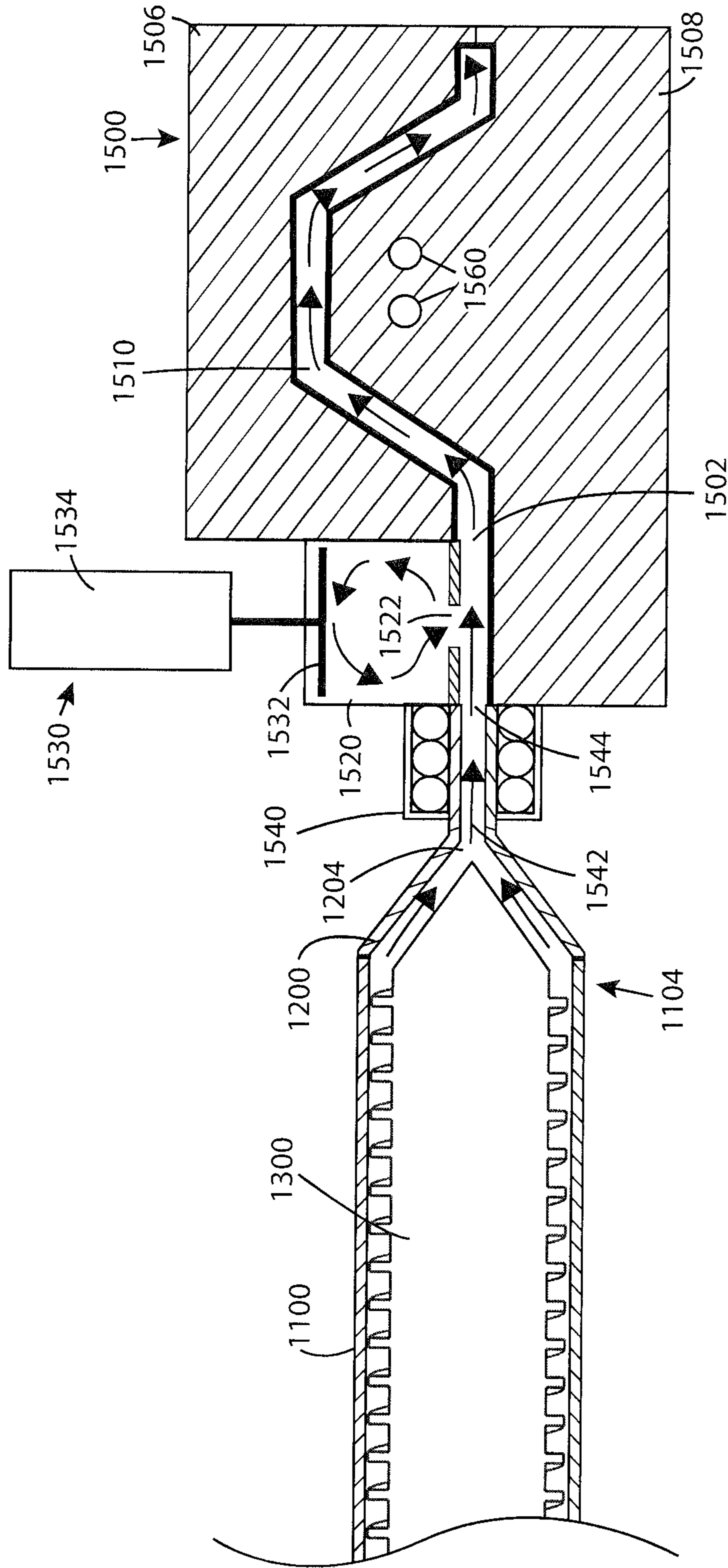


FIG. 28F

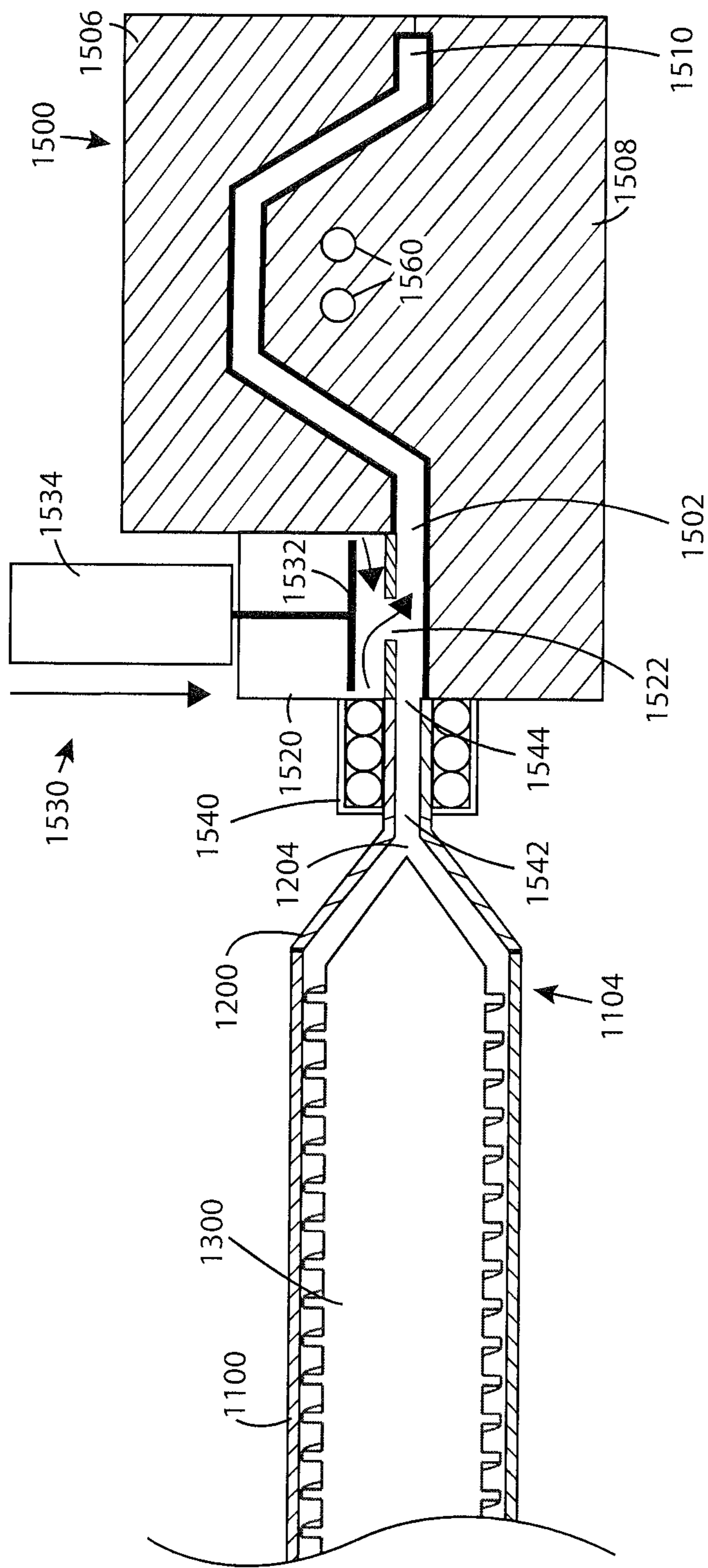


FIG. 28G



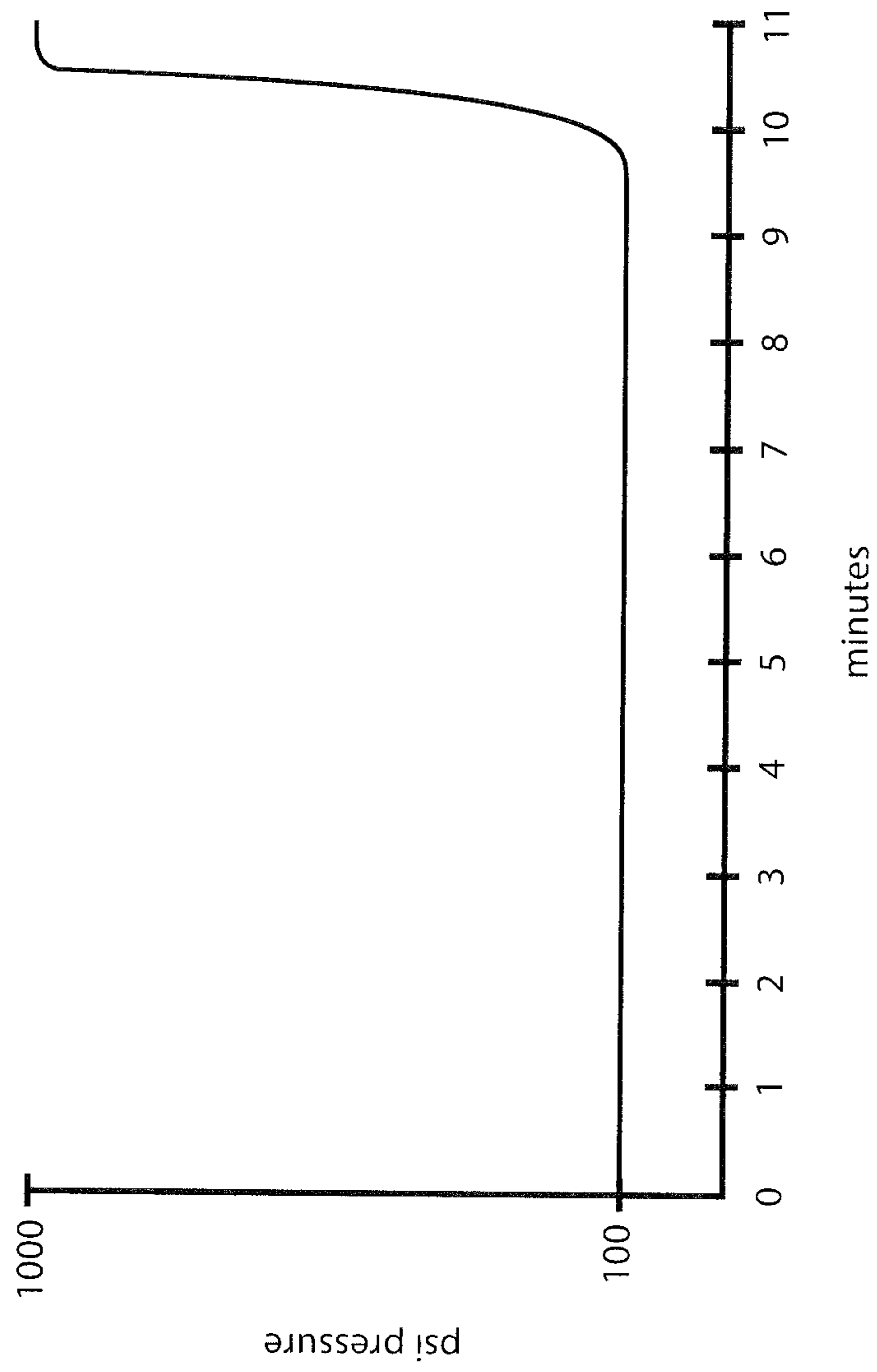


FIG. 29

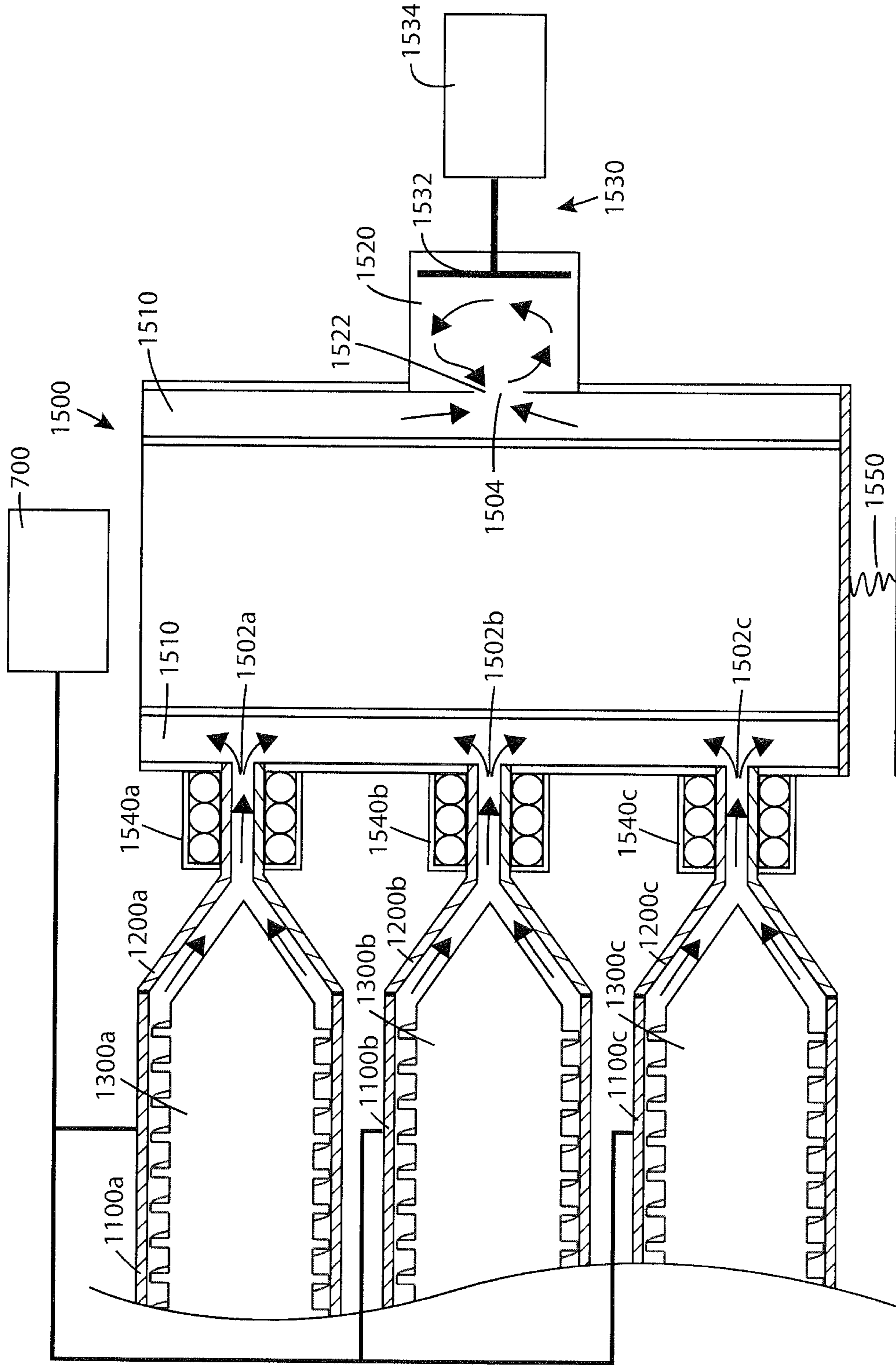


FIG. 30A

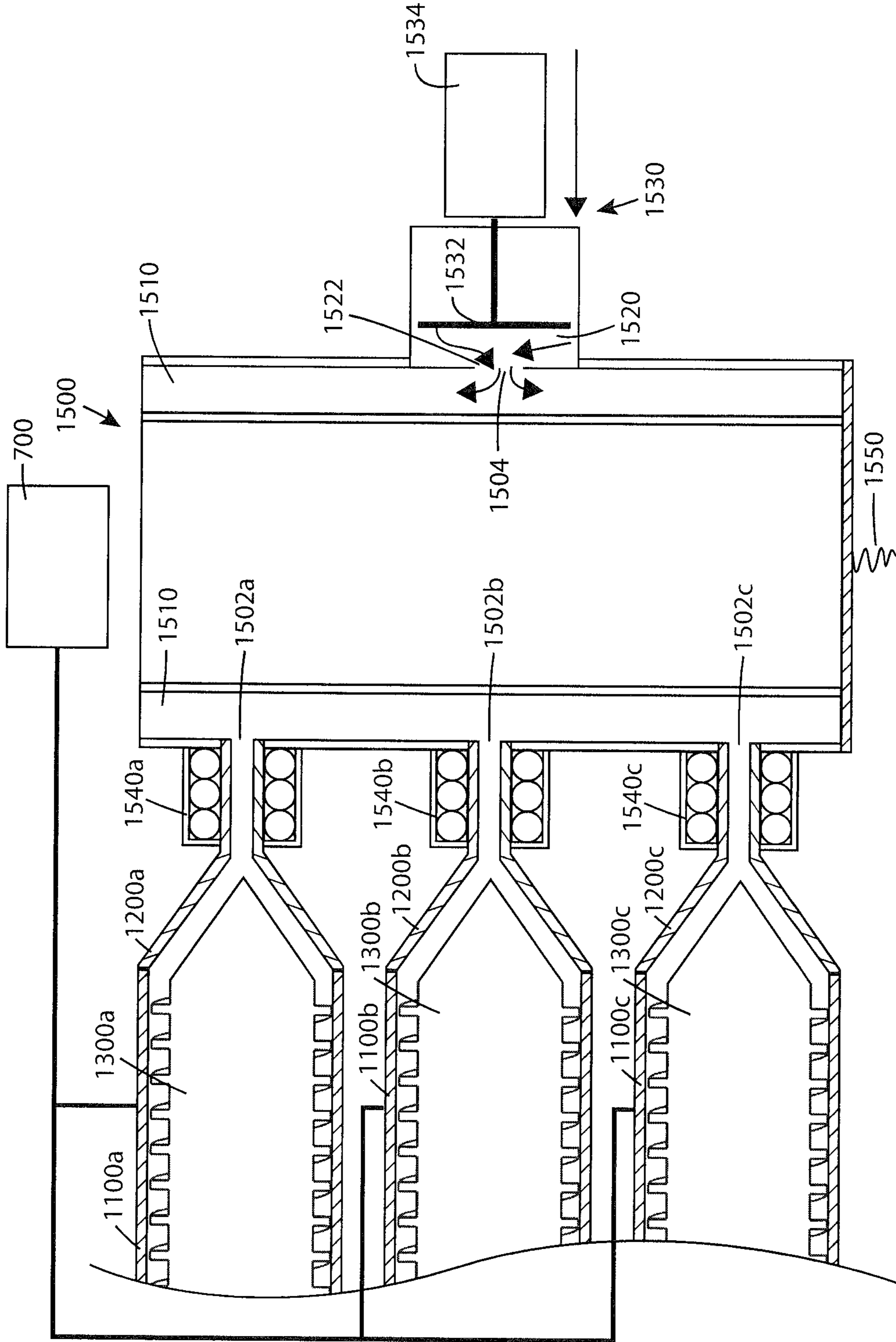


FIG. 30B

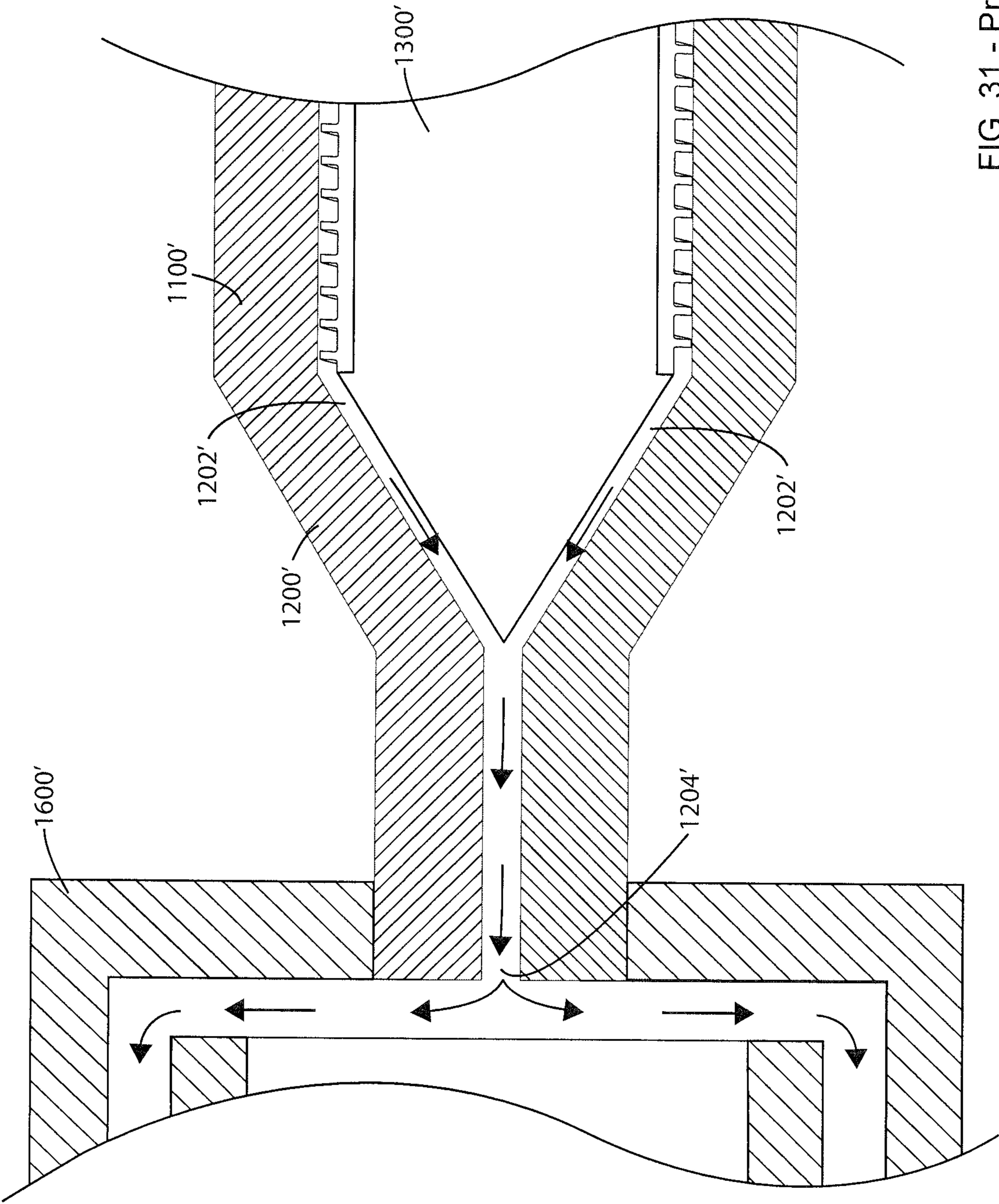


FIG. 31 - Prior Art

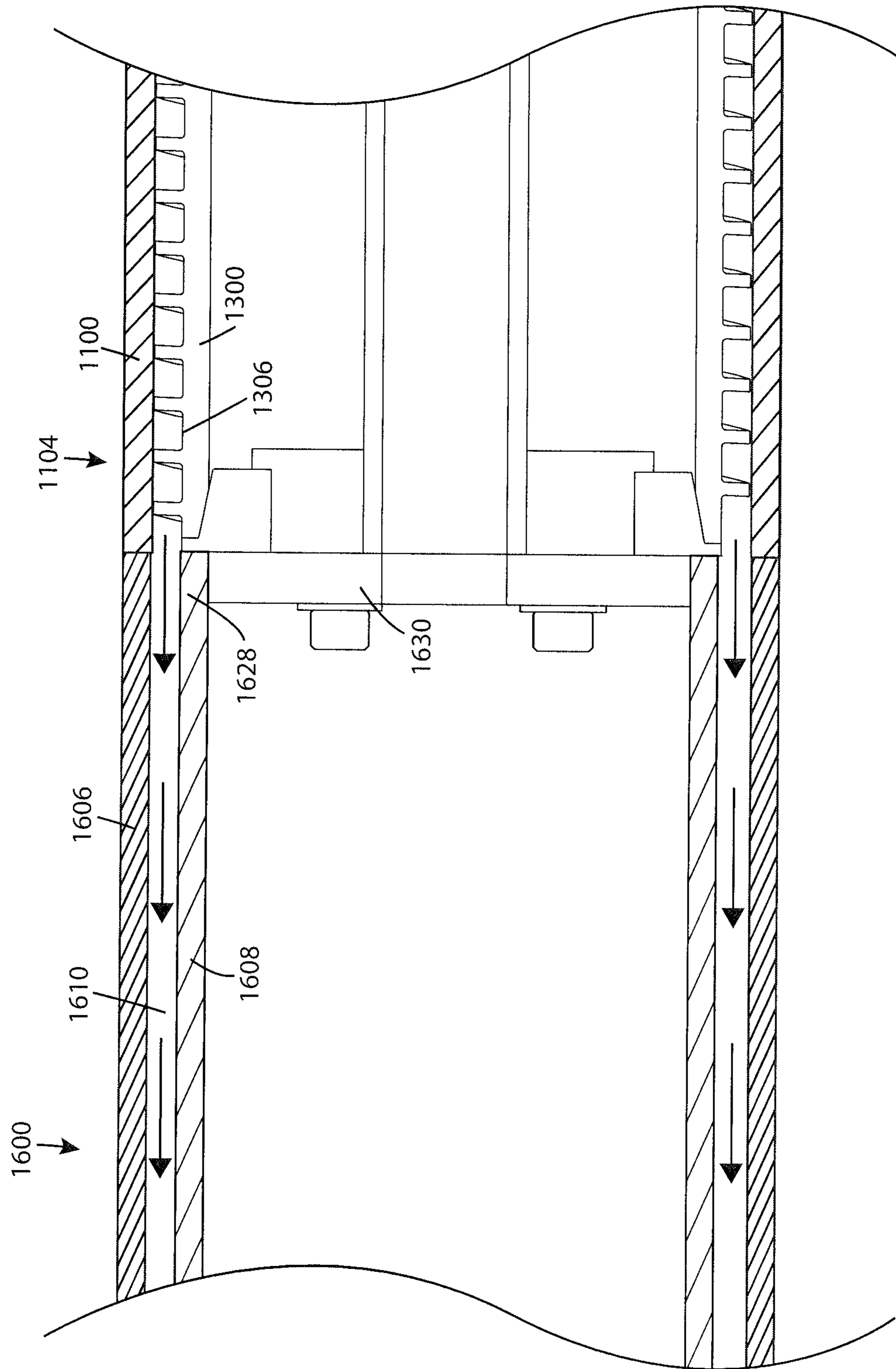


FIG. 32

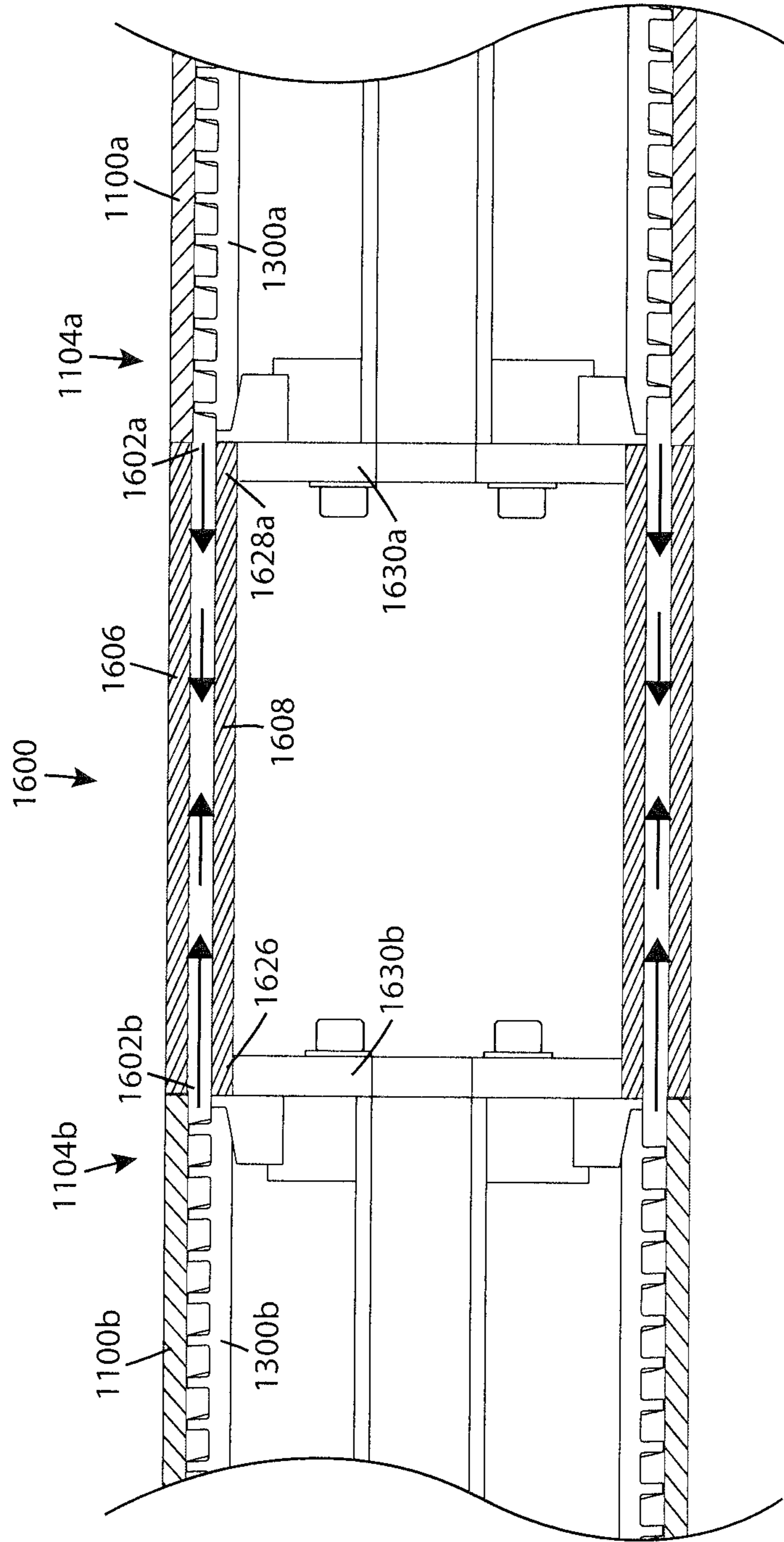


FIG. 33A

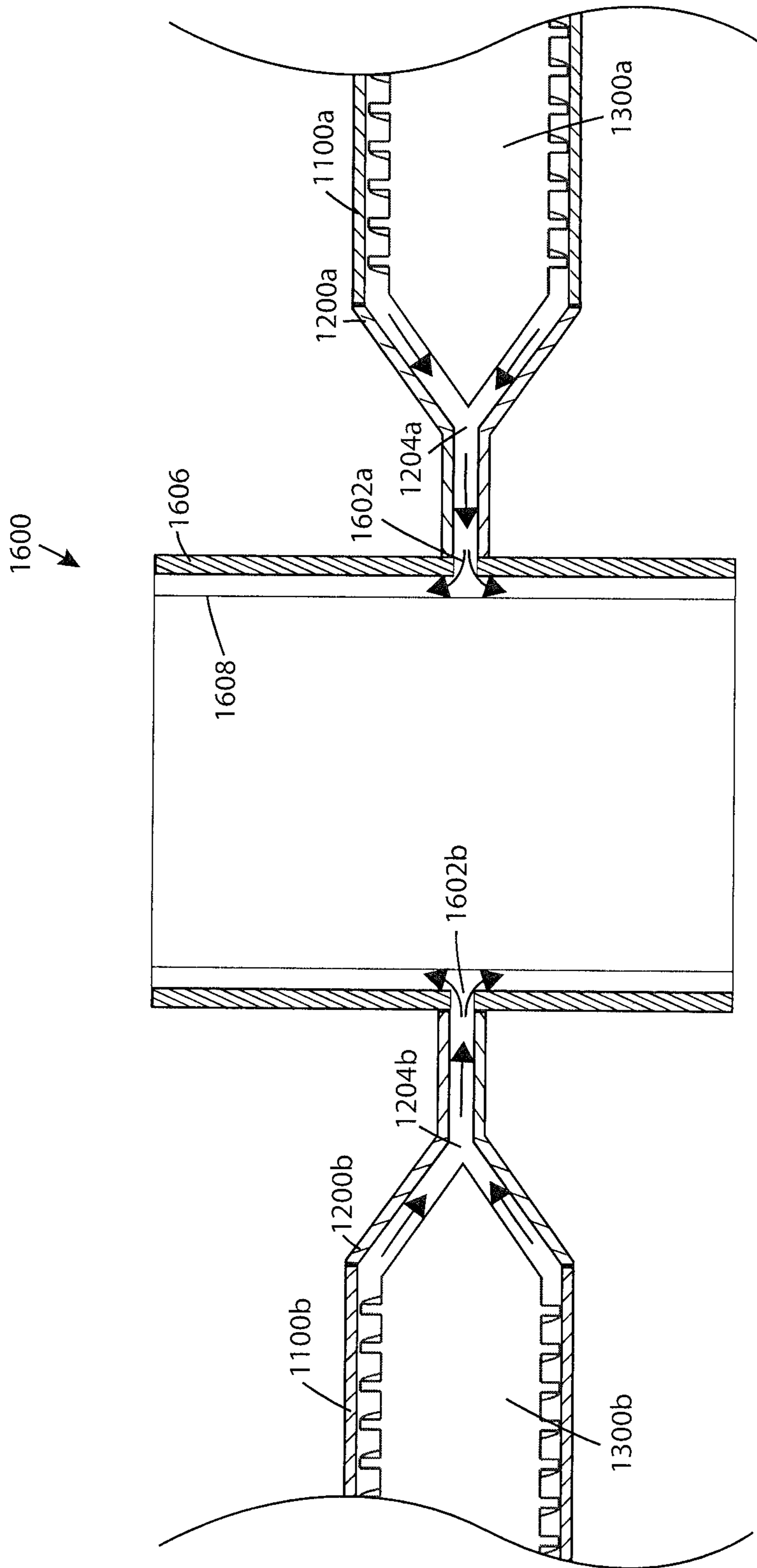


FIG. 33B

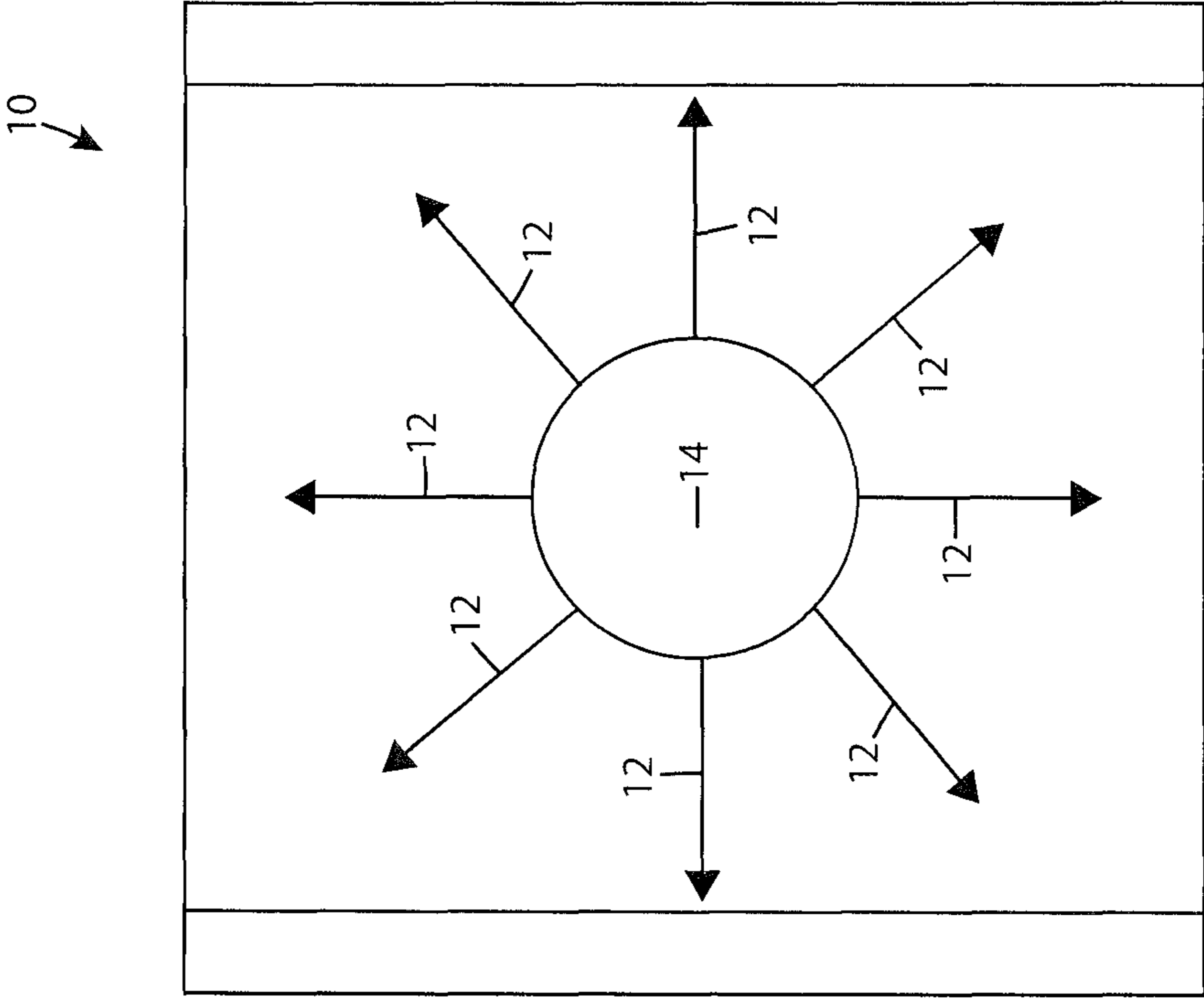


FIG. 34



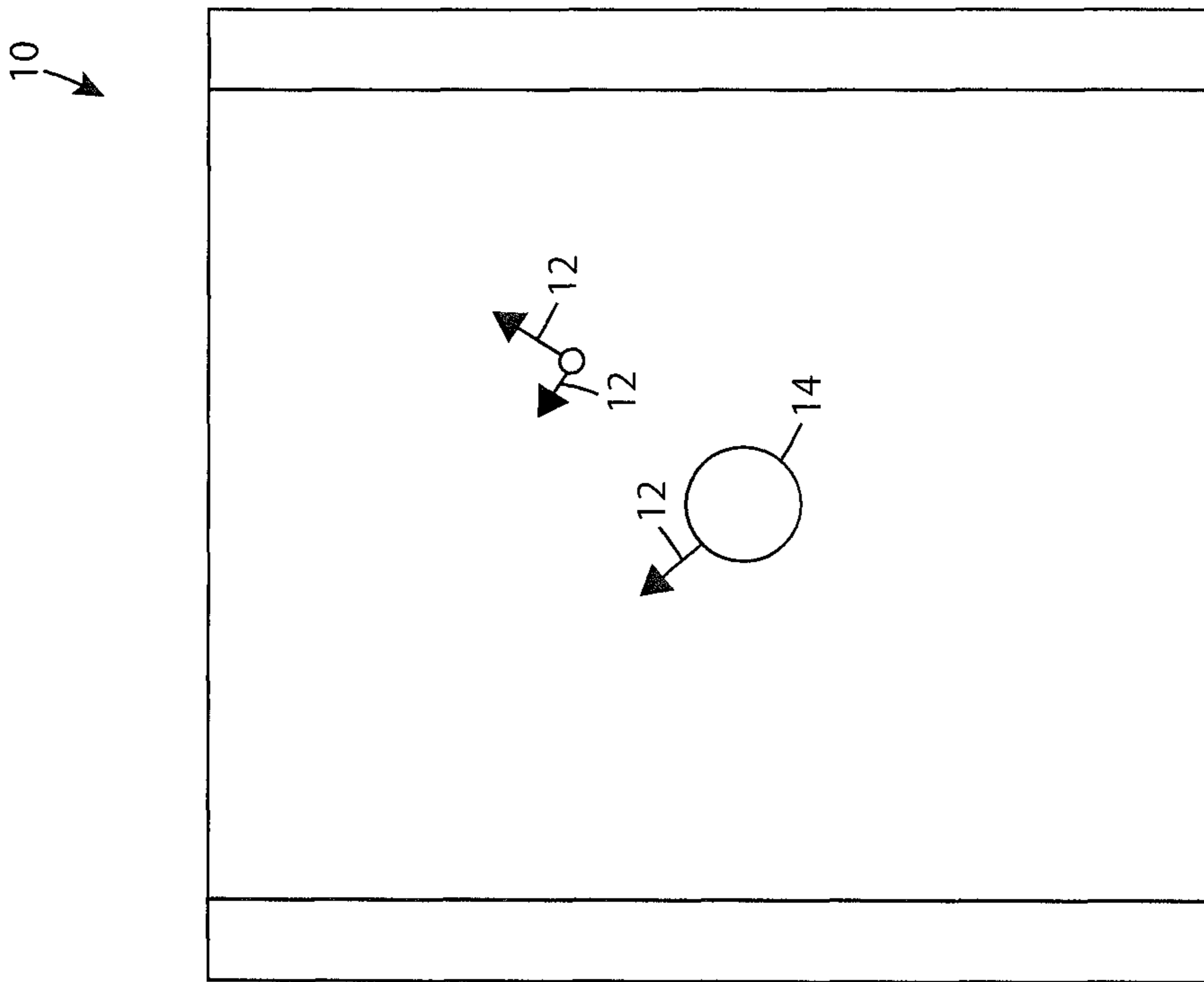


FIG. 35

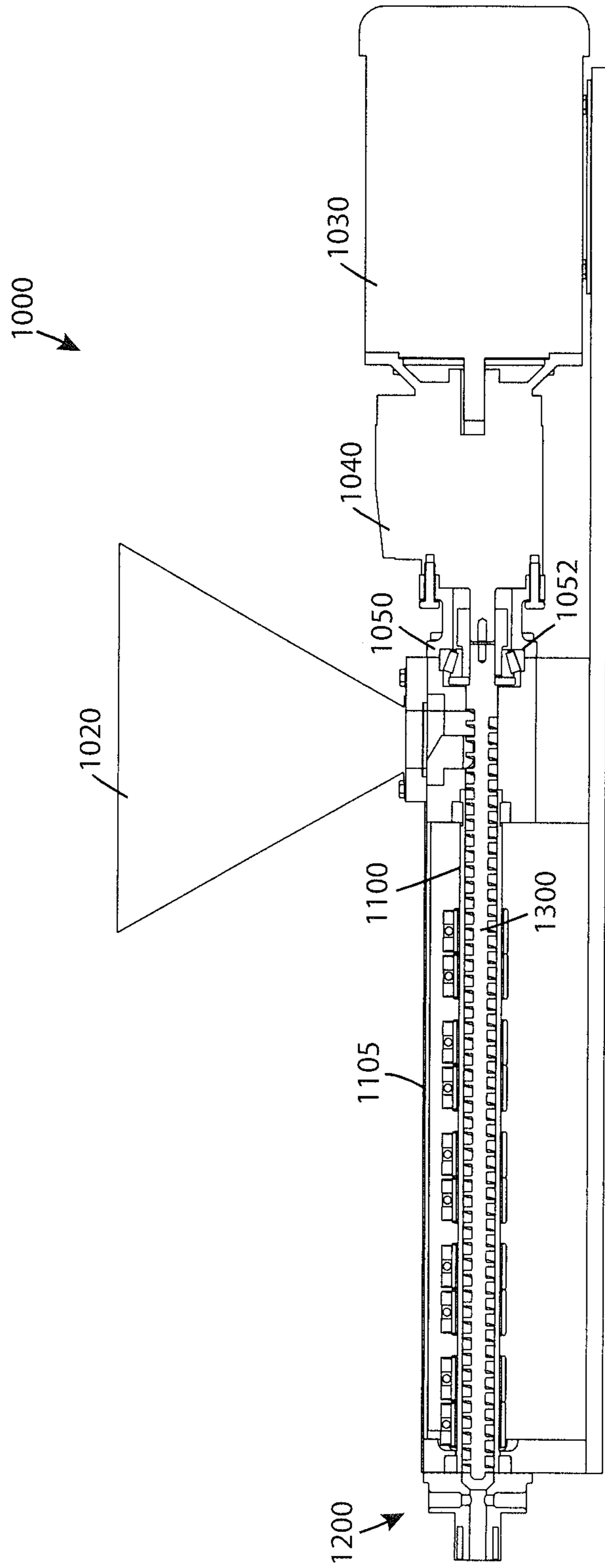


FIG. 36

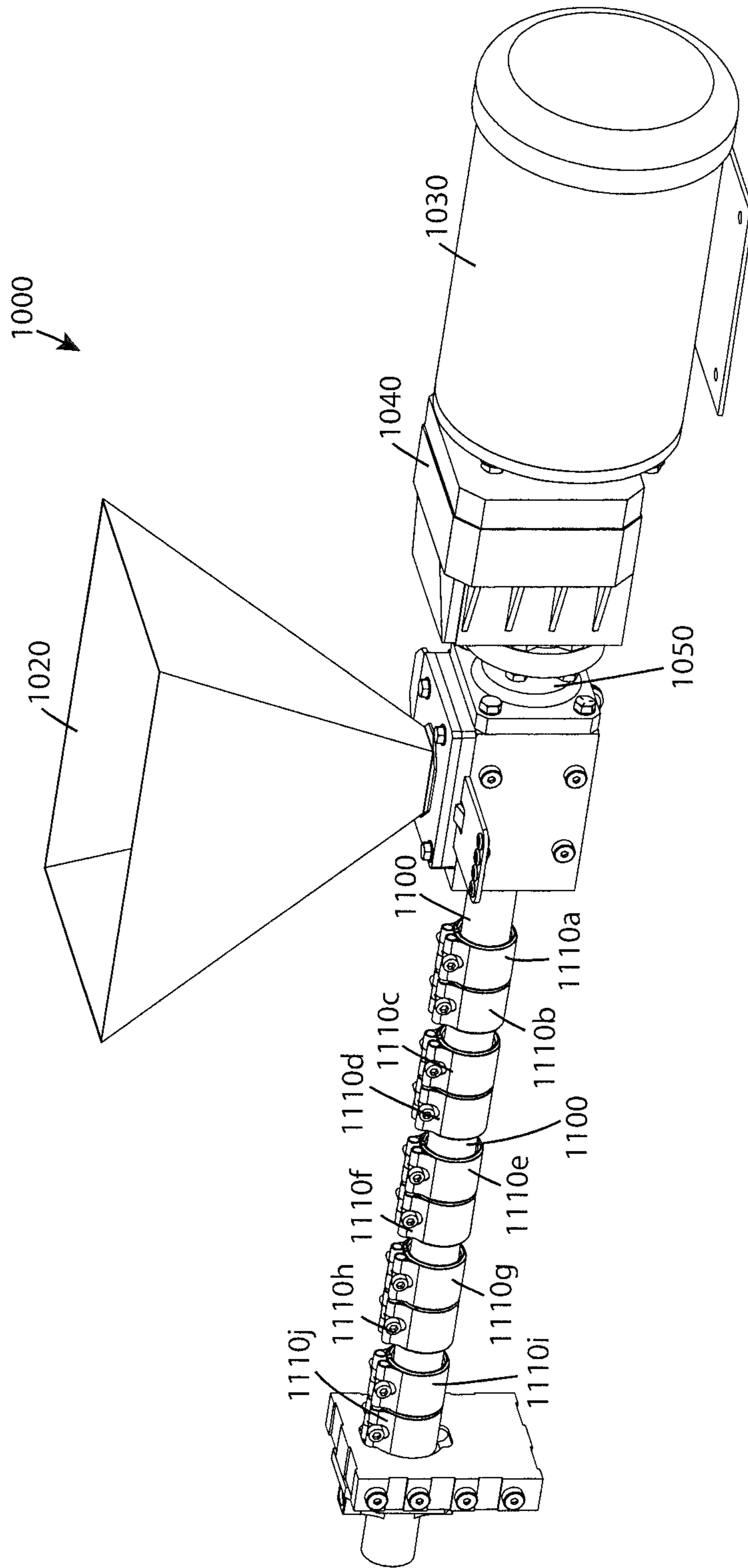


FIG. 37

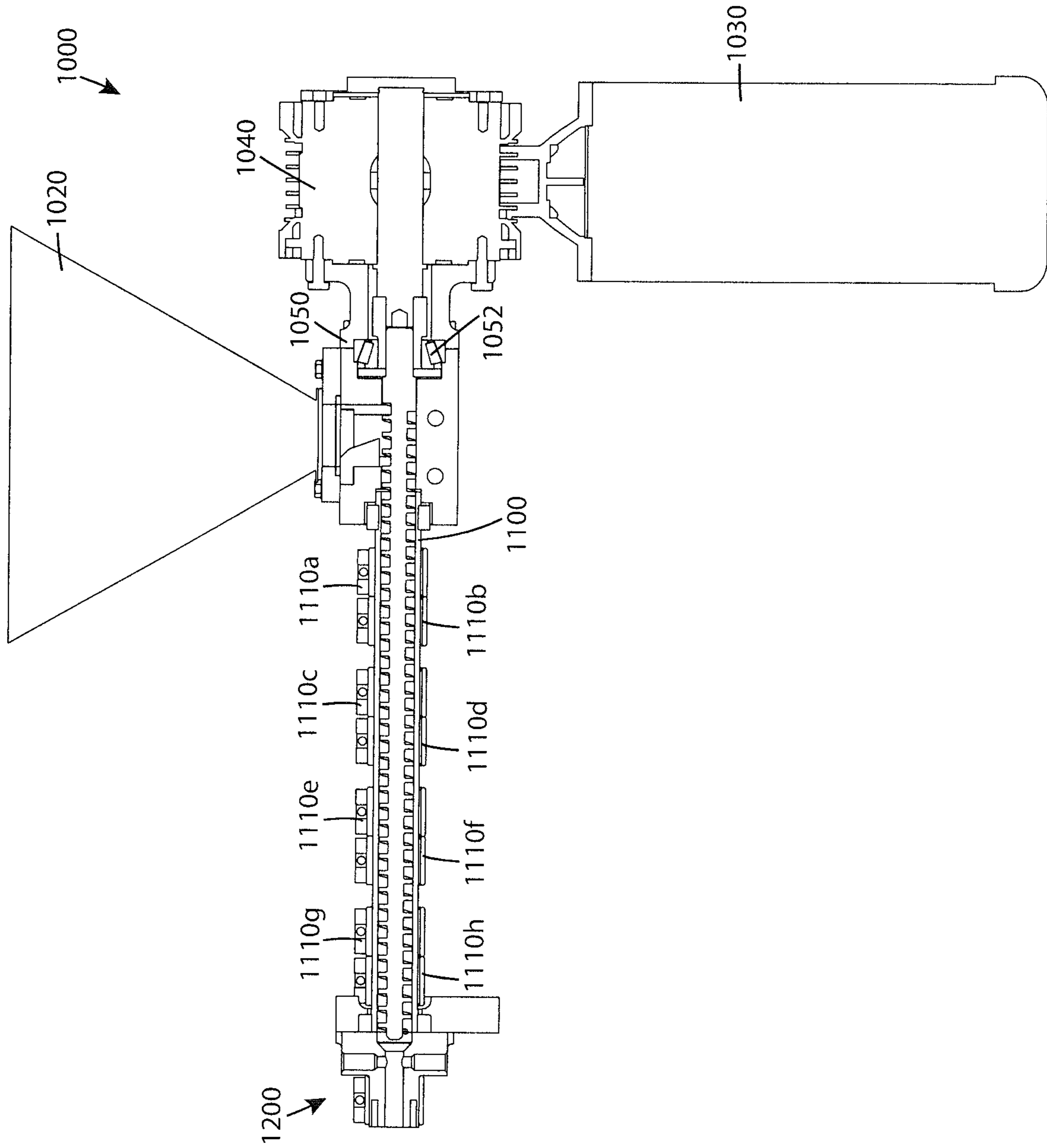


FIG. 38

