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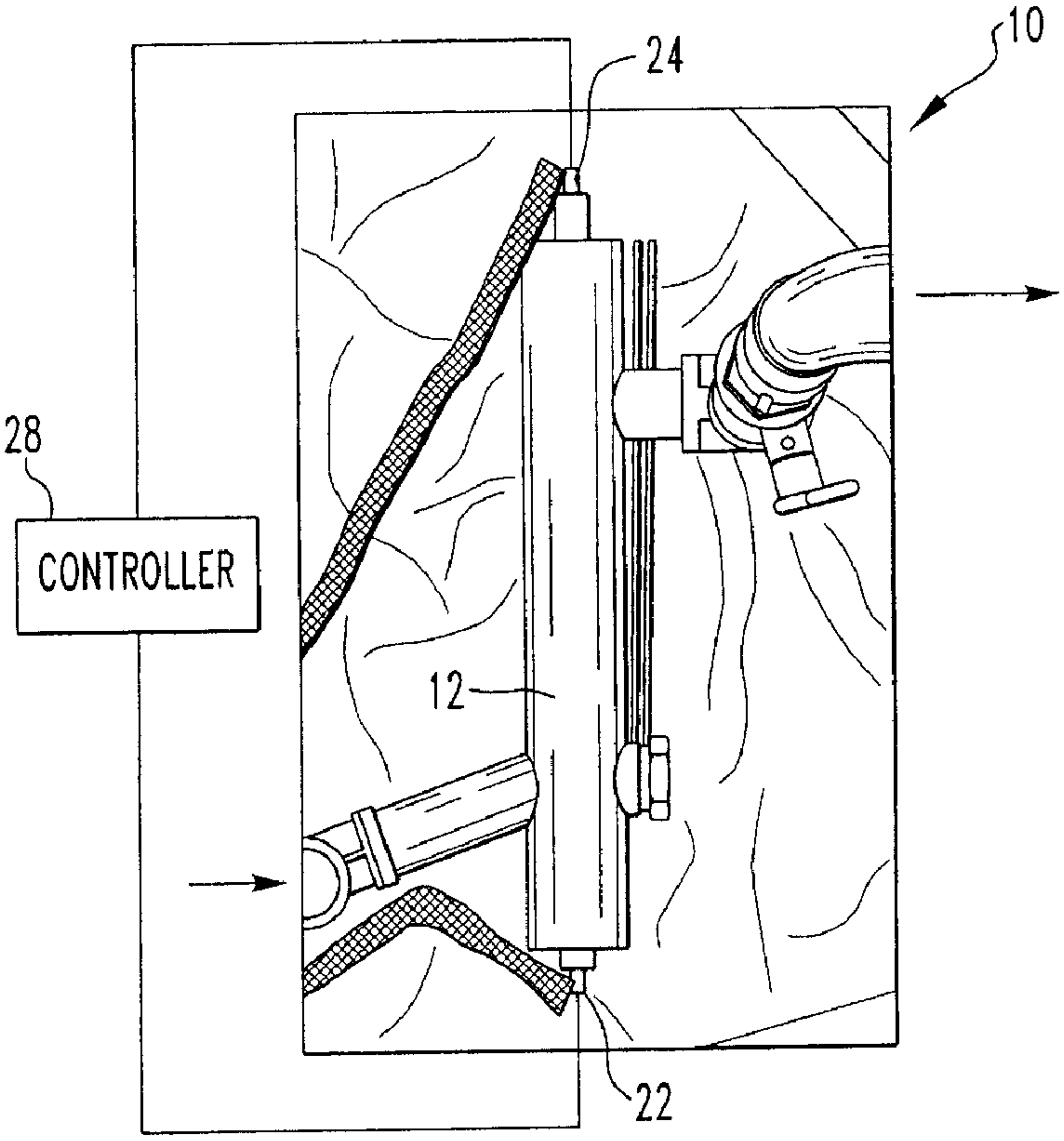
(54) Title: CONICAL-FACED ULTRASONIC TRANSDUCER, FLOW METER, AND METHOD



(57) Abrégé/Abstract:
An ultrasonic transducer for a pipe includes an ultrasonic source which produces plane waves. The transducer includes a housing having a face at least a portion of which is curved, through which the plane waves produced from the ultrasonic source disposed in the housing are emitted and directed outward towards the pipe's interior wall so that a full cross-section of the pipe's interior can be measured. A flow meter for detecting fluid flow rates in a pipe. A method for detecting fluid flow rates in a pipe.

ABSTRACT OF THE DISCLOSURE

An ultrasonic transducer for a pipe includes an ultrasonic source which produces plane waves. The transducer includes a housing having a face at least a portion of which is curved, through which the plane waves produced from the ultrasonic source disposed in the housing are emitted and directed outward towards the pipe's interior wall so that a full cross-section of the pipe's interior can be measured. A flow meter for detecting fluid flow rates in a pipe. A method for detecting fluid flow rates in a pipe.

CONICAL-FACED ULTRASONIC TRANSDUCER, FLOW METER, AND METHOD

FIELD OF THE INVENTION

The present invention is related to determining fluid flow rate in a pipe using an ultrasonic transducer. (As used herein, references to the "present invention" or "invention" relate to exemplary embodiments and not necessarily to every embodiment encompassed by the appended claims.) More specifically, the present invention is related to determining fluid flow rate in a pipe using an ultrasonic transducer where the face of the transducer has at a portion which is shaped such that it causes the plane waves generated by the transducer to be directed outward towards the pipe's interior wall so a full cross-section of the pipe's interior can be measured.

BACKGROUND OF THE INVENTION

This section is intended to introduce the reader to various aspects of the art that may be related to various aspects of the present invention. The following discussion is intended to provide information to facilitate a better understanding of the present invention. Accordingly, it should be understood that statements in the following discussion are to be read in this light, and not as admissions of prior art.

The current invention is applicable for measuring flow rates with ultrasonic transit time technology (e.g., ultrasonic flow meters, or UFMs). The application is specifically developed for a flow meter to monitor chemical injection in subsea oil wells (typically injecting mono-ethylene glycol or MEG). This specific subsea application has flow rates that range from 100 liters/hr to 30,000 liters/hr. For this flow range and product viscosity, the Reynolds number ranges from laminar flow to fully turbulent flow. This range of Reynolds number produces velocity profiles that vary from parabolic to nearly flat. As a flow meter, the average velocity (e.g., integral of velocity profile divided by the area) must be measured.

The current ultrasonic flow meter arrangement uses in one embodiment two transducers at opposing ends of a pipe/tube where one is upstream from the fluid flow and the other is downstream from the fluid flow. Both transducers transmit and receive signals. Each transducer generates plane waves into the fluid. The difference in transit times between the upstream and downstream signal is used to calculate the velocity between the two transducers. This difference in transit time reflects the average fluid velocity projected onto the acoustic path.