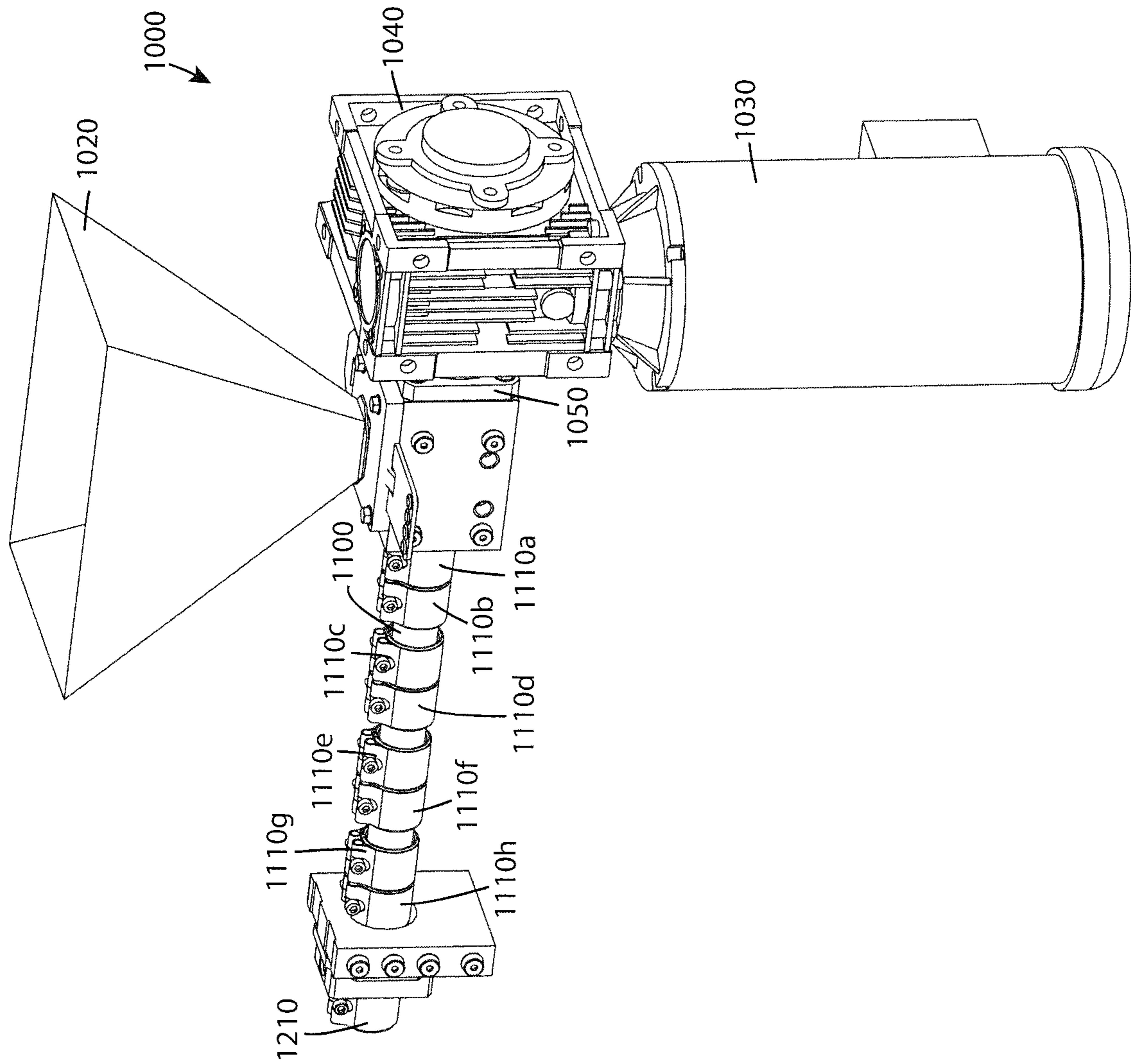


FIG. 39

# 1

## EXTRUDER

### FIELD

This disclosure relates generally to extruders, and more specifically to extruders for extruding a plastic or thermo-plastic material. This disclosure also relates to methods using one or more extruders to produce an extruded or molded plastic part.

### INTRODUCTION

Extruders are typically used to heat and melt a solid input material (e.g. a plastic, or thermoplastic material) and extrude the material in a flowable, or melted state. The extruded, or output, material may be directed through a form or die while it cools and solidifies to form an elongate plastic component having a cross-sectional profile defined by the form or die. Alternatively, the output material may be directed into a mold where it is then cooled and solidifies to form a molded component having a shape defined by the mold.

One source of the heat provided to raise the temperature of the conveyed plastic material as it passes through the extrusion or injection barrel is mechanical shear heating. In shear heating, the plastic material is subjected to shearing or stretching between a rotating screw and a stationary barrel, often while under relatively high pressures (e.g. 2,000 pounds per square inch (psi), up to 30,000 psi or higher), causing heat to develop in the material. Typically, shear heating is a significant source of heat. For example, it may be considered preferable to provide about 50% or more of the heat required to melt the conveyed plastic material through shear heating.