Unless the transducer is larger than the diameter of the pipe/tube, the acoustic path measures a cross-section of velocities that represent an area that is less than the full cross-section of the pipe/tube. Only if the transducer is larger than the tube itself can the full cross-section be measured. A transducer large enough to completely cover the pipe/tube cross-section is not always possible or even practical depending upon the pipe/tube size or pressure (e.g., required wall thicknesses). Some UFMs have used multiple bounces; however, these multiple bounces cannot get the full cross-section.

By measuring the full cross-section, velocity profile effects are addressed (for example any distortions due to hydraulics or changes in the velocity profile due to transition from laminar to turbulent).

BRIEF SUMMARY OF THE INVENTION

The present invention pertains to the measurement of flowing fluid through a pipe. The measurement is performed with a transit time ultrasonic flow meter having transducers that are disposed in alignment with the fluid flow through the pipe. The radiation pattern of the plane waves produced by the transducers propagates through the flowing fluid in the pipe and is used by the flow meter to determine the flow rate of the fluid.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

In the accompanying drawings, the preferred embodiment of the invention and preferred methods of practicing the invention are illustrated as follows:

FIGURE 1 is a standard design of the present invention.

FIGURE 2 is an example of a conical-faced transducer.

FIGURES 3A and 3B show the calculation of the transducer face angles.

FIGURE 4 shows an antenna pattern for transducer shown in FIG. 2.

FIGURE 5A shows an insertion transducer configuration.

FIGURE 5B shows an end cap transducer configuration.

FIGURE 6 is an example of improved linearity possible by integrating the full cross-section.

FIGURE 7 shows that a change in the viscosity from 10 centiStokes (cSt) to 20 cSt to 50 cSt has no effect on the linearity, even over a 200:1 Reynolds number range.

FIGURE 8 shows linearity insensitivity to hydraulic changes.

FIGURE 9 shows an axial view of an insertion transducer with a single support.

FIGURE 10 shows an axial view of an insertion transducer with a double support.

FIGURE 11 shows an axial view of an insertion transducer with a cantilevered support.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the drawings wherein like reference numerals refer to similar or identical parts throughout the several views, and more specifically to FIG. 2 thereof, there is shown an ultrasonic transducer **10** for a pipe **12**. The transducer **10** comprises an ultrasonic source **14** which produces plane waves. The transducer **10** comprises a housing **16** having a face **18** at least a portion of which is curved, through which the plane waves produced from the source **14** disposed in the housing **16** are emitted and directed outward towards the interior wall **26** of the pipe **12** so that a full cross-section of the interior of the pipe **12** can be measured (see FIGS. 3A and 3B). The transducer **10** is a standard transducer **10** available from many suppliers, with the only difference being that the face **18** has at least the portion which is shaped, as described above. The shaped portion of the face **18**, which in one embodiment was made of stainless steel, causes the plane waves to refract as they propagate according to Snell's law through the face **18**, and to be directed outward toward the interior wall **26** of the pipe **12**. Similarly, upon reception, the plane waves at various angles to the shaped portion of the face **18** are refracted back to an angle that can be captured by the transducer **10** according to Snell's law to produce a signal based on the flow rate, as is well known in the art.

At least a portion of the face **18** may be a portion of a cone. In one embodiment the face **18** may be conically shaped. A desired angle, $\varphi_{desired}$, of the conical shape may be defined by the equation:

$$\varphi_{desired} = \tan^{-1}\left[\frac{\frac{D}{2} - \frac{r}{2}}{\frac{L}{2} + \sin\varphi_{face} \cdot \frac{r}{z}}\right]$$

where **D** is the diameter of the pipe **12**; **L** is the length of the pipe **12**; **r** is the radius of the transducer **10**; $\frac{\sin\varphi_{face}}{c_{window}} = \frac{\sin\varphi_{refract}}{c_{fluid}}$; and $\varphi_{desired} = \varphi_{face} - \varphi_{refract}$.

The present invention pertains to a flow meter **20** for detecting fluid flow rates in a pipe **12**, as shown in FIG. 1 and FIG. 5B. The flow meter **20** comprises an upstream ultrasonic transducer **22** having a face **18** at least a portion of which is shaped in communication with the interior of the pipe **12** and positioned so plane waves generated by the upstream transducer **22** are directed outward towards the pipe's interior wall **26** and propagate along the pipe's interior so a full cross-section of the pipe's interior can be measured (see FIGS. 3A and 3B). The flow meter **20** comprises a controller **28** in communication with the upstream transducer **22** which calculates fluid flow rate from the plane waves that have propagated along the pipe's interior. The calculation of fluid flow rate from the received plane waves is well known in the art. [Refer to Chapter 5 in: Physical Acoustics - Principles and Methods, W. P. Mason and R. N. Thurston (Editors), Vol. 14, pp. 407-525, Academic Press (1979).]

The flow meter **20** may include a downstream ultrasonic transducer **24** having a face **18** at least a portion of which is curved in communication with the pipe's interior and positioned so that plane waves generated by the downstream transducer **24** are directed outward towards the pipe's interior wall **26** and propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured, and are received by the upstream transducer **22** which produces an upstream transducer signal. The downstream transducer **24** receives the plane waves from the upstream transducer **22** and provides a downstream transducer signal. The controller **28** is in communication with the upstream and downstream transducers 24 which calculates fluid flow rate from the upstream transducer signal and the downstream transducer signal.

At least a portion of each face **18** may be a portion of a cone. Each face **18** may be conically shaped.

A desired angle, $\varphi_{desired}$, of the conical shape may be defined by the equation:

$$\varphi_{desired} = \tan^{-1}\left[\frac{\frac{D}{2} - \frac{r}{2}}{\frac{L}{2} + \sin\varphi_{face} \cdot \frac{r}{z}}\right]$$

where **D** is the diameter of the pipe **12**; **L** is the length of the pipe **12**; **r** is the radius of the transducer **10**; $\frac{\sin \varphi_{face}}{c_{window}} = \frac{\sin \varphi_{refract}}{c_{fluid}}$; and $\varphi_{desired} = \varphi_{face} - \varphi_{refract}$.

The flow meter **20** may include a support **30** that extends from the pipe **12** wall **26** into the pipe **12** interior upon which the upstream transducer **22** is mounted (see FIG. 5A). FIG. 9 shows a single support **30**. FIG. 10 shows a double support **30** and FIG. 11 shows a cantilevered support **30**.

The present invention pertains to a method for detecting fluid flow rates in a pipe **12**. The method comprises the steps of generating plane waves by an upstream transducer **22** having a face **18** at least a portion of which is curved in communication with the interior of the pipe **12** and positioned so that plane waves are directed outward towards the pipe's interior wall **26** and propagate along the pipe's interior so a full cross-section of the pipe's interior can be measured. There is the step of calculating fluid flow rate from the plane waves that have propagated along the pipe's interior with a controller **28** in communication with the upstream transducer **22**.

There can be the steps of generating plane waves with a downstream ultrasonic transducer **24** having a face **18** at least a portion of which is curved and in communication with the pipe's interior and positioned so that the plane waves are directed outward towards the pipe's interior wall **26** and propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured. There can be a step of receiving the plane waves generated by the downstream transducer **24** at the upstream transducer **22** which produces an upstream transducer signal. There can be the step of receiving the plane waves generated by the upstream transducer **22** at the downstream transducer **24** which produces a downstream transducer signal. There can be the step of providing to the controller **28** in communication with the upstream and downstream transducers the upstream and downstream signals. There can be the step of calculating with the controller **28** fluid flow rate from the upstream transducer signal and the downstream transducer signal.

At least a portion of each face **18** may be a portion of a cone. Each face **18** may be conically shaped. A desired angle, $\varphi_{desired}$, of the conical shape may be defined by the equation:

$$\varphi_{desired} = \tan^{-1}\left[\frac{\frac{D}{2} - \frac{r}{2}}{\frac{L}{2} + \sin\varphi_{face} \cdot \frac{r}{z}}\right]$$

where **D** is the diameter of the pipe **12**; **L** is the length of the pipe **12**; **r** is the radius of the transducer **10**; $\frac{\sin\varphi_{face}}{c_{window}} = \frac{\sin\varphi_{refract}}{c_{fluid}}$; and $\varphi_{desired} = \varphi_{face} - \varphi_{refract}$.

In the operation of the invention, one pair of transducers is used to ensonify the full cross-section of the measuring tube or pipe. The end result is a time of flight measurement that reflects the full cross-section of velocities. This produces a flow meter that is essentially insensitive to changes in viscosity (e.g., Reynolds number) and upstream hydraulics. The present invention uses a transducer **10** having a face **18** at least a portion of which is curved face **18**, and ideally is of a conical shape. The angle of the cone is designed based on the length and size of the measurement tube. The angle of the cone considers refraction (due to Snell's law). The effect of refraction is computed to be insignificant. This conical face **18** makes the acoustic energy radiate out to the sides of the tube from the center of the transducer **10**. At the walls, the sound then reflects back to the center. The result is that the flow meter measures the full cross-section of the measuring tube.

The transducers were at opposing ends of the tube (see FIG. 1). FIG. 1 is a standard design of the present invention. The standard window face **18** of transducer **10** (i.e., the side facing the fluid) is typically flat. The present invention puts a conical face **18** to refract the sound out to the walls (see FIG. 2). FIG. 2 is an example of a conical-faced transducer **10**. The design of the conical face **18** depends upon the dimensions of the measuring tube and the refraction due to the fluid to transducer face **18** interface (e.g., Snell's law). The following calculation is set out with reference to FIG. 3A, which also shows an example antenna pattern. FIG. 3A and 3B show the calculation of the face angles of the transducer **10**.

A desired angle, $\varphi_{desired}$, of the conical shape may be defined by the equation:

$$\varphi_{desired} = \tan^{-1}\left[\frac{\frac{D}{2} - \frac{r}{2}}{\frac{L}{2} + \sin\varphi_{face} \cdot \frac{r}{z}}\right]$$

where **D** is the diameter of the pipe **12**; **L** is the length of the pipe **12**; **r** is the radius of the transducer **10**; $\frac{\sin\varphi_{face}}{C_{window}} = \frac{\sin\varphi_{refract}}{C_{fluid}}$; and $\varphi_{desired} = \varphi_{face} - \varphi_{refract}$.

The radiation pattern or antenna pattern of the transducer face **18** results in a spreading conical pattern (that is, until it hits the walls, at which point it becomes a focusing cone). The antenna pattern for one transducer **10** built (see FIG. 2) is shown in FIG. 4. This antenna had 3.5 MHz transducers and a 12.7-mm-diameter transducer, and the media had a sound velocity of 1500 m/s. FIG. 4 shows an antenna pattern for transducer **10** shown in FIG. 2.

The design of flow meters **20** need not be limited to meters that have the transducers at the ends of tubes. The principles can be used in other arrangements – for examples, see FIG. 5A and FIG. 5B. FIG. 5A shows an insertion transducer **10** configuration. FIG. 5B shows an end cap transducer **10** configuration. There are arrangements at which the transducer **10** may be along one side or the other that uses a portion of a cone to radiate across the pipe **12** using the opposing side as a reflection source **14**.

An example of the invention's improved linearity is demonstrated in FIG. 6, which shows the real performance improvement possible with the invention. The standard line-of-sight approach is represented by triangles. This standard meter had a 0.5-inch transducer **10** in a 1.5-inch-diameter tube. FIG. 6 is an example of improved linearity possible by integrating the full cross-section. FIG. 7 shows that a change in the viscosity from 10 cSt to 20 cSt to 50 cSt has no effect on the linearity, even over a 200:1

Reynolds number range. FIG. 8 shows linearity insensitivity to hydraulic changes. FIG. 8 shows that for changes in the hydraulics (from a non-planar 90-degree elbow coupled with the 70-degree elbow, to three non-planar 90-degree elbows to one planar elbow, the linearity is unaffected. The present invention is not limited to a chemical injection meter since the invention solves the velocity profile integration problem.

FIG. 9 shows an axial view of a transducer **10** with a single support **30**. FIG. 10 shows an axial view of a transducer **10** with double supports **30**. FIG. 11 shows an axial view of a transducer **10** with a cantilevered support **30**.

Although the invention has been described in detail in the foregoing embodiments for the purpose of illustration, it is to be understood that such detail is solely for that purpose and that variations can be made therein by those skilled in the art without departing from the scope of the invention except as it may be described by the following claims.

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

1. An ultrasonic transducer for a pipe, said ultrasonic transducer comprising:

   (a) an ultrasonic source for producing plane waves; and

   (b) a housing having a face at least a portion of which is curved and through which plane waves produced from the source disposed in the housing will be emitted and directed outward in a spreading conical pattern towards the pipe's interior wall so that a full cross-section of the pipe's interior can be measured.

2. An ultrasonic transducer as in Claim 1 wherein at least a portion of the face is a portion of a cone.

3. An ultrasonic transducer as in Claim 2 wherein the face is conically shaped.

4. A flow meter for detecting fluid flow rates in a pipe, said flow meter comprising:

   (a) an upstream ultrasonic transducer having a face at least a portion of which is curved in communication with the pipe interior and positioned such that plane waves generated by the upstream transducer will be directed outward in a spreading conical pattern towards the pipe's interior wall and will propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured; and

   (b) a controller in communication with the upstream transducer, said controller being configured to calculate fluid flow rate from plane waves that have propagated along the pipe's interior.