While shear heating is effective at raising the temperature of the plastic material, there may be one or more disadvantages. For example, excessive shearing of the plastic material may lead to a physical and/or chemical degradation of the polymer molecules within the plastic material.

### SUMMARY

The following introduction is provided to introduce the reader to the more detailed discussion to follow. The introduction is not intended to limit or define any claimed or as yet unclaimed invention. One or more inventions may reside in any combination or sub-combination of the elements or process steps disclosed in any part of this document including its claims and figures.

In accordance with one aspect of this disclosure, an extruder is configured to reduce or minimize the amount of heat imparted to the conveyed plastic material by shear heating. For example, an extruder having a relatively high heat transfer rate through the barrel wall may be provided. The heat transfer rate through the barrel wall may be increased by providing an extrusion barrel made of a material with a high thermal conductivity, and/or by providing a relatively thin-walled extrusion barrel. An increased heat transfer rate through the barrel wall may allow more heat to be transferred through the barrel wall for a given unit of time. Accordingly, more heat per unit time can be transferred to the plastic material being conveyed through the extrusion barrel using one or more barrel heaters, which decreases the amount of shear heating required to melt the plastic material.

Alternatively, or additionally, the geometry of the extrusion barrel and the extrusion screw may be configured to reduce the pressure of the plastic material being conveyed

# 2

through the extrusion barrel, thereby reducing the amount of shear heating. For example, the extrusion barrel and/or extrusion screw may be configured to provide a constant, or decreasing, volumetric compression ratio along the length of the extrusion barrel. Accordingly, plastic material being conveyed through the extrusion barrel may be subjected to pressures sufficient to prevent backflow through the barrel (e.g., if a mold is being fed by the extruder, then the pressure in the barrel may be selected to enable the extruder to fill the mold without backflow through the extruder) and/or to mix material being conveyed through the extrusion barrel if two or more different materials are present.

An advantage of this design is that a thinner walled barrel may be utilized, which enhances the radial thermal conductivity of the barrel. This enables a greater proportion of the heat to be provided from heaters provided on the barrel and less reliance provided from providing heat interior of the barrel (e.g., shear mixing).

The flow rate through the extruder may be substantially lower than traditional high pressure extruders. Therefore a single extruder according to this disclosure may have a lower through put of material per unit time than traditional high pressure extruders. However, by reducing the pressure internal of the barrel, the barrel may be lighter and have a substantially reduced cost. Accordingly, instead of using a single traditional extruder to make a desired number of parts, a plurality of extruders may be obtained, which have the same capacity as a single standard extruder, at the same or lower capital cost.

In accordance with this broad aspect, there is provided an extruder comprising:

- a) a barrel extending from a feed inlet end to an extruder outlet end, the barrel having an inner surface, an outer surface and a wall thickness between the inner and outer surfaces;
- b) at least one heating member provided on (e.g. positioned exterior to and/or interior of) the barrel; and
- c) a screw drive motor drivingly connected to a rotatably mounted screw positioned within the barrel, the screw having a length and a flight thereon, whereby the screw is rotatable at various revolutions per minute (RPM); wherein the screw and barrel are sized such that less than 40%, 30%, 25%, 20%, 15%, 10% or 5% of the heat that is introduced into the material in the barrel is supplied by shearing the material and the remainder is supplied by the at least one heating element.

In some embodiments, a flight clearance between the inner surface of the barrel and an outer extent of the flight is selected such that less than 40%, 30%, 25%, 20%, 15%, 10%, or 5% of the heat that is introduced into the material in the barrel is supplied by shearing the material and the remainder is supplied by the at least one heating element.

In accordance with this broad aspect, there is also provided an extruder comprising:

- a) a barrel extending from a feed inlet end to an extruder outlet end, the barrel having an inner surface, an outer surface and a wall thickness between the inner and outer surfaces;
- b) at least one heating member positioned exterior to the barrel;
- c) a screw drive motor drivingly connected to a rotatably mounted screw positioned within the barrel, the screw having a length and a flight thereon, wherein a flight clearance between the inner surface of the barrel and an outer extent of the flight is from 0.001 to 0.08 inches, optionally, 0.005 to 0.06 inches, 0.005 to 0.04 inches or 0.02 to 0.04 inches; and at least one of the following:

- i) the barrel has a wall thickness of from 0.01 to 0.375 inches, optionally 0.04 to 0.25 inches;
- ii) the volumetric compression ratio, defined as a channel depth of a feed section of the extruder and the channel depth in a metering section of the extruder, is  $\leq 1$ ;
- iii) the barrel comprises at least one of aluminum and copper;
- iv) a flight depth from an outer lateral extent of the flight to an inner lateral extent of a flight along the length of the screw is generally constant;
- v) a flight depth from an outer lateral extent of the flight to an inner lateral extent of a flight along the length of the screw is from 0.2-0.5 inches;
- vi) a land portion of the screw between two adjacent threads of a flight is from 0.125 to 0.5 inches, optionally 0.125 to 0.375 inches or optionally 0.125 to 0.25 inches;
- vii) a land portion of the outward lateral extent of the flight of the screw is between two adjacent threads of a flight is from 0.25 to 0.5 inches;
- viii) the barrel has a section in which solid feed material is liquefied, that is operated at a pressure of 1-1000, psi, optionally, 1-500 psi, 10-400 psi, or 40-200 psi;
- ix) at least 80% of energy provided to the extruder is used to produce heat, optionally, at least 85%, at least 90% or at least 95%; and,
- x) the screw and barrel are sized such that at least 60% of heat that is introduced into material in the barrel is supplied by the at least one heating member and less than 40% of the heat that is introduced into the material in the barrel is supplied by shearing the material.

In accordance with this broad aspect, there is also provided an extruder comprising:

- a) a barrel extending from a feed inlet end to an extruder outlet end, the barrel having an inner surface, an outer surface and a wall thickness between the inner and outer surfaces;
- b) at least one heating member positioned exterior to the barrel;
- c) a screw drive motor drivingly connected to a rotatably mounted screw positioned within the barrel, the screw having a length and a flight thereon, whereby the screw is rotatable at various revolutions per minute (RPM); and
- d) a controller operably connected to the screw drive motor to adjust the RPM of the screw based upon a temperature of material passing through and/or being extruded from the barrel.

In accordance with this broad aspect, there is also provided a method of operating an extruder comprising adjusting the RPM of a screw positioned in a barrel of the extruder based upon a temperature of material passing through and/or being extruded from the barrel.

In some embodiments, the controller is operably connected to the screw drive motor to increase the RPM of the screw subsequent to the temperature of the material passing through and/or being extruded from the barrel increasing above a predetermined value. In some embodiments, the controller is operably connected to the screw drive motor to decrease the RPM of the screw subsequent to the temperature of the material passing through and/or being extruded from the barrel decreasing below a predetermined value. Accordingly, the screw may be rotated at a lower RPM when the material in the extruder is cool, so as to reduce the pressure in the barrel and allow more time for the heater(s)

provided on the barrel to heat the material in the barrel. Once the temperature reaches a desired or preset value, the screw RPM may be increased without increasing the pressure exerted on the barrel.

In some embodiments, the barrel has a wall thickness of from 0.01 to 0.375 inches, optionally from 0.04 to 0.25 inches.

In some embodiments, a flight clearance between the inner surface of the barrel and an outer extent of the flight is from 0.001 to 0.08 inches, optionally, 0.005 to 0.06 inches, 0.005 to 0.04 inches or 0.02 to 0.04 inches.

In some embodiments, the flight clearance remains constant or increases from the feed inlet end to the extruder outlet end.

In some embodiments, the volumetric compression ratio, defined as a channel depth of a feed section of the extruder and the channel depth in a metering section of the extruder, is  $\leq 1$ .

In some embodiments, the barrel comprises at least one of aluminum, copper, steel and stainless steel, and preferably aluminum and/or copper.

In some embodiments, a flight depth from an outer lateral extent of the flight to an inner lateral extent of a flight along the length of the screw is generally constant.

In some embodiments, a flight depth from an outer lateral extent of the flight to an inner lateral extent of a flight along the length of the screw is from 0.2-0.5 inches.

In some embodiments, a land portion of the screw between two adjacent threads of a flight is from 0.125 to 0.5 inches, optionally 0.125 to 0.375 inches or optionally 0.125 to 0.25 inches.

In some embodiments, a land portion of the outward lateral extent of the flight of the screw between two adjacent threads of a flight is from 0.25 to 0.5 inches.

In some embodiments, the barrel has a section in which solid feed material is liquefied, that is operated at a pressure of 1-1000, psi, optionally, 1-500 psi, 10-400 psi, or 40-200 psi.

In some embodiments, at least 80% of energy provided to the extruder is used to produce heat, optionally, at least 85%, at least 90%, or at least 95%.

In some embodiments, the screw and barrel are sized such that at least 60%, 70%, 80% or 90% of heat that is introduced into material in the barrel is supplied by the at least one heating member and less than 40%, 30%, 20% or 10% of the heat that is introduced into the material in the barrel is supplied by shearing the material.

In some embodiments, the screw comprises a first screw section and a second screw section and a thermal insulation member is provided between the first and second screw sections.

In some embodiments, the first screw section is made of a material having lower thermal conductivity than the second screw section.

In some embodiments, the first screw section is provided in a feed section of the extruder and the second screw section is provided downstream of the feed section of the extruder.

In some embodiments, the screw comprises a first screw section and a second screw section and the first screw section is made of a material having lower thermal conductivity than the second screw section.

In accordance with another aspect of this disclosure, an extruder may be used to fill a mold in a molding process. The plastic material output from the extruder may be introduced into the mold at a relatively low pressure, such as the operating pressure of an extruder according to this disclosure, and once the mold is full or partially full, e.g., 75%,

80%, 85%, 90%, 95% or more full, a pressurization member may be used to increase the pressure of the material in the mold.

In typical extrusion or injection molding operations, large plastic components are produced using machines capable of relatively high injection pressures (e.g., 5,000 to 20,000 psi), which are often large, expensive, and may be characterized as being relatively energy inefficient.

Instead of increasing the operating pressure of the extruder, apparatus and methods disclosed herein employ a pressurization member other than extruder to apply pressure to the material within the mold cavity to ensure proper filling of the mold. Such an arrangement allows for large and/or complex mold cavities to be filled using a relatively low-pressure output from an extruder, and subsequently subjected to higher pressures that may be required or desirable to properly fill the mold and/or to compress the flowable material within the mold cavity to improve one or more physical properties of the molded component.

As the plastic material exiting the extruder is in a flowable state due to its elevated temperature, if the flowable material is allowed to cool, it will begin to solidify, which may not be desirable until the mold has been completely filled and pressurized by the pressurization member. Accordingly, the mold preferably includes one or more heating elements to maintain the plastic material within the mold cavity at an elevated temperature during the mold filling process.

Another possible advantage of this approach relates to the production of molded components with relatively complicated geometries, and/or the production of relatively large molded components. In this respect, since the molding process outlined above does not rely on the output or operating pressure of the extrusion barrel to provide the maximum pressure on the flowable material within the mold cavity (instead relying on one or more pressurization members), such a molding process can be 'scaled up' to provide higher molding pressures (e.g. for use with molds with relatively complex internal cavities and/or with molds for relatively large molded components) without having to 'scale up' the operating pressure of the extruder.

In accordance with this broad aspect, there is provided an extruder and molding assembly comprising an extruder positioned upstream from a mold, the mold having a mold cavity and a separate pressurization member fluidly connected to the mold cavity (e.g., a piston, source of pressurized fluid, etc. to drive some of the extrudate into the mold) wherein the extruder is operable at a first pressure to fill at least a majority of the mold cavity and the pressurization member is operable to fill a remainder of the mold cavity.

In some embodiments, the assembly further comprises an isolation mechanism (e.g., a valve, solidifying part of the extruded material between the mold and the extruder) operable to isolate an interior of the extruder containing a screw from the mold cavity.

In some embodiments, the extruder is operable at a pressure of 1-500 psi when filing the mold and the pressurization member is operable at a pressure above 500 psi to fill the remainder of the mold cavity.

In some embodiments, the extruder is operable at a pressure of 10-200 psi when filing the mold and the pressurization member is operable at a pressure above 1000 psi to fill the remainder of the mold cavity.

In some embodiments, the assembly further comprises a storage chamber positioned between the pressurization member and the mold cavity whereby operation of the pressurization member drives material from the storage chamber into the mold cavity.

In some embodiments, the storage chamber is fluidically connected to an outlet end of the extruder whereby the extruder fills the storage chamber concurrently with filling the mold cavity.

In some embodiments, the storage chamber is positioned on an opposite side of the mold cavity to the extruder.

In some embodiments, the isolation member comprises a valve.

In some embodiments, the isolation member comprises a cooling chamber between the mold cavity and the extruder whereby liquefied extrudate is solidified in the cooling chamber prior to operation of the pressurization member.

In some embodiments, the assembly further comprises a mold heater.

Also in accordance with this broad aspect, there is also provided a method of operating an extruder and molding assembly having a mold cavity comprising using the extruder to fill at least a majority of the mold cavity at a first pressure and using a pressurization member which is fluidically connected to the mold cavity at an alternate location than the extruder to fill a remainder of the mold cavity.

In some embodiments, the method further comprises isolating an interior of the extruder containing a screw from the mold cavity prior to using the pressurization member.

In some embodiments, the method further comprises operating the extruder at a pressure of 1-500 psi when filing the mold and operating the pressurization member at a pressure above 500 psi to fill the remainder of the mold cavity.

In some embodiments, the method further comprises operating the extruder at a pressure of 10-200 psi when filing the mold and operating the pressurization member at a pressure above 1,000 psi to fill the remainder of the mold cavity.

In some embodiments, operation of the extruder also fills a storage chamber positioned between the pressurization member and the mold cavity and operation of the pressurization member drives material from the storage chamber into the mold cavity.

In some embodiments, operation of the extruder fills the storage chamber concurrently with filling the mold cavity.

In some embodiments, liquefied extrudate is solidified in a cooling chamber positioned between the extruder and the mold cavity prior to operation of the pressurization member.

In some embodiments, the mold is heated during at least a portion of the filling of at least a majority of the mold cavity at the first pressure.

In some embodiments, the mold is at an elevated temperature during the filling of at least a majority of the mold cavity at the first pressure whereby plastic extruded into the mold is in a flowable state when the pressurization member is actuated.

In accordance with another aspect of this disclosure, an extruder may be used to mold a component without converging or diverging the flowable material after it has exited the extrusion barrel. In accordance with this aspect, the plastic material output from an extruder barrel is directed into an annular mold cavity having an annular thickness substantially equal to the channel depth at the output end of the extrusion barrel.

In accordance with this broad aspect, there is provided an extruder and molding assembly comprising:

- a) a mold having a mold cavity and a passage extending from a mold inlet to the mold cavity, the passage defining a mold annular gap; and,
- b) an extruder positioned upstream from the mold, the extruder having a barrel outlet and a screw, the screw



spaced from an inner surface of the barrel to define a barrel annular gap between a lateral outer extent of a flight provided on the screw and the inner surface of the barrel;

wherein the barrel annular gap is substantially the same size as the mold annular gap.

In some embodiments, the passage has an absence of a spider.

In some embodiments, the mold is a mold for a pipe.

In some embodiments, the mold is a mold for a pipe having a diameter greater than 0.5 inches.

In accordance with this broad aspect, there is also provided a method of operating an extruder and molding assembly having a mold cavity comprising flowing an extrudate generally linearly from a barrel outlet of the extruder into the mold cavity.

In some embodiments, the method further comprises using the mold cavity to produce a section of pipe.

In some embodiments, the method further comprises using the mold cavity to produce a section of pipe having a diameter greater than 0.5 inches.

In typical injection molding operations, the flowable material is injected into the mold cavity at relatively high pressures (e.g., 5,000 to 20,000 psi) and flow rates (e.g., 2 to 20 ounces per second). A possible downside of such a process is the potential for the introduction of strain orientation lines within the plastic component. Strain orientation lines may cause (or be symptomatic of) a molded component to having a lower strength than an otherwise similar component with less (or no) strain orientation. In some applications, it may be considered necessary to subject a molded component to one or more post molding strain relieving operations, to ensure the molded plastic component is not structurally compromised by the strain orientation introduced during the molding process.

In another broad aspect, a molded plastic component produced by the processes disclosed herein may have reduced strain orientation as compared to components produced by typical injection molding processes.

Since the molding processes disclosed herein fill the mold cavity at a relatively low pressure and material flow rate, the potential for strain orientation lines to be formed within the molded component may be reduced or eliminated. Accordingly, such a process may produce a molded component with fewer (or no) strain orientation lines without any post molding treatment or a milder post molding treatment. Advantageously, such a component may not require any post molding strain relieving operations.

In accordance with this broad aspect, there is provided a plastic molded part wherein plastic in a portion of the part has an absence of strain orientation lines wherein the part is not subjected to a post molding stress relieving operation.

In some embodiments, at least 50%, 60%, 70%, 75%, 80%, 90% or more of the part has an absence of strain orientation lines.

In accordance with this broad aspect, there is also provided a method of molding a plastic part comprising introducing a first portion of the plastic into a mold cavity at a first pressure and rate such that the first portion of the plastic has an absence of strain orientation lines wherein the part is not subjected to a post molding stress relieving operation.

In some embodiments, at least 50%, 60%, 70%, 75%, 80%, 90% or more of the plastic is introduced into the mold cavity at a first pressure and rate such that the first portion of the plastic has an absence of strain orientation lines.

In some embodiments, at least 50%, 60%, 70%, 75%, 80%, 90% or more of the plastic is introduced into the mold cavity at a pressure less than 400 psi.

In some embodiments, a remainder of the plastic is introduced into the mold cavity at a pressure greater than 500 psi.

In some embodiments, a remainder of the plastic is introduced into the mold cavity at a pressure greater than 1,000 psi.

It will be appreciated by a person skilled in the art that a method or apparatus disclosed herein may embody any one or more of the features contained herein and that the features may be used in any particular combination or sub-combination.

These and other aspects and features of various embodiments will be described in greater detail below.

#### BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the described embodiments and to show more clearly how they may be carried into effect, reference will now be made, by way of example, to the accompanying drawings in which:

FIG. 1A is a perspective view of an extruder in accordance with one embodiment;

FIG. 1B is a perspective view of the extruder of FIG. 1, with the outer housing removed;

FIG. 2 is a rear perspective view of the extruder of FIG. 1, with the outer housing removed;

FIG. 3 is a perspective cross-section view of the extruder of FIG. 1;

FIG. 4 is a cross-section view of the extruder barrel of FIG. 1;

FIG. 5 is a cross-section view of an extruder barrel in accordance with another embodiment, with portions of the barrel walls being reinforced;

FIG. 6 is a cross-section view of an extruder barrel in accordance with another embodiment, with the wall thickness increasing from the inlet end to the outlet end of the barrel;

FIG. 7 is a cross-section view of an extruder barrel in accordance with another embodiment, with the wall thickness increasing step-wise from the inlet end to the outlet end of the barrel;

FIG. 8 is a cross-section view of an extruder barrel in accordance with another embodiment, with a reinforcing band at the outlet end of the barrel;

FIG. 9 is a cross-section view of an extruder barrel in accordance with another embodiment, with the wall thickness increasing from the inlet end to the outlet end of the barrel, and with the inner walls of the barrel diverging from the inlet end to the outlet end of the barrel;

FIG. 10 is a cross-section view of an extruder barrel in accordance with another embodiment, with the wall thickness increasing step-wise from the inlet end to the outlet end of the barrel, and with the inner walls of the barrel diverging from the inlet end to the outlet end of the barrel;

FIG. 11 is a cross-section view of a prior art injection barrel and screw;

FIG. 12 is a cross-section view of an extrusion screw in accordance with one embodiment;

FIG. 13 is a cross-section view, to scale, of an extrusion screw in a thin-walled extrusion barrel in accordance with one embodiment;

FIG. 14 is a cross-section view, to scale, of an extrusion screw in a thin-walled extruder barrel in accordance with another embodiment;

FIG. 15 is a cross-section view, to scale, of an extrusion screw in a thin-walled extruder barrel in accordance with another embodiment;

FIG. 16 is a cross-section view, to scale, of an extrusion screw in a thin-walled extruder barrel in accordance with another embodiment;

FIG. 17 is a cross-section view, to scale, of an extrusion screw in a thin-walled extruder barrel in accordance with another embodiment;

FIG. 18 is a cross-section view, to scale, of an extrusion screw in a thin-walled extruder barrel in accordance with another embodiment;

FIG. 19 is a cross-section view, to scale, of an extrusion screw in accordance with another embodiment;

FIG. 20 is an end section view, to scale, of two different extruder barrels;

FIG. 21 is an end section view of a multi-start extrusion screw;

FIG. 22 is an end section view of a standard extrusion screw;

FIG. 23A is a cross-section view of a three-piece extrusion screw in accordance with one embodiment;

FIG. 23B is a cross-section view of a two-piece extrusion screw in accordance with one embodiment;

FIG. 24 is a cross-section view of a three-piece extrusion screw in accordance with another embodiment;

FIGS. 25A-25C are schematic circuit drawings of an electrical control system for the extruder of FIG. 1, in accordance with one embodiment;

FIG. 26 is a logic flow diagram for the control of the extruder of FIG. 1, in accordance with one embodiment;

FIG. 27 is a schematic example plot of both temperature and screw speed versus time;

FIGS. 28A-28D are schematic cross-section views of an extruder and a pressurization member coupled to a mold, in accordance with one embodiment;

FIGS. 28E-28G are schematic cross-section views of an extruder and a pressurization member coupled to a mold, in accordance with another embodiment;

FIG. 29 is a schematic example plot of pressure versus time;

FIGS. 30A-30B are schematic cross-section views of three injection units and a pressurization member coupled to a mold, with a weight sensor positioned below the mold;

FIG. 31 is a cross-section view of a prior art injection unit nozzle coupled to a mold having a cylindrical mold cavity;

FIG. 32 is a cross-section view of an extruder coupled to a mold having a cylindrical mold cavity in accordance with one embodiment;

FIG. 33A is a cross-section view of an extruder coupled to each end of a mold having a cylindrical mold cavity in accordance with one embodiment;

FIG. 33B is a cross-section view of an extruder coupled to each end of a mold having a cylindrical mold cavity in accordance with another embodiment;

FIG. 34 is a schematic illustration of a molded plastic part, showing strain orientation lines resulting from a typical prior art injection molding process;

FIG. 35 is a schematic illustration of a molded plastic part produced by the extrusion processes described herein;

FIG. 36 is a cross-section view of an extruder in accordance with another embodiment;

FIG. 37 is a perspective view of the extruder of FIG. 36;

FIG. 38 is a cross-section view of an extruder in accordance with another embodiment; and

FIG. 39 is a perspective view of the extruder of FIG. 38.

The drawings included herewith are for illustrating various examples of articles, methods, and apparatuses of the teaching of the present specification and are not intended to limit the scope of what is taught in any way.

## DESCRIPTION OF EXAMPLE EMBODIMENTS

Various apparatuses, methods and compositions are described below to provide an example of an embodiment of each claimed invention. No embodiment described below limits any claimed invention and any claimed invention may cover apparatuses and methods that differ from those described below. The claimed inventions are not limited to apparatuses, methods and compositions having all of the features of any one apparatus, method or composition described below or to features common to multiple or all of the apparatuses, methods or compositions described below. It is possible that an apparatus, method or composition described below is not an embodiment of any claimed invention. Any invention disclosed in an apparatus, method or composition described below that is not claimed in this document may be the subject matter of another protective instrument, for example, a continuing patent application, and the applicant(s), inventor(s) and/or owner(s) do not intend to abandon, disclaim, or dedicate to the public any such invention by its disclosure in this document.

The apparatuses, methods and compositions may be used to extrude and/or mold various materials, such as a plastic material and optionally a thermoplastic material. The thermoplastic material may be one or more of acrylonitrile butadiene styrene (ABS), polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), polyethylene (PE), low molecular weight PE, high density PE, ultra high molecular weight PE, polyethylene terephthalate (PET), polystyrene (PS), polycarbonate (PC), acrylic, polypropylene (PP), polybutylene terephthalate (PBT), polyvinyl acetate, ethylene-vinyl acetate (EVA), or the like. Preferably, the thermoplastic material is one or more of PVC and CPVC.

### General Description of Preferred Embodiments Utilizing Combinations of Various Aspects

FIGS. 1A to 3 exemplify an extruder, referred to generally as 1000. Extruder 1000 may be used to heat and melt an input material (e.g. a plastic, or thermoplastic material which may be solid) and extrude the material in a flowable, or melted state. The extruded, or output, material may be used to fill a mold in a molding process, as will be discussed further subsequently. It will be appreciated that extruder 1000 may receive any material input known in the extruder art.

As shown in FIG. 1A, extruder 1000 may be enclosed in a housing, which in the illustrated embodiment includes a plurality of solid panels 1005 and perforated panels 1003. Solid panels 1005 may have one or more cutouts or apertures 1007 to provide access to components inside the housing. It will be appreciated that the housing may be made from any suitable material (e.g. metal, plastic, and the like), and that in alternate embodiments the housing may be formed of more or fewer panels. In some embodiments, an outer housing may not be provided.

Extruder 1000 may include one or more user input devices that allow a user to initiate and/or control the operation of the extruder. For example, user input devices may include one or more of power switches 1012, 1014, emergency stop 1016; and a display 1018, which may be a touch screen display. Extruder 1000 may also include one or more user output devices that allows a user to monitor the operation of the extruder. For example, user output devices

## 11

may display **1018**, and/or one or more audio and/or visual output devices, such as lights, buzzers, speakers, and the like (not shown).

Turning to FIGS. **1B** to **3**, extruder **1000** also includes an input member for introducing the material into the extruder. The input member may be an input hopper **1020** for receiving the input material (e.g. a solid pelletized plastic). As perhaps best seen in FIG. **3**, material received in hopper **1020** is directed through a feedthroat **1062** in a feed block **1060** where it is introduced into the channels of an extrusion screw **1300**. Rotation of the screw **1300** advances or conveys the pelletized input material from a first, or input end **1302** of the extrusion screw towards a second, or output end **1034** of the extrusion screw **1300**, thereby conveying the material through an extrusion barrel **1100** from a first, or input end **1102** of the barrel to a second, or output end **1104** of the barrel.

As the material is conveyed through the extrusion barrel **1100** by the screw **1300**, heat from one or more (e.g., a plurality of) heating elements **1110a-f** positioned about the outer surface **1108** of the extrusion barrel **1100** is transferred through the extrusion barrel wall to the conveyed material via the inner barrel surface **1106**, raising the temperature of the material and thereby causing the material to transition to a flowable, or melted state. It will be appreciated that more or fewer heating elements **1110** may be provided in alternative embodiments.

The input material continues to be conveyed by the extrusion screw **1300** towards the output end **1104** of the extrusion barrel **1100**, where it is ejected as a flowable liquid material. In the example illustrated in FIG. **3**, the material is ejected from the extruder via an ejection nozzle **1200**. More specifically, the flowable material exits the output end **1104** of the extruder barrel **1100** and enters the input end **1202** of the nozzle **1200**, flows through the nozzle, and is ejected from the output end **1204** of the nozzle.

As exemplified, a heating element **1210** may also be positioned about the outer surface of output nozzle **1200**. Heat from heating element **1210** is transferred through the nozzle body to the conveyed material via the inner nozzle surfaces, and may be used to control the temperature of the material flowing within the output nozzle **1200**. It will be appreciated that more or fewer (i.e. zero) nozzle heating elements **1210** may be provided in alternative embodiments.

The extrusion screw **1300** is rotated by screw drive motor **1030**. Screw drive motor **1030** is preferably an electric motor, such as an alternating current (AC) motor (asynchronous or synchronous), a direct current (DC) motor, and the like. The screw drive motor **1030** is drivingly coupled to the extrusion screw directly or via a drive transmission member, e.g., an optional gearbox **1040**, which is preferably a reduction gearbox. The use of a reduction gearbox allows the use of a higher-speed, lower power motor, which may be more efficient and/or less expensive to purchase and/or operate than a lower speed, higher power motor.

In FIGS. **1A** to **3**, the extrusion screw **1300** is coupled to the gearbox **1040** via a screw mounting member **1044**. Screw **1300** may be coupled to screw mounting member **1044** using any suitable method known in the art, such as a threaded coupling, a keyed joint, and the like. Screw mounting member **1044** is itself coupled to gearbox **1040** using any suitable method, which may be the same or different than the coupling between screw **1300** and screw mounting member **1044**.

As illustrated in FIGS. **1A** to **3**, the input and output to gearbox **1040** are at right angles, allowing motor **1030** to be positioned at an angle to extrusion screw **1300**. Alternatively,

## 12

as shown in FIGS. **36** and **37**, the input and output to gearbox **1040** may be on opposite sides of the gearbox, allowing motor **1030** to be positioned generally in-line with extrusion screw **1300**. Alternatively, as shown in FIGS. **38** and **39**, the input and output to gearbox **1040** may be at right angles, but motor **1030** may be positioned below extrusion screw **1300**. It will be appreciated that gearbox **1040** and/or one or more mechanical or viscous couplings may be provided to allow any suitable relative position of motor **1030** and extrusion screw **1300**.

Extrusion screw **1300** may be rotationally supported within extrusion barrel **1100** by the gearbox **1040** (or motor **1030**, if a gearbox is not provided) and/or by one or more bearings, which may include at least one end thrust bearing **1050**. End thrust bearing **1050** is configured to allow rotation of screw **1300**, and to resist the expected axial forces exerted on screw **1300** in a direction towards the input end **1302** of the extrusion screw (e.g. due to backpressure of the material being conveyed by screw **1300**, and/or a partial or complete obstruction of output nozzle **1200**).

As exemplified, extrusion screw **1300** may be hollow. Alternately, or in addition, the output end **1304** of extrusion screw **1300** may be provided with a nose cone **1310**. Nose cone **1310** may assist with directing the output material from the output end **1104** of the extruder barrel **1100** to the input **1202** of nozzle **1200**. Nose cone **1310** is preferably mounted to extrusion screw **1300** in a manner that allows it to be axially advanced and retracted relative to screw **1300**, e.g. using an optional knockout rod **1042** that extends through the hollow extrusion screw and the screw mounting member **1044**. The ability to axially advance nose cone **1310** using knockout rod **1042** may be useful when clearing a blockage of output material (e.g. when removing a clogged nozzle **1200**).

## Extrusion Barrel

FIGS. **4** to **10** exemplify different embodiments of an extrusion barrel **1100**, each of which may be used with the extruder **1000** disclosed herein. Extrusion barrel **1100** comprises an elongate metal conduit extending between a first or inlet end **1102** and a second or outlet end **1104**. The wall of extrusion barrel **1100** has an inner surface **1106** and an outer surface **1108**. In use, an extrusion screw **1300** is positioned interior of the extrusion barrel, and as noted above, the material to be extruded may be conveyed within the extrusion barrel from the inlet end **1102** to the outlet end **1104** by rotating of the screw.

As shown in FIG. **4**, extrusion barrel **1100** may have a substantially constant wall thickness and a substantially constant inner diameter along its length. In other words, the radial distance between the axial centerline of the barrel **1100** and the inner surface **1106** of the barrel may be substantially constant, and the radial distance between the inner surface **1106** and the outer surface **1108** of the barrel wall may also be substantially constant.

Extrusion barrel **1100** preferably has a relatively thin wall thickness, particularly in comparison to barrels used in typical extrusion or injection molding machines. For example, extrusion barrel **1100** may have a wall thickness of from between 0.01 to 0.375 inches, or from between 0.04 to 0.25 inches.

Providing a relatively thin-walled extrusion barrel may have one or more advantages. First, the rate of heat transfer through the extrusion barrel wall is proportional to the wall thickness of the barrel. Without wishing to be bound to any particular theory, the rate of heat transfer through the barrel wall may be characterized as:

$$H = kA \left( \frac{T_o - T_i}{L_w} \right) \quad (1)$$

where H is the amount of heat per second flowing through a portion of the wall with surface area A and a wall thickness  $L_w$ , assuming a relatively small difference between the temperature  $T_o$  of the outer surface of the barrel wall and the temperature  $T_i$  of the inner surface of the barrel wall, such that a constant thermal conductivity k can be assumed for the wall material. Accordingly, all other parameters remaining constant, a decrease in the barrel wall thickness  $L_w$  results in a higher heat transfer rate through the barrel wall.

For example, FIG. 20 is an end-section view, to scale, of a first extrusion barrel **1100a** having an inner diameter of 1", an outer diameter of 2", and a wall thickness of 0.5", and a second extrusion barrel **1100b** having an inner diameter of 1", an outer diameter of 1.240", and a wall thickness of 0.120". Assuming barrels **1100a** and **1100b** are made from the same material, extrusion barrel **1100b** will have a relatively higher heat transfer rate through its barrel wall than extrusion barrel **1100a**.

An extrusion barrel **1100** having relatively high heat transfer rate through the barrel wall may have one or more advantages. For example, an increased thermal transfer rate allows more heat to be transferred through the barrel wall for a given unit of time. Accordingly, more heat per unit time can be transferred to the plastic material being conveyed through the extrusion barrel. Thus, it follows that the plastic material needs to spend less time in the extrusion barrel to have the necessary amount of heat transferred to it to melt the plastic material and/or less shear heating is required. As a consequence, if the material is liquefied or the feed material is of a size that seats within the threads of a screw, the extrusion screw **1300** may be rotated at a higher speed (i.e. a higher RPM) to convey the material through the extrusion barrel in a shorter amount of time without incurring excessive pressures that inhibit the use of thinner walled barrels as disclosed herein.

If the extrusion screw **1300** operates at a higher RPM, this may in turn allow a lower ratio gearbox to be used (as the operating RPM of the screw **1300** may be closer to the efficient operating RPM of the output shaft of the screw drive motor **1030**). As a lower ratio gearbox typically has a higher overall mechanical efficiency than a higher ratio gearbox, all else being equal, increasing the operating speed of the extrusion screw **1300** may be expected to increase the overall efficiency of extruder **1000**. For example, typical extrusion or injection molding machines may couple the drive motor to the screw using a gearbox with a ratio of about 40:1 or 60:1. Gearboxes with these reduction ratios typically have a mechanical efficiency of about 62% to 68%. In contrast, gearbox **1040** may have a ratio of about 10:1 or 20:1. Gearboxes with these lower reduction ratios typically have a higher mechanical efficiency, e.g. from about 79% to 86%.

Also, increasing the operating speed of the extrusion screw **1300** may also allow a higher speed, lower power motor **1030** to be used, which may have a lower operating and/or capital cost as compared to a higher power and/or lower speed motor.

Based on the increased heat transfer rate through the wall of barrel **1100** (and the corresponding increase in the amount of heat that can be supplied to the conveyed material from the barrel heaters), and the increased operating speed of the extrusion screw (and the corresponding increase in gearbox

and/or drive motor efficiency), in some configurations at least 60% of the total energy provided to extruder **1000** may be used to produce heat that is used to increase the temperature of the conveyed plastic material. In alternative configurations, at least 70%, 75%, 80%, 85%, 90%, or at least 95% of the total energy provided to extruder **1000** may be used to produce heat. For example, 70%, 75%, 80%, 85%, 90%, or at least 95% of the total energy provided to extruder **1000** may be used to power one or more heating elements and the remainder may be used to power the screw motor.

Extrusion barrel **1100** is preferably made from a material that has a relatively high thermal conductivity, such as copper or aluminum. Using such a material may further increase the heat transfer rate through the barrel wall, which may provide or enhance one or more of the advantages noted above.

One possible disadvantage of providing an injection barrel having a relatively thin wall and/or made from a relatively high thermal conductivity material is that the strength (e.g. pressure rating) of the extrusion barrel may be lower than if the barrel were provided with a relatively thick wall and/or made from a material having a higher strength, but a relatively lower thermal conductivity. Thus, the maximum operating pressure within the extrusion barrel **1100** may be relatively low, particularly in comparison to barrels used in typical extrusion or injection molding machines.

The strength of extrusion barrel **1100** may be increased using one or more approaches, which may be used alone or in combination. For example, the extrusion barrel may be made from a stronger, but less thermally conductive material, such as steel, stainless steel, or the like. In some embodiments, the extrusion barrel may be made from a very high strength material (e.g. a high-strength nickel alloy such as Monel™, available from Special Metals Corporation of New Hartford, N.Y., U.S.A.). If the material used to make barrel **1100** has a sufficiently high strength, the reduction in the necessary wall thickness to provide a desired pressure rating may mitigate or offset the decreased thermal conductivity of the material.

Alternatively, or additionally, as shown in FIG. 5, extrusion barrel **1100** may be provided with one or more reinforcing bands of material **1120** positioned against all or a portion of the outer circumference of the barrel. In the illustrated example, reinforcing band **1120** is provided proximate the output end **1104** of the extrusion barrel, where the internal pressure is expected to be relatively high (generally speaking, during operation of the extruder **1000** the internal pressure within the extrusion barrel **1100** increases as the plastic material is conveyed from the feed throat or input end **1102** to the output end **1104**). In the illustrated embodiment, a portion of the outer surface **1108** of the extrusion barrel is recessed where the reinforcing band **1120** is provided, so that the outer diameter of the reinforcing band is substantially the same as the diameter of the outer surface **1108** in the un-reinforced portion. Alternatively, as shown in FIG. 8, the extrusion barrel **1100** may have a substantially constant wall thickness, and the inner diameter of the reinforcing band **1120** may be substantially equal to the diameter of the outer surface **1108**.

Alternatively, or additionally, the wall thickness of the extrusion barrel may vary along the length of the barrel. Accordingly, the thicker portions of the barrel wall may provide increased strength, at the expense of a decreased heat transfer rate through the thicker barrel wall.