5. A flow meter as in Claim 4, further comprising a downstream ultrasonic transducer, wherein the downstream ultrasonic transducer has a face at least a portion of which is curved and in communication with the pipe's interior and positioned such that plane waves generated by the downstream transducer will be directed outward towards the pipe's interior wall and will propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured, and further such that the plane waves generated by the downstream transducer will be received by the upstream transducer which will in turn produce an upstream transducer signal, with the downstream transducer receiving the plane waves from the upstream transducer and providing a downstream transducer signal, and with the controller in communication with the upstream and downstream transducers such that the controller can calculate fluid flow rate from the upstream transducer signal and the downstream transducer signal.

6. A flow meter as in Claim 5 wherein at least a portion of the face of the upstream transducer is a portion of a cone, and wherein at least a portion of the face of the downstream transducer is a portion of a cone.

7. A flow meter as in Claim 6 wherein the face of the upstream transducer is conically shaped, and wherein the face of the downstream transducer is conically shaped.

8. A flow meter as in Claim 7, wherein a support extends from the pipe wall into the pipe interior, and wherein the upstream transducer is mounted on said support.

9. A method for detecting fluid flow rates in a pipe, said method comprising the steps of:

(a) generating plane waves with an upstream transducer having a face at least a portion of which is curved in communication with the pipe interior and positioned such that the plane waves generated by the upstream transducer are directed outward in a spreading conical pattern towards the pipe's interior wall and propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured;

(b) providing a controller in communication with the upstream transducer; and

(c) by means of said controller, calculating fluid flow rate from the plane waves that have propagated along the pipe's interior.

10. A method as in Claim 9 including the further steps of:

(c) generating plane waves with a downstream ultrasonic transducer having a face at least a portion of which is curved in communication with the pipe's interior and positioned such that the plane waves generated by the downstream ultrasonic transducer are directed outward towards the pipe's interior wall and propagate along the pipe's interior so that a full cross-section of the pipe's interior can be measured;

(d) receiving the plane waves generated by the downstream transducer at the upstream transducer such that the upstream transducer produces an upstream transducer signal;

(e) receiving the plane waves generated by the upstream transducer at the downstream transducer such that the downstream transducer produces a downstream transducer signal;

(f) providing the upstream and downstream signals to the controller; and

(g) by means of the controller, calculating fluid flow rate from the upstream transducer signal and the downstream transducer signal.

11. A method as in Claim 10 wherein at least a portion of the face of the upstream transducer is a portion of a cone, and wherein at least a portion of the face of the downstream transducer is a portion of a cone.

12. A method as in Claim 11 wherein the face of the upstream transducer is conically shaped, and wherein the face of the downstream transducer is conically shaped.

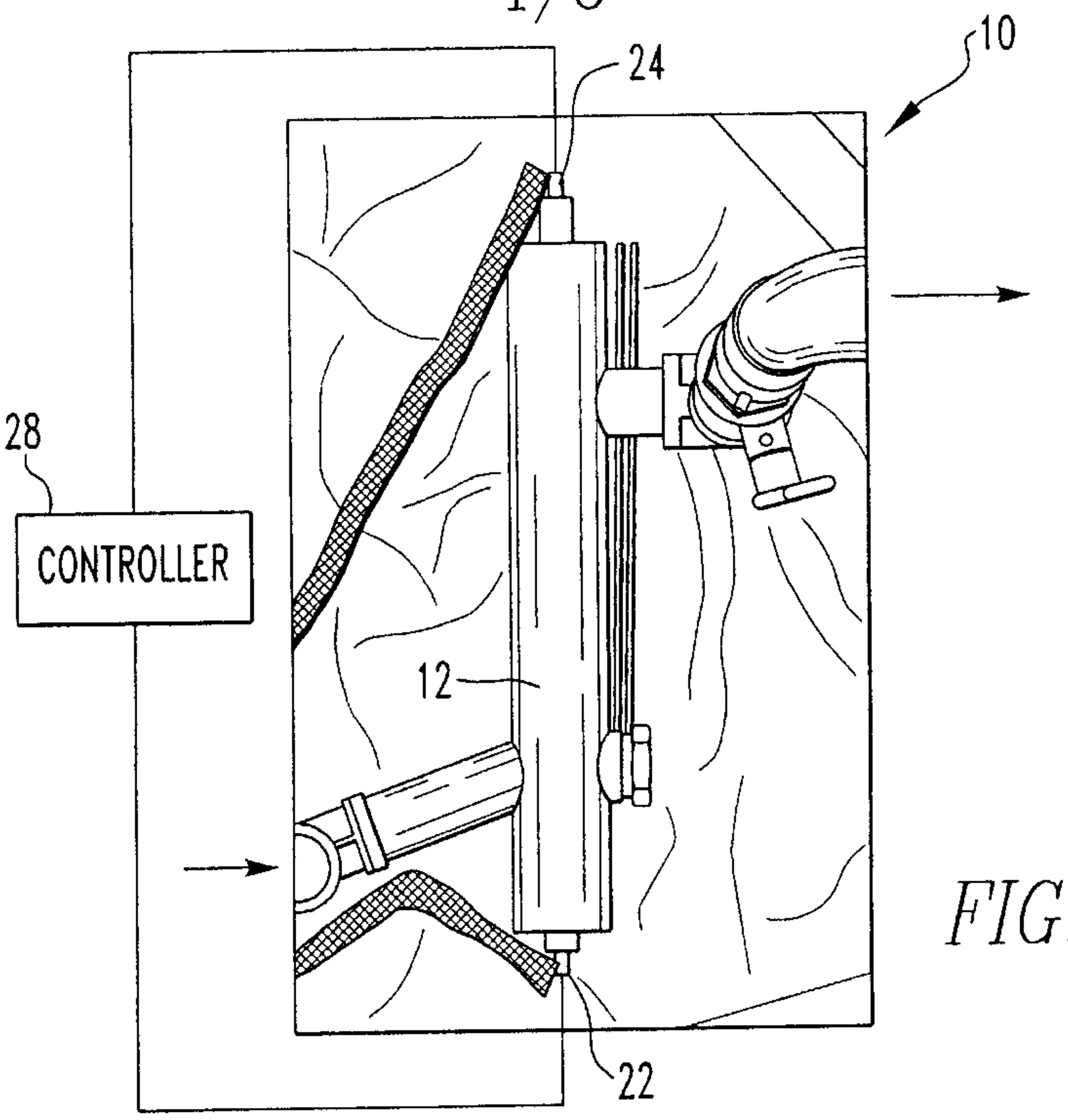


FIG.1

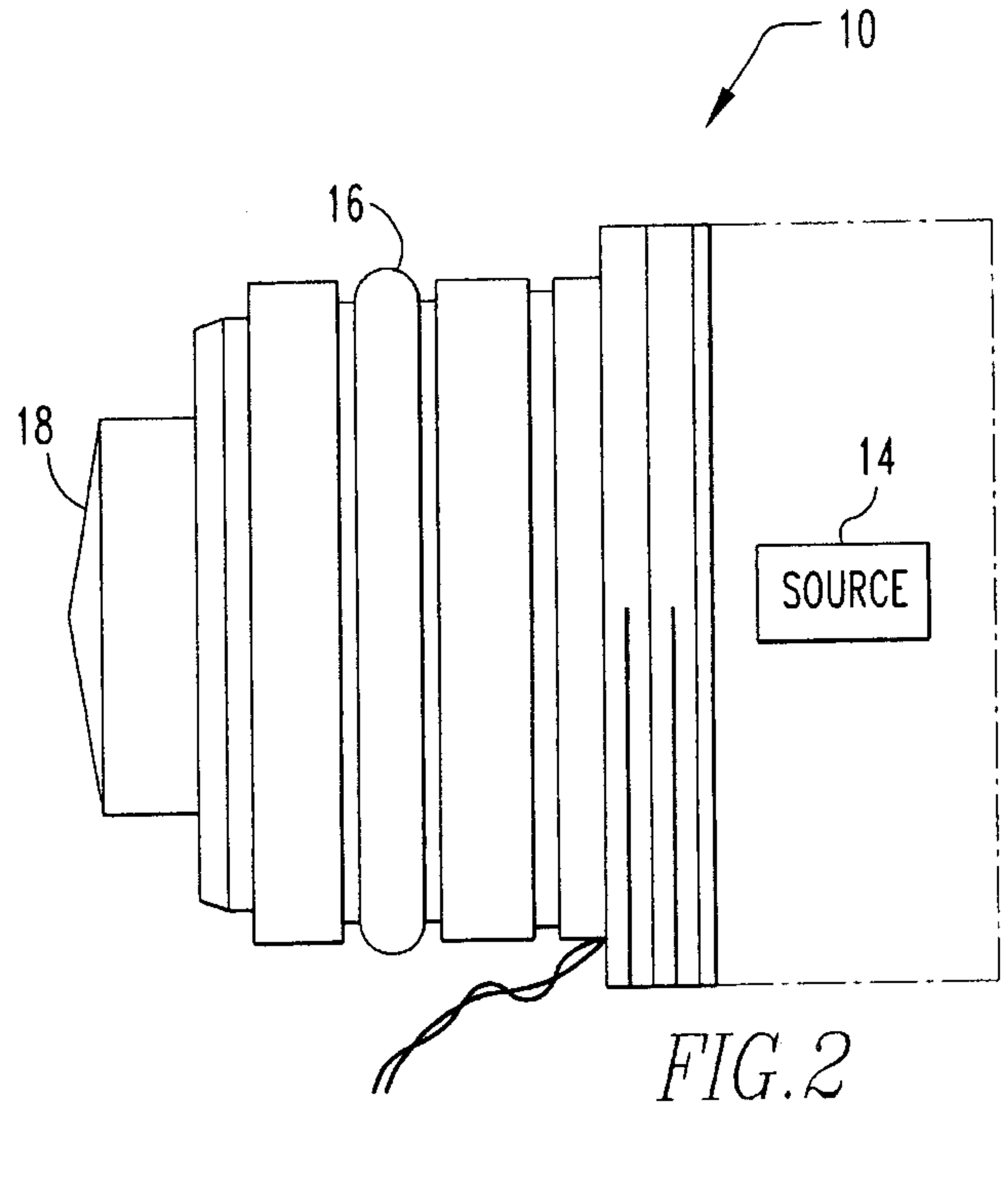


FIG.2

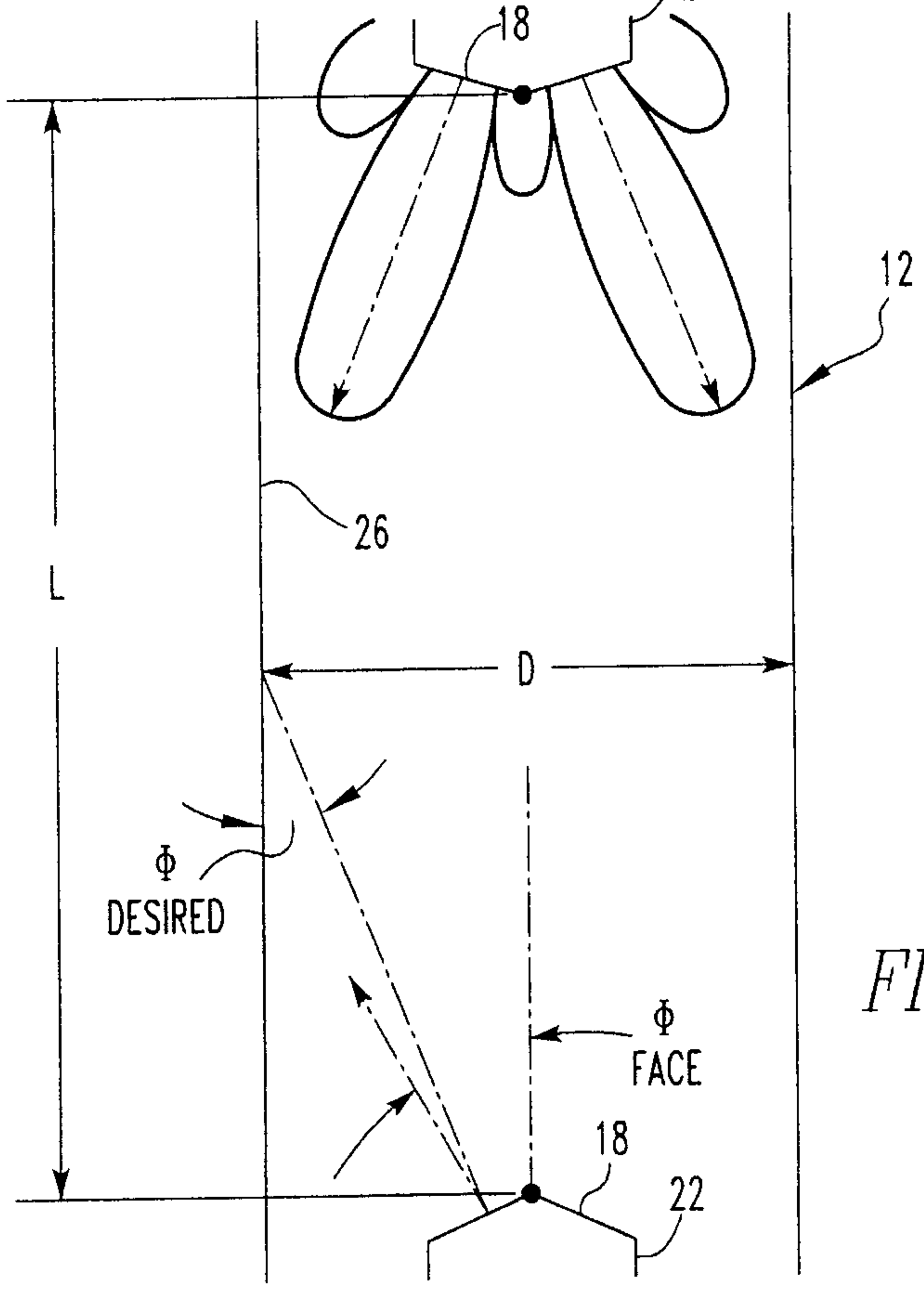
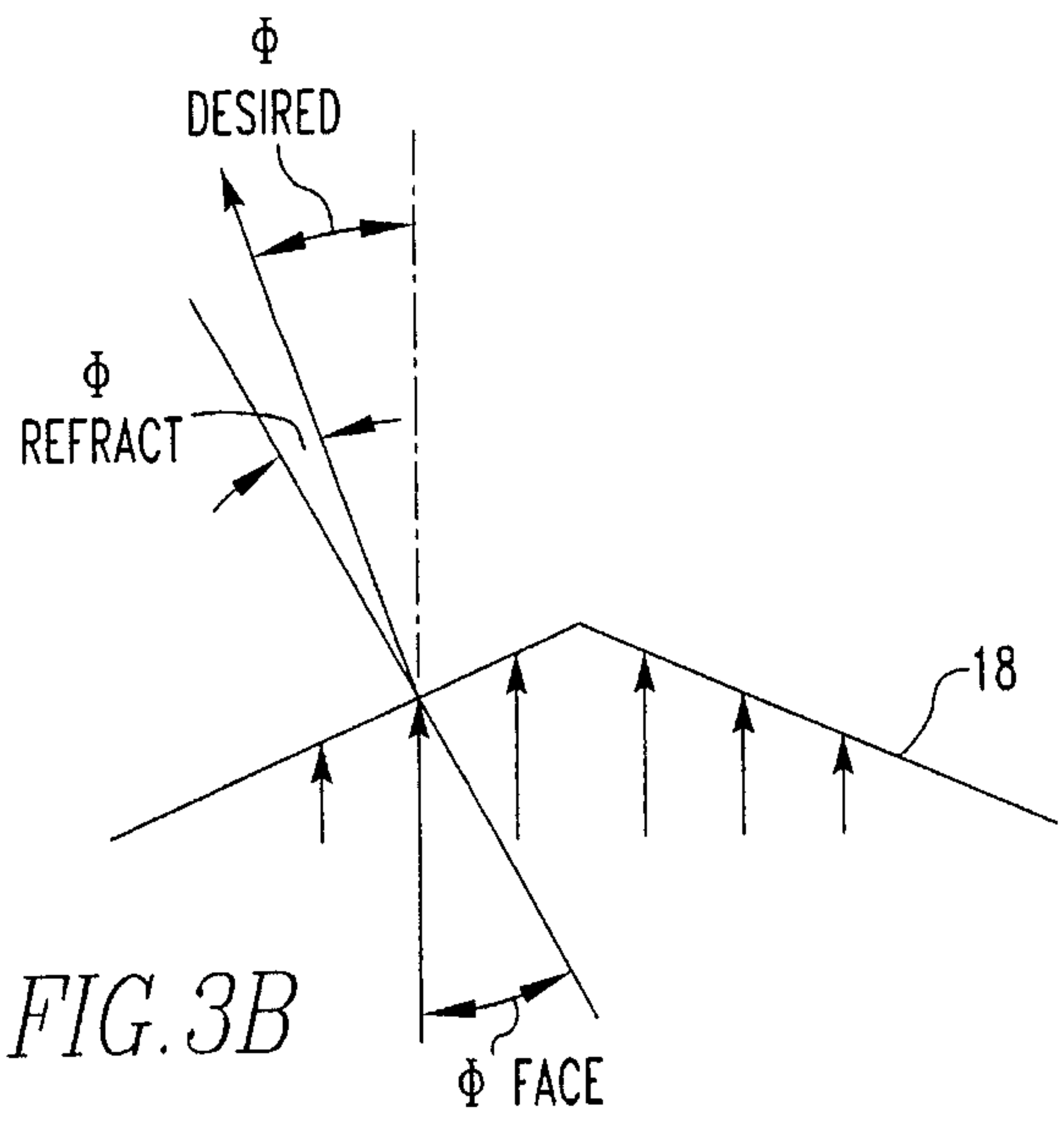