For example, as shown in FIG. 6, extrusion barrel **1100** may have a substantially constant inner diameter, and a

uniformly increasing wall thickness from the input end **1102** to the output end **1104**. In other words, the radial distance between the axial centerline of the barrel **1100** and the inner surface **1106** of the barrel may be substantially constant, and the radial distance between the inner surface **1106** and the outer surface **1108** of the barrel wall may increase along the length of the barrel.

Alternatively, as shown in FIG. 7, extrusion barrel **1100** may have a substantially constant inner diameter, and a wall thickness that increases step-wise from the input end **1102** to the output end **1104**.

In the embodiments illustrated in FIGS. 4 to 8, the extrusion barrel **1100** has a substantially constant inner diameter. In one or more alternative embodiments, the inner diameter of the extrusion barrel **1100** may increase along its length. In other words, the radial distance between the axial centerline of the barrel **1100** and the inner surface **1106** of the barrel may increase from the input end **1102** to the output end **1104**. It will be appreciated that any such barrel may use one or more reinforcing members as disclosed here. FIG. 9 illustrates an extrusion barrel **1100** having an increasing inner diameter and a uniformly increasing wall thickness, and FIG. 10 illustrates an extrusion barrel **1100** having an increasing inner diameter and step-wise increases in wall thickness. While not shown, it will be appreciated that an extrusion barrel **1100** may alternatively have an increasing inner diameter and a constant wall thickness.

#### Extrusion Screw

FIG. 11 illustrates an extrusion screw and barrel that may be representative of those used in typical extrusion or injection molding machines. Notably, the injection screw **1300'** has a variable profile along its length, which may be characterized generally as a feed section **1322'**, a transition or mixing section **1324'**, and a metering section **1326'**. As shown, the flight depth  $d_{FF}$  in the feed section **1322'** (flight depth being defined as the radial distance between the outer diameter of the screw flight **1308** and the outer diameter of the screw shaft **1306**) is substantially constant. However, the flight depth  $d_{FT}$  in the transition or mixing section **1324'** decreases along the length of this section. The flight depth  $d_{FM}$  in the metering section **1326'** is substantially constant, but is less than the flight depth  $d_{FF}$  in the feed section.

Such a screw **1300'**, when used with an extrusion barrel **1100'** having a constant inner diameter, results in the channel depth  $d_{CF}$  in the feed section **1322'** (channel depth being defined as the radial distance between the inner surface of the barrel and the outer diameter of the screw shaft) being substantially constant, the channel depth  $d_{CT}$  in the transition or mixing section **1324'** decreasing along the length of this section, and the channel depth  $d_{CM}$  in the metering section **1326'** is substantially constant, but is less than the channel depth  $d_{CF}$  in the feed section. Such an arrangement effectively reduces the annular volume between the screw and the inner surface of the barrel along the length of the barrel between the input end **1102'** and the output end **1104'**. This reduction in volume increases the compression of the material being extruded as it is conveyed along the barrel. In other words, the screw **1300'** shown in FIG. 110 has a volumetric compression ratio (defined as the channel depth in the metering section divided by a channel depth in the feed or transition section of the extruder) of less than one. As discussed previously, such an arrangement may increase the amount of heat imparted to the conveyed plastic material by shear heating.

Also of note, the wall of the barrel **1100'** is relatively thick. This is typically a result of the relatively high pressure required to effectively melt the material being conveyed by

shear heating, which in turn requires a barrel having a sufficient strength and/or pressure rating to withstand the expected operating pressures. As noted above, all else being equal a thicker barrel wall reduces the heat transfer rate through the barrel wall, which reduces the ability and/or efficiency of supplying heat to the conveyed material via one or more barrel heaters.

FIG. 12 illustrates a preferred extrusion screw **1300** according to this disclosure that may be used with an extruder **1000** in accordance with at least one embodiment disclosed herein. Screw **1300** has a diameter  $D$  measured from the outer radial extents of the flight. In contrast to extrusion screws that may be representative of those used in typical extrusion or injection molding machines (e.g. as shown in FIG. 11), the extrusion screw in FIG. 12 has as constant or generally constant profile along its effective length, which may be characterized generally as a feed section **1322**, a transition or mixing section **1324**, and a metering section **1326**. As shown, the flight depths  $d_{FF}$ ,  $d_{FT}$ , and  $d_{FM}$  in the feed section **1322**, transition or mixing section **1324**, and metering section **1326**, respectively, may be equal or substantially equal.

Such a screw **1300**, when used with an extrusion barrel **1100** having a constant inner diameter, results in a constant channel depth  $d_C$  along the entire effective length of the screw. Such an arrangement provides an effectively constant annular volume between the screw and the inner surface of the barrel along the length of the barrel. Accordingly, the screw shown in FIG. 12 may be characterized as having a volumetric compression ratio of one. Also, if the screw shown in FIG. 12 were used with an extrusion barrel **1100** having an increasing inner diameter, the channel depth  $d_C$  would be increasing along the length of the barrel, resulting in a volumetric compression ratio of greater than one.

Other aspects of extrusion screw **1300** are the flight pitch  $p_F$ , being the axial distance along the screw between crest of one thread and the next, and the flight length  $L_F$  (which may alternatively be referred to as the screw lead), being the axial distance along the screw covered by one complete rotation (i.e. 360°) of the screw. (It will be appreciated that for a single-start screw, the flight length and flight pitch are the same.) The screw **1300** illustrated in FIG. 12 has a substantially constant flight pitch  $p_F$  along its length.

Another aspect of extrusion screw **1300** is the flight width  $W_F$  (which may alternatively be referred to as the land length), being the axial thickness of a screw thread. The screw **1300** illustrated in FIG. 12 has a substantially constant flight width  $W_F$  along its length.

Suitable dimensions for screw **1300** are provided below in Table 1:

TABLE 1

Screw diameter	Flight pitch $p_F$	Flight width $W_F$	Flight depth $d_F$
1"	0.25" to 0.5"	0.125" to 0.250"	0.2" to 0.5"
2"	0.25" to 0.5"	0.125" to 0.375"	0.2" to 0.5"
6"	0.25" to 0.5"	0.125" to 0.500"	0.2" to 0.5"

Preferably, the flight pitch  $p_F$  and the flight width  $W_F$  are substantially constant for screw **1300**. However, the flight depth  $d_F$  may be increased along the length of the screw **1300** from the input end **1302** to the output end **1304**, which may assist in providing a volumetric compression ratio of less than or equal to one.

Another aspect of extrusion screw **1300** is the ratio of its length to its outer diameter, which may be referred to as its

L/D ratio. Screw **1300** preferably has an L/D ratio of 24:1. That is, a screw **1300** with a 1" diameter is preferably 24" long, and a screw **1300** with a 2" diameter is preferably 48" long. L/D may range from about 10:1 to about 30:1.

#### Extrusion Barrel and Extrusion Screw

For an extrusion screw and barrel used in typical extrusion or injection molding machines, the radial gap between the outer screw flight diameter and the inner surface of the barrel is relatively small, for example, between about 0.001" and 0.002". This relatively stringent tolerance may be required to maintain an increased compression of the material being extruded (e.g. to facilitate shear heating), and/or to prevent mixing at the barrel wall, which may be considered undesirable.

In contrast, in extruder **1000**, the radial gap between the outer diameter of screw **1300** and the inner surface **1106** of extrusion barrel **1100** is preferably between 0.001" to 0.08", more preferably from between 0.005" and 0.060", still more preferably from between 0.005" and 0.040", and most preferably from between 0.020" and 0.040". These reduced tolerances may result in decreased manufacturing, assembly, operating, and/or repair costs for extruder **1000**.

Examples of various extrusion screw and barrel designs are illustrated in FIGS. **13** to **19**. FIG. **13** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 1"; the flight pitch  $p_F$  is 0.25"; the flight width  $W_F$  is 0.125"; the flight depth  $d_F$  is 0.200" (constant); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.010".

FIG. **14** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 1"; the flight pitch  $p_F$  is 0.5"; the flight width  $W_F$  is 0.25"; the flight depth  $d_F$  is 0.500" (increasing towards outlet end **1302**); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.375".

FIG. **15** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 2"; the flight pitch  $p_F$  is 0.25"; the flight width  $W_F$  is 0.125"; the flight depth  $d_F$  is 0.200" (constant); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.010".

FIG. **16** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 2"; the flight pitch  $p_F$  is 0.5"; the flight width  $W_F$  is 0.375"; the flight depth  $d_F$  is 0.500" (increasing towards outlet end **1302**); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.375".

FIG. **17** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 6"; the flight pitch  $p_F$  is 0.25"; the flight width  $W_F$  is 0.125"; the flight depth  $d_F$  is 0.200" (constant); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.010".

FIG. **18** is a cross-section view, to scale, of an extrusion screw **1300** in a thin-walled extrusion barrel **1100** having a uniform thickness and parallel inner walls, where: the screw diameter is 6"; the flight pitch  $p_F$  is 0.5"; the flight width  $W_F$  is 0.5"; the flight depth  $d_F$  is 0.500" (increasing towards outlet end **1302**); the barrel wall to screw gap  $G$  is 0.030"; and the barrel wall thickness  $L_W$  is 0.375".

FIG. **19** is a cross-section view, to scale, of an extrusion screw **1300**, where: the screw diameter is 1"; the screw

length is 24"; the flight pitch  $p_F$  is 0.25" at the input end **1302**, increasing to 0.5" at the output end **1304**; the flight width  $W_F$  is 0.125"; the flight depth  $d_F$  is 0.200" (increasing towards outlet end **1302**).

#### Melting Plastic in Extruder

As discussed previously, in typical extrusion or injection molding machines, the heat provided to raise the temperature of the conveyed plastic material as it passes through the extrusion or injection barrel is provided primarily by mechanical shear heating. Further, the barrel wall thickness required to contain the operating pressures required for significant shear heating may reduce the maximum heat transfer rate through the barrel wall, reducing the amount of energy that can be conveyed to the plastic material via barrel heaters. For example, in some prior art machines, approximately 90% of the total energy supplied to operate the machine may be supplied to the drive motor, with the remaining 10% being supplied to one or more barrel heaters.

In contrast, during the operation of extruder **1000**, a majority, and preferably a substantial majority, of the heat provided to raise the temperature of the conveyed plastic material as it passes through the extrusion barrel is provided by non-mechanical heat sources.

For example, extruder **1000** preferably includes an extrusion barrel **1100** having relatively high heat transfer rate through the barrel wall, which increases the amount of heat barrel heaters **1110** can provide to the plastic material in a given amount of time. This may allow barrel heaters **1110** to provide at least 60%, 65%, 70%, 75%, 80%, 85%, 90%, or at least 95% of the total amount of heat provided to the conveyed material during its time in the extrusion barrel **1100**, with the remaining heat being provided as a result of mechanical shear heating.

Alternatively, or additionally, extruder **1000** includes an extrusion screw **1300** configured to provide a volumetric compression ratio of greater than one. This may reduce the pressure of the plastic material within the extrusion barrel, which may result in less heat being provided as a result of mechanical shear heating, as compared with an extruder operating at a higher extrusion barrel pressure.

Alternatively, or additionally, in extruder **1000**, the radial gap between the outer diameter of screw **1300** and the inner surface **1106** of extrusion barrel **1100** may be relatively high (e.g. from between 0.020" and 0.040"). Such a radial barrel gap may increase the ability of the plastic material to mix at or near the barrel wall, and/or may contribute to a reduction in the pressure of the plastic material within the extrusion barrel (e.g. by allowing more material to 'spill over' and flow between adjacent flight threads). Accordingly, such barrel gap may result in less heat being provided as a result of mechanical shear heating, as compared with an extruder having a smaller radial barrel gap.

#### Extruder Operating Pressure

In typical extrusion or injection molding machines, in which the conveyed plastic material is heated primarily by mechanical shear heating, the operating pressure within the extrusion/injection barrel is typically quite high. In contrast, during the operation of extruder **1000**, the conveyed plastic material is heated primarily by the barrel heating elements (i.e. by non-mechanical heat sources). This may allow extruder **1000** to be operated with a much lower operating pressure within the extrusion barrel.

For example, as discussed herein extrusion screw **1300** and/or extrusion barrel **1100** may be configured to provide a volumetric compression ratio of greater than one as the material is conveyed through the extrusion barrel (i.e. the annular volume between the screw and the inner surface of

the barrel per unit length of the barrel may increase along the length of the barrel). In contrast to typical machines, which are configured to compress (and thereby increase the pressure of) the conveyed material as it approaches the exit of the barrel, extruder **1000** may be configured to decompress (and thereby decrease the pressure of) the conveyed material as it approaches the exit of the barrel.

An extruder **1000** with a relatively low barrel operating pressure may have one or more advantages. For example, as discussed above, to increase the rate of heat transfer through the extrusion barrel wall, extrusion barrel **1100** preferably has a relatively thin wall thickness. Operating with a lower barrel operating pressure may allow for a thinner barrel wall to be used, as the required strength of the barrel is lower.

In some examples, extruder **1000** may be configured to operate with a barrel operating pressure of less than 1,000 pounds per square inch (psi), less than 750 psi, 500 psi, 400, 300 or 200 psi and above 20, 40, 50, 75, 100 or 150 psi, such as between 10 and 400 psi, or between 40 and 200 psi.

#### Experimental Results

Example material throughput results for an extruder according to the disclosure set out herein are shown in Table 2. The tests were conducted using a 20 melt HDPE polymer from Premier Plastics Resins of Lake Orion Mich., a 19.3:1 L/D screw with a 0.325" flight pitch, a 0.250" land (i.e. flight width), a 0.250" flight depth, and a 0.9325 inch diameter D made of 7075 T6 aluminum, a 304 stainless steel schedule 80 pipe as the extrusion barrel, a 10:1 mechanical reduction gearbox and a 3 phase 230 VAC 1 horsepower inverted duty induction screw drive motor controlled with a GS2 1P0 inverter drive from Automation direct.

Table 2 shows the flowrates obtained and the associated screw RPM, with the barrel heaters configured to provide the indicated extruder barrel temperature zones, listed from the feed section to the output or metering section of the extruder barrel. The barrel temperature zones are listed from the inlet hopper to the outlet end of the nozzle, with four temperature zones along the barrel length and one zone on the output nozzle.

TABLE 2

Test No.	Barrel temperature zones (° C.)	Screw drive (RPM)	Average flowrate (pounds of extruded plastic per hour)
1	235/250/250/250/250	85	6.0
2	235/250/250/250/250	150	13.2
3	235/250/250/250/250	85	7.4
4	235/250/250/250/250	150	16.5
5	235/275/275/275/275	170	17.6
6	235/275/275/275/275	175	21.35
7	235/275/275/275/275	175	17.95
8	235/275/275/275/275	175	22.1
9	235/275/275/275/275	175	20.4
10	235/275/275/275/275	175	22.8
11	235/275/275/275/275	175	19.5
12	235/275/275/275/275	175	18.43
13	235/275/275/275/275	175	22.82
14	235/275/275/275/275	175	22.31
15	250/285/285/285/285	175	22.55
16	250/285/285/285/300	175	19.75

#### Notes:

For tests 3 and 4, springs that control the down pressure of the feed plate at the inlet to the screw were "backed off" or loosened as compared to tests 1 and 2;

For tests 6 to 14, the barrel zone temperatures were adjusted while holding screw RPM constant;

Tests 7 and 11 were conducted using a spring-loaded aluminum insert

#### Extruder Control Based of Screw RPM v Temperature

In accordance with another aspect of this disclosure, which may be used with one or more of the aspects of an

extruder and/or mold disclosed herein, the operating speed of extruder screw **1300** may be adjusted based on a temperature of the flowable material flowing through and/or being output by the extruder. This aspect may be used by itself or with any one or more other aspects of extruder **1000** disclosed herein.

In accordance with this aspect, the temperature of the material is increased prior to increasing the speed of rotation of the screw. For example, prior to increasing the screw RPM, the barrel zone temperature(s) are increased. Accordingly, more power may be provided to some or all of the barrel heaters for a period of time prior to increasing the RPM of the screw. The time delay may be selected, based on inter alia the thermal conductivity of the barrel and the desired increase in screw speed. The time delay may be from 3 to 60 seconds, 10 to 50 seconds, 15 to 45 seconds, or 20 to 40 seconds.

Increasing the temperature of the material prior to increasing the screw RPM may assist in maintaining a relatively low barrel operating pressure, as increasing the temperature of the material may lower its viscosity prior to subjecting the material to increased mechanical force from the increased screw RPM. Maintaining a relatively low barrel operating pressure may reduce the stress imposed on the material during extrusion, and/or allow the use of a more thermally conductive barrel such as copper or aluminum.

Conversely, the screw RPM may be decreased and the barrel zone temperature(s) may then be decreased. Accordingly, less power may be provided to some or all of the barrel heaters for a period of time prior to decreasing the RPM of the screw. The time delay may be selected, based inter alia on the thermal conductivity of the barrel and the desired decrease in screw speed. The time delay may be from 3 to 60 seconds, 10 to 50 seconds, 15 to 45 seconds, or 20 to 40 seconds.

Decreasing the temperature of the material prior to decreasing the screw RPM may prevent the material from unwanted thermal degradation, as decreasing the screw RPM may increase the time it takes for the material to travel through the barrel (i.e. material residence time). If the screw RPM is decreased prior to decreasing the barrel temperature, the material may be exposed to a barrel temperature that is too high for the expected increased residence time based on the lower screw RPM and may result in burning or degradation of the material. As exemplified in FIG. 27, in response to a desire to increase (or decrease) the screw RPM by 10%, the barrel temperature is increased/decreased by 10° C., about 15 seconds before the screw RPM is changed.

#### Molding Using Extruder and Pressurization Member

In accordance with another aspect of this disclosure, which may be used with one or more of the aspects of an extruder and/or mold disclosed herein, extruder **1000** may be used to fill a mold in a molding process.

In accordance with this aspect, the plastic material output from extruder **1000**, which is in a flowable or melted state, is directed into the mold at a relatively low pressure, and once the mold is full (or mostly full), a pressurization member is used to increase the pressure of the material in the mold, and/or fill the remainder of the mold with plastic material.

As discussed above, the flowable plastic material may exit the extruder **1000** at a relatively low pressure (e.g. below 1,000 psi, or below 500 psi, or between about 10 and about 200 psi) as compared to typical extrusion/injection machines. Where the output pressure of the extruder **1000** is not sufficient to properly fill a mold (e.g. a mold having a complex interior cavity), instead of increasing the operating

pressure of extruder **1000** (which, as discussed previously, may negatively impact the overall efficiency of the extruder), a pressurization member other than extruder **1000** may be used to apply pressure to the material within the mold cavity to ensure proper filling of the mold. Such an arrangement allows for large and/or complex mold cavities (or at least a majority of such cavities) to be filled using the relatively low-pressure output from extruder **1000**.