24
18
12
26
L
D
Φ
DESIRED
Φ
FACE
18
22

FIG.3A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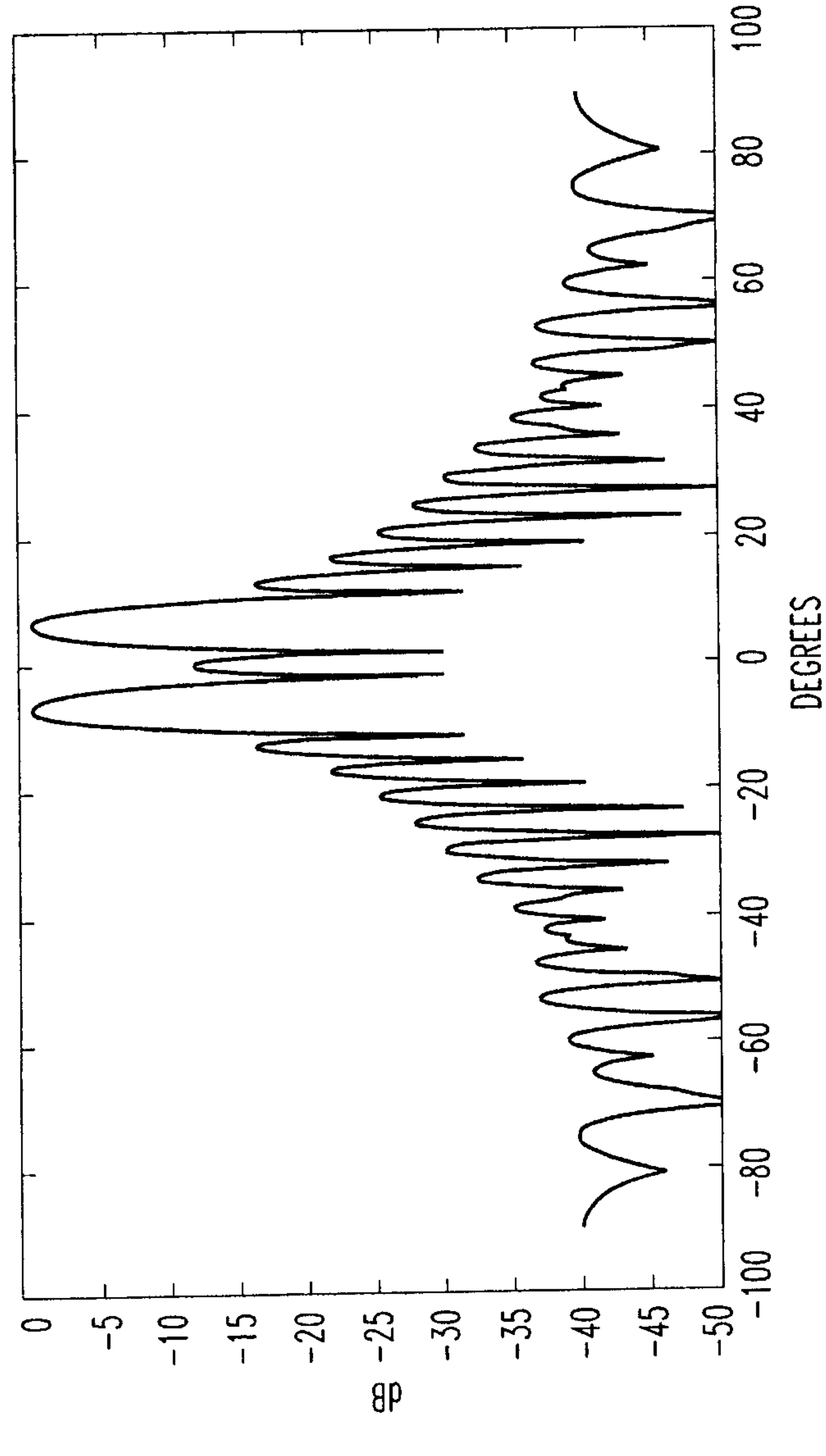
Φ
REFRACT
18
Φ FACE