An example embodiment of this aspect will be discussed with reference to FIGS. **28A-D**. As illustrated in FIG. **28A**, nozzle **1200** of extruder **1000** is in fluid communication with a cavity **1510** defined by a mold **1500**. More specifically, the output end **1204** of nozzle **1200** is fluidically coupled to an inlet **1542** of an isolation member **1540** (the purpose of which will be discussed further below), and an outlet **1544** of isolation member **1540** is coupled to a mold inlet port **1502**. Mold inlet port **1502** provides fluid communication to mold cavity **1510**, which in the illustrated example is defined by opposing mold halves **1506** and **1508**.

Mold cavity **1510** is also accessible via a mold pressurization port **1504**, which in the illustrated example is in fluid communication with an optional storage or overflow chamber **1520**. Accordingly, flowable material exiting nozzle **1200** is able to flow into mold cavity **1510** and also into storage chamber **1520**.

A pressurization member **1530** (the purpose of which will be discussed further below), is also operatively connected to mold pressurization port **1504**. In the illustrated example, pressurization member **1530** includes a piston **1532** and an actuator **1534**. It will be appreciated that any other pressurization member may be used including a source of pressurized fluid, a high pressure extruder and the like.

To fill a mold, first, as shown schematically in FIG. **28B**, flowable material exits nozzle **1200** and, after passing through isolation member **1540**, the flowable material enters mold cavity **1510** via mold inlet port **1502**.

As shown in FIG. **28C**, as more flowable material enters the mold cavity **1510**, at least some flowable material exits mold cavity **1510** via mold pressurization port **1504** and enters storage chamber **1520**, which begins to fill with flowable material.

Once mold cavity **1510** and/or storage chamber **1520** are filled (or almost filled) with flowable plastic material, as extruder **1000** continues to output flowable material, the pressure of the flowable material at the mold inlet port **1502** and/or the nozzle output **1204** of extruder **1000** will start to increase (as there is no further volume into which the additional flowable material can flow).

In response to (or prior to) the operating pressure of extruder **1000** increasing due to mold cavity **1510** and storage chamber **1520** being full (or mostly full) of flowable material, isolation member **1540** may be actuated to fluidically isolate the mold cavity **1510** and storage chamber **1520** from extruder nozzle **1200**. In the illustrated example, isolation member **1540** includes a valve that can be closed to prevent fluid communication between the inlet **1542** and the outlet **1544** of isolation member **1540**. When closed, the valve of isolation member **1540** prevents flowable plastic material from exiting mold cavity **1510**, and also prevents further flowable plastic material from nozzle **1200** of extruder **1000** from entering the mold cavity (e.g. by directing the flow of output material into a run-off conduit).

Alternatively, or additionally, isolation member **1540** may include one or more cooling elements that are operable to selectively cool at least a portion of the flowable material between the inlet **1542** and the outlet **1544** until the flowable material solidifies. Once solidified, the plastic material

forms a barrier preventing flow between the flowable material on either side of isolation member **1540**, effectively fluidically isolating the mold cavity **1510** and storage chamber **1520** from extruder nozzle **1200** (i.e. preventing flowable plastic material from exiting mold cavity **1510**, and also preventing further flowable plastic material from extruder **1000** from entering the mold cavity). Any other member or process step that isolates the extruder from the mold cavity (e.g., delinking the mold and the extruder and applying a pressurization member in its place) may be used.

Turning to FIG. **28D**, once mold cavity **1510** and storage chamber **1520** are filled (or almost filled) with flowable plastic material, and isolation member **1540** has been actuated to prevent flowable plastic material from exiting mold cavity **1510**, pressurization member **1530** is used to selectively increase the pressure of material in cavity **1510**. For example, the piston **1532** may be actuated by actuator **1530** to reduce the effective volume of storage chamber **1520**. Since the volume of mold cavity **1510** remains constant, reducing the effective volume of storage chamber **1520** reduces the overall volume of the mold cavity and storage chamber. Compressing the flowable plastic material in this manner (i.e. by reducing the volume of the cavity in which it is positioned) will lead to an increase in pressure of the flowable plastic material.

The use of pressurization member **1530** to apply pressure to the material within the mold cavity to ensure proper filling allows mold **1500** to be filled (or substantially filled) with flowable material at a first, relatively low pressure (e.g. less than 500 psi, 400, 300 or 200 psi) from extruder **1000**, but also allows the flowable material within the mold cavity **1510** to be subsequently exposed to a second, relatively high pressure (e.g. above 500 psi, 600, 700, 800, 900 or 1000 psi), which may be required to properly fill the mold (e.g. to ensure the flowable material completely fills a mold having a complex interior cavity), or otherwise desirable during the molding operation (e.g. compressing the flowable material within the mold cavity may improve one or more physical properties of the molded component).

For example, as shown in FIG. **29**, flowable material may be initially introduced into a mold cavity at a relatively low pressure, e.g. 100 psi. Depending on the output flow rate of the extruder **1000** and the volume of the mold cavity being filled, this process may take up the majority, or a substantial majority, of the time required for the mold filling operation, e.g. about 10 minutes in the illustrated example. However, once the mold cavity has been filled (or substantially filled) using output from extruder **1000**, additional flowable material may be subsequently introduced into the mold cavity at a relatively high pressure, e.g. 1000 psi, using pressurization member **1530**.

In the example illustrated in FIGS. **28A-D**, the pressurization member **1530** and the extruder nozzle **1200** are positioned of opposite sides of mold **1500**. Alternatively, pressurization member **1530** may be positioned of the same side of mold **1500** as extruder nozzle **1200**. For example, as shown in FIGS. **28E-G**, storage or overflow chamber **1520** is positioned downstream of isolation member **1540**, but upstream of mold inlet port **1502**. Accordingly, after exiting outlet **1544** of isolation member **1540**, the flowable material may be flow either into mold cavity **1510** (via mold inlet **1502**) or into storage chamber **1520** (via storage chamber inlet **1522**).

As shown in FIG. **28F**, flowable material enters both the mold cavity **1510** and storage chamber **1520**, until each are full (or almost full) of flowable material.



Once mold cavity **1510** and storage chamber **1520** are filled (or almost filled) with flowable plastic material, isolation member **1540** is actuated to fluidically isolate the mold cavity **1510** and storage chamber **1520** from extruder nozzle **1200**. Next, pressurization member **1530** is actuated to increase the pressure of material in cavity **1510** (e.g. by advancing piston **1532** to reduce the effective volume of storage chamber **1520**).

Positioning the pressurization member **1530** and extruder nozzle **1200** of the same side of mold **1500** may have one or more advantages. For example, only one mold inlet port **1502** is required, as compared with two mold ports **1502**, **1504** that would be required if the pressurization member is located downstream of mold **1500**. This arrangement may also allow for a more compact design.

In the examples illustrated in FIGS. **28A-G**, one extruder **1000** and one pressurization member **1530** were connected to a mold **1500**. Alternatively, two or more extruders **1000** may be used with a single mold **1500**.

For example, as shown in FIGS. **30A-30B**, three extruders **1000** may be provided, with a nozzle **1200a-c** of each respective extruder **1000a-c** in fluid communication with a cavity **1510** defined by a mold **1500**, which in the illustrated example is an annular mold cavity. More specifically, the output end **1204a-c** of each nozzle **1200a-c** is coupled to a respective mold inlet port **1502a-c** via a respective isolation member **1540a-c**. Mold inlet ports **1502a-c** provides fluid communication to a single mold cavity **1510**.

In the illustrated example, mold cavity **1510** is also in fluid communication with storage or overflow chamber **1520** and pressurization member **1530**. Accordingly, flowable material exiting nozzles **1200a-c** is able to flow into mold cavity **1510** and also into storage chamber **1520**. It will be appreciated that more than one overflow chamber **1520** and/or more than one pressurization member **1530** may be provided in alternative embodiments.

Also shown is optional weight sensor **1550**, which may be used to determine the mass of the flowable material within the mold **1500** and/or storage chamber **1520**. Accordingly, data from sensor **1550** may be used instead of and/or in addition to, data from one or more pressure sensors, flow meters volume sensors in storage chamber **1520** (not shown) to determine how much flowable material has been introduced into mold cavity **1510**, and/or how much additional flowable material is required to fill the mold.

As shown in FIG. **30B**, once mold cavity **1510** and storage chamber **1520** are filled (or almost filled) with flowable plastic material, isolation members **1540a-c** may be actuated to fluidically isolate the mold cavity **1510** and storage chamber **1520** from extruder nozzles **1200a-c**. Subsequently or concurrently, pressurization member **1530** may be actuated to increase the pressure of material in cavity **1510** (e.g. by advancing piston **1532** to reduce the effective volume of storage chamber **1520**). A central control unit **700** may be provided to coordinate the operation of extruders **1000a-c** and/or pressurization member **1530**.

As the plastic material exiting extruder is in a flowable state due to its elevated temperature, if the flowable material is allowed to cool, it will begin to solidify, which may not be desirable until the mold has been completely filled and pressurized by the pressurization member. Accordingly, mold **1500** preferably includes one or more mold heating elements **1560** that are operable to maintain the flowable plastic material within the mold cavity at an elevated temperature (which may be the same or different than the temperature at which the material exits the extruder **1000**) during the mold filling process so that the plastic material

remains in a flowable state until the mold has been completely filled and pressurized by the pressurization member. Once the mold has been pressurized, mold **1500** is preferably at least partially cooled so that the flowable material solidifies and the molded component can then be removed from the mold.

#### Molded Plastic Component

The use of extruder **1000** in a molding process may have one or more advantages over typical injection molding machines. For example, as noted above, extruder **1000** is typically more energy efficient than typical molding machines.

Another possible advantage relates to the production of molded components with relatively complicated geometries, and/or the production of relatively large molded components. In this respect, since the molding process outlined above using extruder **1000** does not rely on the output or operating pressure of the extrusion barrel **1100** to provide the maximum pressure on the flowable material within the mold cavity (instead relying on one or more pressurization members to apply a higher pressure than could otherwise be applied by extruder **1000**), such a molding process can be 'scaled up' to provide higher molding pressures (e.g. for use with molds with relatively complex internal cavities and/or with molds for relatively large molded components) without having to 'scale up' the operating pressure of extruder **1000**.

Another possible advantage relates to the properties of the molded plastic components produced by this process. In typical injection molding operations, the flowable material is injected into the mold cavity at relatively high pressures and flow rates, which leads to the mold cavity being filled in a relatively short period of time. A possible downside of such a process is the potential for the introduction of strain orientation lines within the plastic component.

For example, FIG. **34** is a schematic illustration of a molded plastic part **10** as may be produced using a typical prior art injection molding process, showing strain orientation lines **12** radiating outwardly from the location **14** of the mold port. These strain orientation lines may cause (or by symptomatic of) a molded component to having a lower strength than an otherwise similar component with less (or no) strain orientation. Alternatively, or additionally, strain orientation lines may cause (or by symptomatic of) a molded component to be more prone to deformation during a post-mold cooling process, and/or in response to being subsequently heated. In some applications, it may be considered necessary to subject a molded component to one or more post molding strain relieving operations, to ensure the molded plastic component is not structurally compromised by the strain orientation introduced during the molding process.

Since the molding process outlined above using extruder **1000** fills the mold cavity (or almost all of the mold cavity, e.g., 75%, 80%, 85%, 90% or 95% or more) at a relatively low pressure and material flow rate, the potential for strain orientation lines to be formed within the molded component may be reduced or eliminated. Accordingly, such a process may produce a molded component with fewer (or no) strain orientation lines. For example, FIG. **35** is a schematic illustration of a molded plastic part **10** as may be produced by the extrusion processes described herein, showing strain orientation lines **12** radiating outwardly from the location **14** of one or more mold ports. Such a component may not require any post molding strain relieving operations.

#### Extruding Pipe

In typical injection molding operations, as illustrated schematically in FIG. **31**, the flowable material generally

converges as it passes the output end of the extrusion/injection screw **1300'**, e.g. via a nozzle **1200'**, and subsequently diverges outwardly towards the outer portion of the mold cavity **1510'**. While this divergence-convergence may have one or more advantages in certain applications, it may also have one or more disadvantages. For example, by directing all of the flowable material through the output end **1204'** of nozzle **1200'**, the flowable material flow-rate may be decreased, and/or the pressure required to maintain a desired flowable material flow-rate may be increased. Also, when extruding pipe or other annular forms, a spider is typically provided in the flow path between the extrusion barrel and the mold die, e.g. to maintain the position of an inner die mandrel within the flow path. While such spiders may be configured to provide a minimal impact on the flow of the flowable material (e.g. by minimizing the annular cross-section within the flow path), they nonetheless obstruct the flow (at least partially), they therefore act to decrease the flowable material flow-rate and/or increase the pressure required to maintain a desired flowable material flow-rate.

In accordance with another aspect of this disclosure, extruder **1000** may be used to mold a component without converging the flowable material after it has exited the extrusion barrel **1100**, to produce hollow elongate objects. This aspect may be used by itself or with any one or more other aspects of extruder **1000** disclosed herein.

In accordance with this aspect, the plastic material output from extruder **1000**, which is in a flowable or melted state, is directed into an annular mold cavity having an outer diameter substantially equal to the inner diameter of the output end **1104** of the extrusion barrel **1100**, and an inner diameter substantially equal to the outer diameter of the screw shaft **1306** of screw **1300**. Put another way, the annular thickness of the mold cavity is substantially equal to the channel depth  $d_c$  at the output end **1104** of the extrusion barrel (e.g., +/-20%, 15%, 10% or 5%).

As discussed above, the flowable plastic material may exit the extruder **1000** at a relatively low pressure (e.g. below 1,000 psi, or below 500 psi, or between about 10 and about 200 psi) as compared to typical extrusion/injection machines. Where the output pressure of the extruder **1000** is not sufficient to provide or maintain a desired flowable material flow-rate through a divergent nozzle, instead of increasing the operating pressure of extruder **1000** (which, as discussed previously, may negatively impact the overall efficiency of the extruder), the flow path of the flowable material may be modified to reduce the pressure required to fill the mold.

An example embodiment of this aspect will be discussed with reference to FIGS. **32-33B**. As illustrated in FIG. **32**, the output end **1104** of extrusion barrel **1100** is coupled to an inlet **1602** to annular mold cavity **1610**, which in the illustrated example is defined by an outer mold wall **1606** and an inner mold wall **1608**. The inner diameter of outer mold wall **1606** is substantially equal to the inner diameter of the output end **1104** of the extrusion barrel **1100**, and the outer diameter of inner mold wall **1608** is substantially equal to the outer diameter of the screw shaft **1306** of screw **1300**. By using a mold cavity **1610** having an annular thickness that is substantially equal to the channel depth  $d_c$  at the output end **1104** of the extrusion barrel, and by directing the flowable material from the extrusion barrel **1100** into the mold cavity **1610** in a substantially straight path (i.e. without converging or diverging), the pressure required to maintain a desired flowable material flow-rate into the mold cavity **1610** may be reduced or minimized, allowing the use of an

extruder **1000** having a relatively low output pressure. The reduction in backpressure due to directing the flowable material from the extrusion barrel **1100** into the mold cavity **1610** in a substantially straight path may also reduce strain in the molded component.

An axial end **1628** of inner mold wall **1608** may be rotationally coupled to the output end **1304** of extrusion screw **1300** via rotational coupler **1630**, so that extrusion screw **1300** may rotate relative to non-rotating inner mold wall **1608**.

Optionally, an extruder **1000** may be provided for each end of an annular mold, allowing the mold to be filled faster than if only one extruder **1000** were used. For example, as illustrated in FIG. **33A**, the output end **1104a** of extrusion barrel **1100a** is coupled to an inlet **1602a** to annular mold cavity **1610**, and the output end **1104b** of extrusion barrel **1100b** is coupled to an inlet **1602b** to annular mold cavity **1610**. Also, the axial end **1628** of inner mold wall **1608** may be rotationally coupled to the output end **1304a** of extrusion screw **1300a** via rotational coupler **1630a**, and the axial end **1626** of inner mold wall **1608** may be rotationally coupled to the output end **1304b** of extrusion screw **1300b** via rotational coupler **1630b**. This arrangement allows extrusion screws **1300a-b** to rotate independently of each other, and to rotate relative to non-rotating inner mold wall **1608**.

Alternatively, as illustrated in FIG. **33B**, the nozzle outlet **1204a** of extruder **100a** may be coupled to an inlet **1602a** to annular mold cavity **1610**, and the nozzle outlet **1204b** of extruder **1000b** may be coupled to an inlet **1602b** to annular mold cavity **1610**. This arrangement allows the use of two or more extruders **1000** to fill a single annular mold **1600**, but in contrast to the example illustrated in FIG. **33A**, the flowable material is directed from the extrusion barrels **1100a**, **1100b** into the mold cavity **1610** along converging and diverging paths.

#### Extruder Control Electronics

Reference is next made to FIGS. **25A-25C** illustrating a block diagram of control electronics **1400** in accordance with an example embodiment. Control electronics **1400** are provided as an example and there can be other embodiments of control electronics **1400** with different components or a different configuration of the components described herein.

Referring first to FIG. **25C**, control electronics **1400** comprise processing unit **1402**, display and user interface **1404** (e.g. for receiving control instructions for operating extruder **1000** during an extrusion or molding operation, and which may include which may include display **1018**), network interface unit **1406**, motor drive **1408**, peripheral device interface unit **1410**, power supply circuitry **1412**, and one or more barrel control modules **1424**.

Processing unit **1402** controls the operation of extruder **1000**. Processing unit **1402** can be any suitable processor, controller or digital signal processor that can provide sufficient processing power processor depending on the configuration, purposes and requirements of extruder **1000** as is known by those skilled in the art. For example, processing unit **1402** may be a high performance general processor. In alternative embodiments, processing unit **1402** can include more than one processor with each processor being configured to perform different dedicated tasks. In alternative embodiments, specialized hardware may be used to provide some of the functionality provided by processing unit **1402**.

Display and user interface **1404** can include any suitable display **1018** that provides visual information depending on the configuration of extruder **1000**. For instance, display **1018** can be a display suitable for a laptop, tablet, or handheld device such as an LCD-based display and the like.

User interface **1404** can include at least one of a keyboard, a touch screen, a thumbwheel, a track-pad, a track-ball, and the like again depending on the particular implementation of extruder **1000**. In some cases, some of these components can be integrated with one another.

Network interface unit **1406** can be any interface that allows the extruder **1000** to communicate with other devices or computers. In some cases, network interface unit **1406** can include at least one of a serial port, a parallel port or a USB port that provides USB connectivity. Network interface unit **1406** may optionally include a wireless interface unit, which can be a radio (e.g. a transceiver or a transmitter) that communicates utilizing CDMA, GSM, GPRS or Bluetooth protocol according to standards such as IEEE 802.11a, 802.11b, 802.11g, or 802.11n. Network interface unit **1406** can be used by extruder **1000** to communicate with other devices or computers using any suitable wired or wireless protocol.

Peripheral device interface unit **1410** can be any interface that allows the extruder **1000** to communicate with other components of an extruding or molding apparatus. For example, peripheral device interface unit **1410** may enable two-way communication with a puller, a winder, a water bath, and the like. The data being shared may include the tension of a puller or winder filament (to control winding speed), the diameter of the filament measured in at least one axis and at least one point, a temperature of the water bath, a water bath level, data indicating that a reel is full, and the like.