FIG.3B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-20
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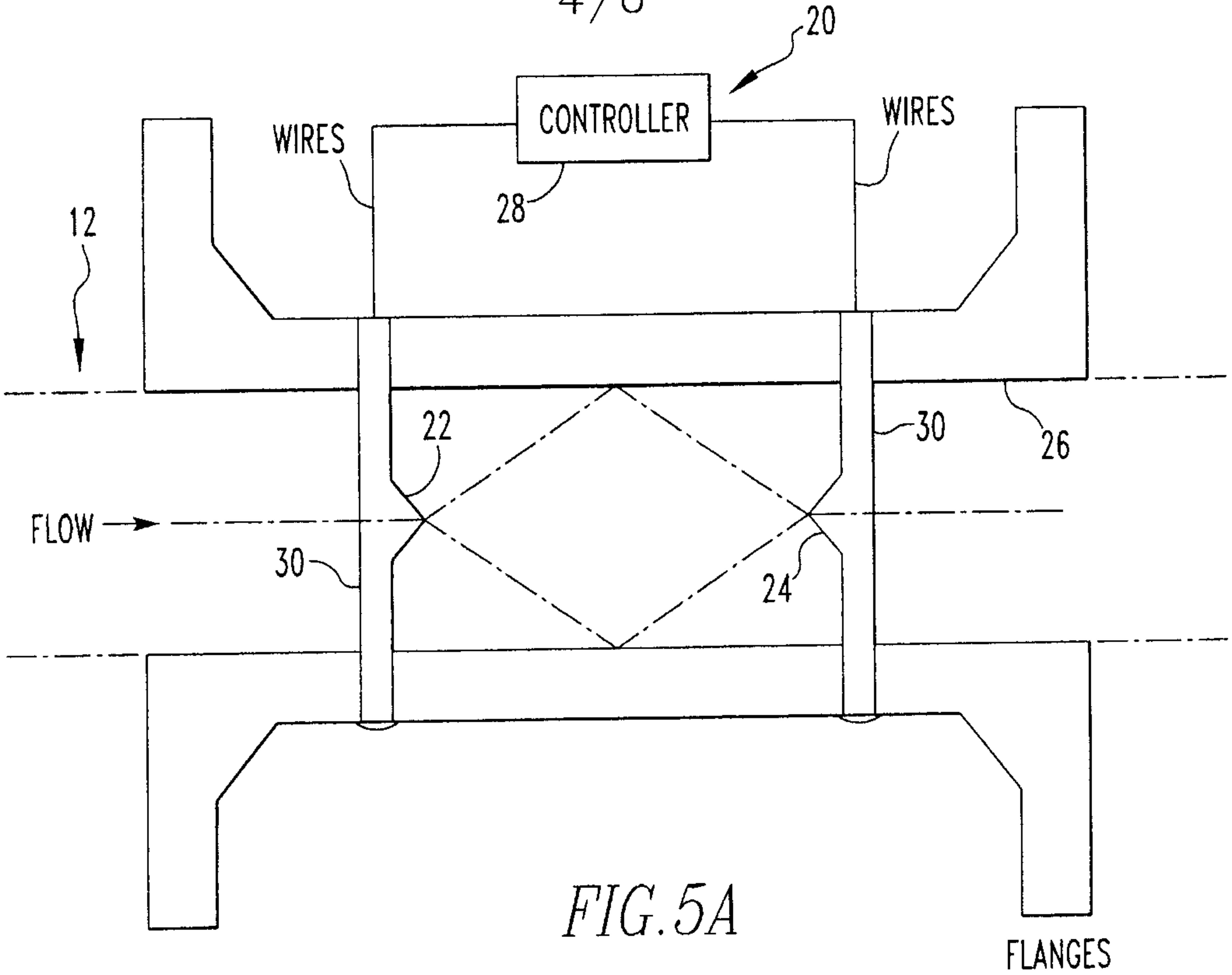
20
40
60
80
100
DEGREES