Power supply circuitry **1412** may include a power source **1414** (which can be any suitable power source that provides power to extruder **1000**, such as a source of AC or DC power). Power source **1414** may provide power to one or more components of extruder **1000**, including screw drive motor **1030** (and/or a solid state motor drive for motor **1030**, such as a variable-frequency drive (VFD) or the like), one or more barrel control modules **1424**, and one or more nozzle control modules **1426**. Power source **1414** preferably provides power to these components via one or more power relays **1422**.

Turning to FIG. 25A, barrel control module **1424** comprises processing unit **1430**, barrel heaters **1110** (which preferably include corresponding and/or integrated thermocouples or other temperature sensors **1112**), one or more optional signaling members **1432**, and nozzle control module **1426**.

Processing unit **1430** controls the operation of barrel control module **1424**. Processing unit **1430** can be any suitable processor, controller or digital signal processor that can provide sufficient processing power processor depending on the configuration, purposes and requirements of barrel control module **1424** as is known by those skilled in the art. For example, processing unit **1430** may be a high performance general processor. In alternative embodiments, processing unit **1430** can include more than one processor with each processor being configured to perform different dedicated tasks. In alternative embodiments, specialized hardware may be used to provide some of the functionality provided by processing unit **1430**.

Barrel heaters **1110** may be any member that is capable of raising the temperature of extrusion barrel **1100**. As exemplified, barrel heaters **1110** comprise a resistive heating element. The resistive heating elements may be heated by power circuitry **1412** or they may be connectable to an external source of current.

Temperature sensors **1112** may be any suitable sensor, such as a thermocouple, a thermistor and the like, that may

be located, e.g., on the outer surface **1108** or the inner surface **1106** of extrusion barrel **1100**, and configured to measure a temperature of the barrel. At steady state conditions, a signal representing the temperature of the barrel in one location may be indicative of an adjacent location. For example, the temperature of the outer surface **1108** of barrel **1100** may be indicative of the temperature of a flowable material being conveyed past the inner surface **1106** of the barrel **1100**.

Signaling members **1432** may be provided as an alternative to, or in addition to, display screen **1080**. For example, an audio signaling member such as an electroacoustic transducer (or speaker) may be configured to provide an audible tone in response to a sensor detecting that a predetermined temperature and/or pressure has been reached, and/or when otherwise directed by control electronics **1400**. As another example, one or more indicator lights (such as LEDs) may be provided on extruder **1000** and configured to emit a signal (e.g. illuminate, strobe, and/or change colour) in response to detecting that a predetermined temperature and/or pressure has been reached, and/or when otherwise directed by control electronics **1400**.

Turning to FIG. 25B, nozzle control module **1426** comprises processing unit **1434**, nozzle heater **1210** (which preferably includes one or more corresponding and/or integrated thermocouples or other temperature sensors **1212**), one or more optional plastic temperature sensors **1222**, and one or more pressure sensors **1220** and/or overpressure sensors **1221**.

Processing unit **1434** controls the operation of nozzle control module **1426**. Processing unit **1434** can be any suitable processor, controller or digital signal processor that can provide sufficient processing power processor depending on the configuration, purposes and requirements of nozzle control module **1426** as is known by those skilled in the art. For example, processing unit **1434** may be a high performance general processor. In alternative embodiments, processing unit **1434** can include more than one processor with each processor being configured to perform different dedicated tasks. In alternative embodiments, specialized hardware may be used to provide some of the functionality provided by processing unit **1434**.

Nozzle heater **1210** may be any member that is capable of raising the temperature of extrusion nozzle **1200**. As exemplified, nozzle heater **1210** comprises a resistive heating element. The resistive heating element may be heated by power circuitry **1412** or may be connectable to an external source of current.

Temperature sensors **1212** and **1222** may be any suitable sensor, such as a thermocouple, a thermistor and the like. Sensor **1212** may be located, e.g., on the outer surface of nozzle **1200**, and configured to measure a temperature of the nozzle. Temperature sensor **1222** may be located, e.g., in or adjacent the flow conduit between nozzle inlet **1202** and nozzle outlet **1204**, and configured to measure a temperature of a flowable material being conveyed through and/or output from the nozzle **1200**.

Pressure sensors **1220** and **1221** are operable to measure the pressure of the flowable material being conveyed through the nozzle **1200**. Pressure sensors may be any suitable sensor, such as pressure transducers, piezoelectric transducers and the like. For example, a pressure sensor may be located in fluid communication with a flowable material being conveyed through the nozzle **1200**. Other suitable pressure sensors may be used, such as or one or more strain gauges located on e.g. the outer surface of nozzle **1200**.

## Extruder Control Method

An example embodiment for a method for operating extruder **1000** will now be described with reference to FIG. **26** and is shown generally as **100**.

The method starts at **102**, where the main power to extruder is turned on. At **104** the control electronics **1400** perform an initialization routine. At **106**, the nozzle **1200** is checked to determine how many nozzle boards are connected, how many heating zones are present, the names of the heating zones, and what type of head unit is present and the associated heating zones, heating zone names, and pressure sensors present. If extruder **1000** is being operated in an extrusion mode of operation, the method proceeds to **108a**, and if extruder **1000** is being operated in a mold mode of operation, the method proceeds to **108b**. Steps similar to both modes of operation have been similarly numbered.

At **108**, a user may be prompted to load previously used settings for the extrusion/molding operation. If the previously used settings are selected, the method proceeds to **112**. Otherwise, the method proceeds to **110**, where a user inputs and/or selects the settings to be used.

At **112**, the extrusion system is initialized, and at **114** the control electronics may monitor one or more temperature sensors to determine if the barrel heaters have reached a desired temperature (e.g., the temperature input at **108** or **110**). If the barrel heaters have not reached the desired temperature, at **116** the heaters may be cycled until the desired temperature is reached. Cycling the heaters may involve turning the heaters on and off to maintain a preset temperature window. The number of heaters on at a given time may also be also controlled so as to never exceed the total electric current (power) available to the heaters.

Once the desired barrel heater temperature is determined to have been reached at **114**, control electronics proceeds to actuate the screw drive motor **1030**, resulting in rotation of the extrusion screw **1300** within barrel **1100**.

At **120**, the control electronics verify that any emergency stop switches have not been actuated. If an actuation of an emergency stop switch is detected, at **122** the screw drive motor **1300** and the barrel heaters **1110** may be turned off, and an error may be displayed (e.g. via display **1018**).

If actuation of an emergency stop switch is not detected, at **124** the control electronics may determine if one or more other predetermined error conditions have been detected, in which case the method proceeds to **122** where the heaters and motor may be turned off and an error displayed.

At **126** the control electronics may monitor one or more temperature sensors to determine if each of the zones in barrel **1100** have reached their desired temperature (e.g., the temperature input at **108** or **110**). If a barrel zone has not reached its desired temperature, at **128** the barrel heaters **1110** for that zone are turned on and the method proceeds to **132**. Also at **128**, a power management module may prevent a barrel heater from turning on to prevent the total power draw from the active or “on” barrel heaters exceeding the maximum current available. In such a case, the power management module may prioritize which barrel heaters are to be turned (and/or remain) on, e.g. by allowing the zone(s) that have the greatest difference between an actual and a target temperature to stay on longer than zone(s) that have a temperature closer to their target temperatures, thereby reducing the maximum temperature difference from the preset temperatures. Otherwise (i.e. if each barrel zone has reached its desired temperature), at **130** the barrel heaters **1110** are turned off and the method proceeds to **132**.

At **132**, the control electronics determine if any settings have been changed by a user. If one or more settings are

determined to have been changed, at **134** the control electronics may update the target values for one or more monitored parameters. Otherwise, the method proceeds to **136**.

At **136**, the control electronics determine if any feedback has been received from one or more peripheral devices. If feedback has been received, at **138** the control electronics may adjust the temperature in one or more barrel zones (e.g. via activation (or deactivation) of barrel heaters **1110**), and/or adjust the speed of the screw drive motor **1030**. For example, if a measured diameter of a filament of extruded material is detected as being smaller than a target diameter, the speed of a puller may be reduced and/or the melt temperature in one or more barrel zones may be increased and/or the screw speed may be increased. Likewise, if a measured diameter of a filament of extruded material is detected as being larger than a target diameter, the speed of a puller may be increased and/or the melt temperature in one or more barrel zones may be decreased and/or the screw speed may be decreased. Otherwise, the method proceeds to **140a** (if extruder **1000** is being operated in an extrusion mode of operation) or **144** (if extruder **1000** is being operated in a mold mode of operation).

If extruder **1000** is being operated in a mold mode of operation, at **144** the control electronics may determine, e.g. using one or more pressure sensors, if a pressure error has been detected. If so, the method proceeds to **122b** where the screw drive motor **1300** and the barrel heaters **1110** may be turned off, and an error may be displayed (e.g. via display **1018**). If a pressure error is not detected, the method proceeds to **146**.

At **146**, the control electronics determine if the target conditions specified for an “Autopack” routine have been reached. For example, when a mold is filled, a pressure sensor (e.g. in the output nozzle **1200**) will see a rapid increase in pressure, as the output is effectively blocked by the filled mold. When this occurs, an “Autopack” routine may be initiated, in which the screw speed is adjusted to maintain a preset output or “pack” pressure while the mold is cooled, so that additional plastic is available to counteract possible shrinkage that may occur during cooling. If the “Autopack” conditions have been met, the method proceeds to **148**, where the control electronics adjust the temperature in one or more barrel zones and/or adjust the speed of the screw drive motor to maintain a target value for the packing pressure.

At **148**, the control electronics determine the Autopack routine is finished. For example, the Autopack routine may automatically terminate after maintaining the user preset “pack” pressure for a user preset time period. Alternatively, or additionally, the Autopack routine may automatically terminate when a user preset temperature (e.g. a mold temperature) is reached. If so, the method proceeds to **142b**. Otherwise, the method proceeds to **140b**.

If, at **146**, the control electronics determine that the target conditions specified for an Autopack routine have not been reached, the method proceeds to **140b**.

At **140**, the control electronics determine if a user has requested that the extruder **1000** shut down. If a shutdown request has been received, at **142** the screw drive motor **1300** and the barrel heaters **1110** are turned off, and the method ends at **152**. Otherwise, the method returns to **120**.

## Optional Multi-Start Extrusion Screw

In accordance with another aspect of this disclosure, extrusion screw **1300** may be a multi-start screw. This aspect may be used by itself or with any one or more other aspects of extruder **1000** disclosed herein.

In accordance with this aspect, an extrusion screw **1300** has two or more screw flights wrapped around the screw, as is known in the art. For example, FIG. **21** is an end section view of a four-start screw **1300**, with flights **1330a-d** spaced about the central screw body. In contrast, FIG. **22** is an end section view of a single start screw **1300**, with flight **1330** wrapped about the central screw body.

#### Optional Multi-Component Extrusion Screw

In accordance with another aspect of this disclosure, extrusion screw **1300** may be constructed from more than one part. This aspect may be used by itself or with any one or more other aspects of extruder **1000** disclosed herein.

In accordance with this aspect, an extrusion screw **1300** may be made from two or more parts. For example, as shown in FIG. **23A**, an extrusion screw **1300** includes a first screw body section **1312**, a second screw body section **1314**, and a nose cone **1310**. First and second screw body sections may be joined using any suitable method, such as a threaded coupling, a keyed joint, welding and the like.

Alternatively, as shown in FIG. **23B**, an extrusion screw **1300** may have a one-piece screw body section **1318**.

One possible advantage of using a two-part screw body is that thermal conduction across the joint between the two screw sections may be less than if the screw body were integrally formed out of a single material. This relatively lower thermal conduction may reduce or minimize thermal conduction between the screw body sections.

Reduced thermal conduction along the screw **1300** may have one or more advantages. For example, in the illustrated embodiments the first screw body section **1312** and second screw body section **1314** are dimensioned such that, when screw **1300** is positioned in extrusion barrel **1100**, first screw body section **1312** is positioned in the feed zone of the extruder, and second screw body section **1314** is positioned downstream of the feed zone (e.g. in the heating zone) of the extruder. Thus, use of such a two-component screw body may reduce or minimize thermal transfer from the heating zone to the feed zone via the screw **1300**.

In some embodiments, first and second screw body sections may be made from different materials, which may further minimize any thermal conduction from the heating zone to the feed zone via the screw **1300**. For example, first screw body section **1312** may be made from a material that has a relatively low thermal conductivity as compared with the material from which the second screw body section **1314** is made. In some embodiments, first screw body section **1312** may be made of steel or stainless steel, and second screw body section **1314** may also be made of steel or stainless steel, or may be made of aluminum or copper.

Optionally, extrusion screw **1300** may also have an additional component for reducing the thermal connection along the screw **1300**. For example, as shown in FIG. **24**, an extrusion screw **1300** includes an insulating spacer **1316** positioned between the first screw body section **1312** and the second screw body section **1314**. The use of an insulating spacer may further inhibit thermal conduction between the first and second screw body section, which may further reduce or minimize thermal conduction from the heating zone to the feed zone via the screw **1300**.

As used herein, the wording “and/or” is intended to represent an inclusive-or. That is, “X and/or Y” is intended to mean X or Y or both, for example. As a further example, “X, Y, and/or Z” is intended to mean X or Y or Z or any combination thereof.

While the above description describes features of example embodiments, it will be appreciated that some features and/or functions of the described embodiments are suscep-

tible to modification without departing from the spirit and principles of operation of the described embodiments. For example, the various characteristics which are described by means of the represented embodiments or examples may be selectively combined with each other. Accordingly, what has been described above is intended to be illustrative of the claimed concept and non-limiting. It will be understood by persons skilled in the art that other variants and modifications may be made without departing from the scope of the invention as defined in the claims appended hereto. The scope of the claims should not be limited by the preferred embodiments and examples, but should be given the broadest interpretation consistent with the description as a whole.

The invention claimed is:

1. An extruder comprising:

a) a barrel extending from a feed inlet end to an extruder outlet end, the barrel having an inner surface, an outer surface and a wall thickness between the inner and outer surfaces;

b) at least one barrel heater positioned exterior to the barrel;

c) a screw drive motor drivingly connected to a rotatably mounted screw positioned within the barrel, the screw having a length from the feed inlet end of the barrel to the extruder outlet end of the barrel and the length has a single flight having a plurality of threads, whereby the screw is rotatable at various revolutions per minute (RPM), the screw is a flow inducing member that delivers plastic to a mold; and

d) a controller operably connected to the screw drive motor to adjust the RPM of the screw based upon a temperature of material passing through and/or being extruded from the barrel

wherein the barrel has a section that has a diameter of up to 2.405 inches in which solid feed material is liquefied that is operated at a pressure of 10-200 psi,

wherein a flight clearance between the inner surface of the barrel and an outer extent of the flight is from 0.005 to 0.04 inches, and

wherein the single flight has a flight depth from an outer lateral extent of the flight to an inner lateral extent that is generally constant and a flight width that is generally.

2. The extruder of claim 1 wherein the controller is operably connected to the screw drive motor to increase the RPM of the screw subsequent to the temperature of the material passing through and/or being extruded from the barrel increasing above a predetermined value.

3. The extruder of claim 1 wherein the controller is operably connected to the screw drive motor to decrease the RPM of the screw subsequent to the temperature of the material passing through and/or being extruded from the barrel decreasing below a predetermined value.

4. The extruder of claim 1 wherein the barrel has a wall thickness of from 0.01 to 0.375 inches.

5. The extruder of claim 1 wherein the flight clearance remains constant or increases from the feed inlet end to the extruder outlet end.

6. The extruder of claim 5 wherein the volumetric compression ratio, defined as a ratio of a channel depth of a feed section of the extruder to a channel depth in a metering section of the extruder, is  $\leq 1$ .

7. The extruder of claim 1 wherein the barrel comprises at least one of aluminum, copper, steel, and stainless steel.

8. The extruder of claim 1 wherein a flight depth from an outer lateral extent of the flight to an inner lateral extent of a flight along the length of the screw is from 0.2-0.5 inches.

## 33

9. The extruder of claim 1 wherein a land portion of the screw between two adjacent threads of a flight is from 0.125 to 0.5 inches.

10. The extruder of claim 1 wherein a land portion of the outward lateral extent of the flight of the screw between two adjacent threads of a flight is from 0.25 to 0.5 inches.

11. The extruder of claim 1 wherein the section of the barrel in which solid feed material is liquefied is operated at a pressure of 40-200 psi.

12. The extruder of claim 1 wherein at least 60% of energy provided to the extruder is used to produce heat.

13. The extruder of claim 1 wherein the screw and barrel are sized such that at least 70% of heat that is introduced into material in the barrel is supplied by the at least one barrel heater and less than 30% of the heat that is introduced into the material in the barrel is supplied by shearing the material.

14. The extruder of claim 1 wherein the screw and barrel are sized such that at least 80% of heat that is introduced into material in the barrel is supplied by the at least one barrel heater and less than 20% of the heat that is introduced into the material in the barrel is supplied by shearing the material.

15. The extruder of claim 1 wherein the screw comprises a first screw section and a second screw section and a thermal insulation member is provided between the first and second screw sections.

16. The extruder of claim 15 wherein the first screw section is made of a material having lower thermal conductivity than the second screw section.

17. The extruder of claim 15 wherein the first screw section is provided in a feed section of the extruder and the second screw section is provided downstream of the feed section of the extruder.

18. The extruder of claim 1 wherein the screw comprises a first screw section and a second screw section and the first screw section is made of a material having lower thermal conductivity than the second screw section.

## 34

19. The extruder of claim 1, wherein the extruder produces a flow of 11 lbs per hour per inch<sup>2</sup> to 43 lbs per hour per inch<sup>2</sup>.

20. The extruder of claim 4, wherein the screw is the sole flow inducing member.

21. The extruder of claim 1, wherein the screw is a single channel screw.

22. An extruder comprising:

a) a barrel extending from a feed inlet end to an extruder outlet end, the barrel having an inner surface, an outer surface and a wall thickness between the inner and outer surfaces;

b) at least one barrel heater positioned exterior to the barrel;

c) a screw drive motor drivingly connected to a rotatably mounted screw positioned within the barrel, the screw having a length and a flight having a plurality of threads thereon, whereby the screw is rotatable at various revolutions per minute (RPM) and is a sole flow inducing member that delivers plastic to a mold; and

d) a controller operably connected to the screw drive motor to adjust the RPM of the screw based upon a temperature of material passing through and/or being extruded from the barrel

wherein the barrel has a section that has a diameter of up to 2.405 inches in which solid feed material is liquefied that is operated at a pressure of 10-200 psi,

wherein a flight clearance between the inner surface of the barrel and an outer extent of the flight is from 0.005 to 0.04 inches, and

wherein a flight depth from an outer lateral extent of the flight to an inner lateral extent of the flight along the length of the screw is generally constant and a flight width is generally constant along the length of the screw.

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