FIG.4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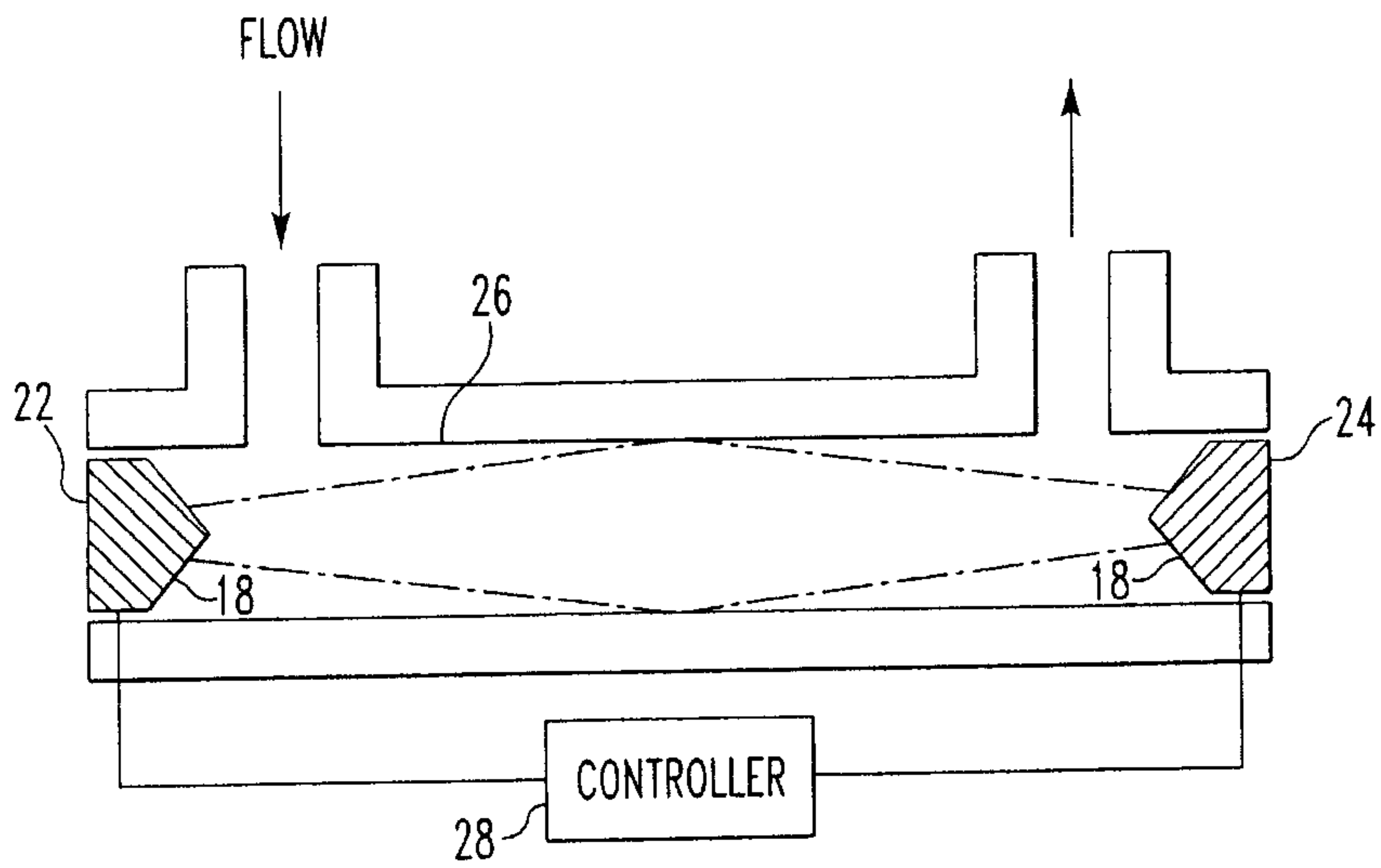
WIRES
28
12
22
30
26
FLOW
30
24
FLANGES

FIG.5A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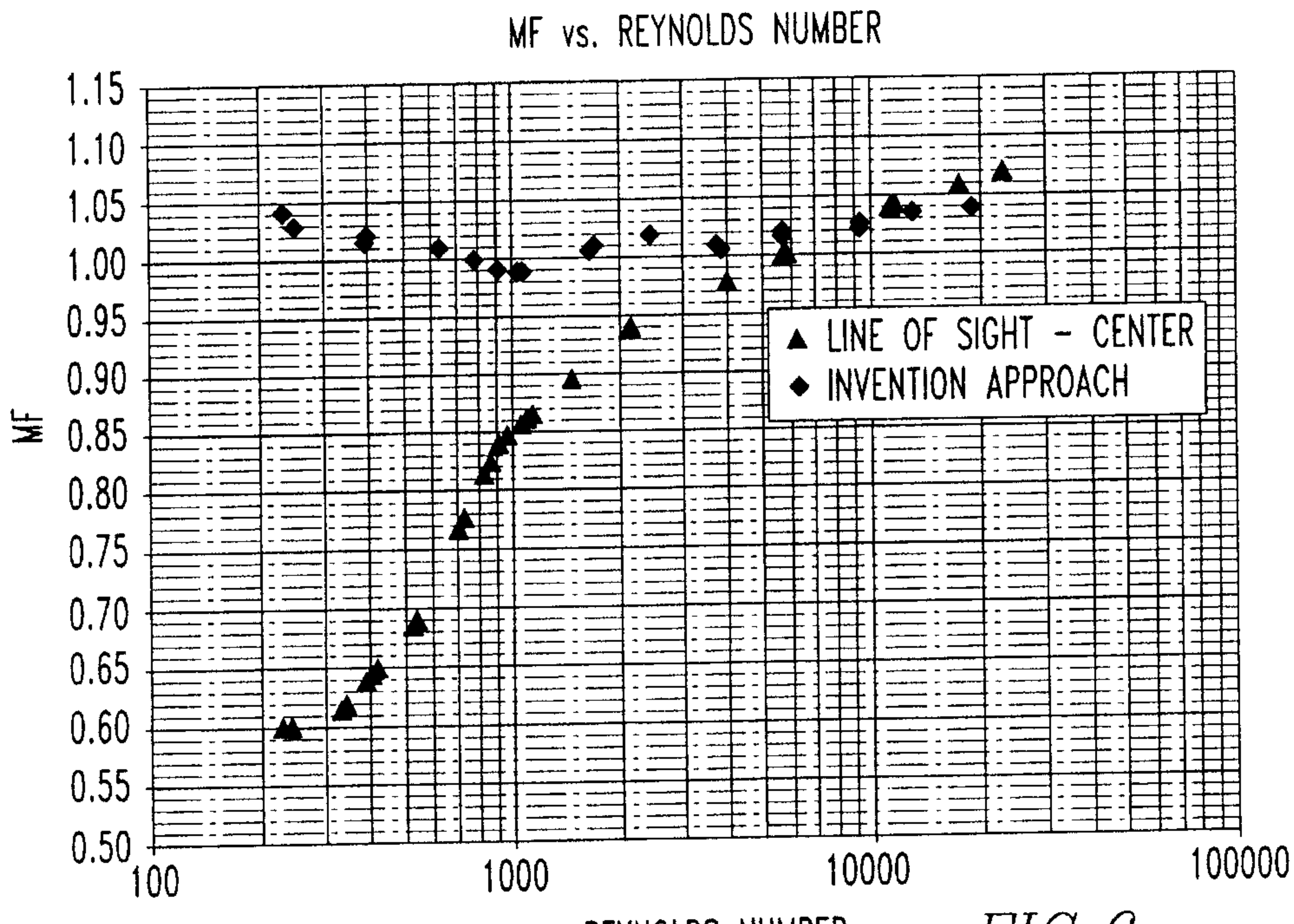
18
18
CONTROLLER
28

FIG.5B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10000
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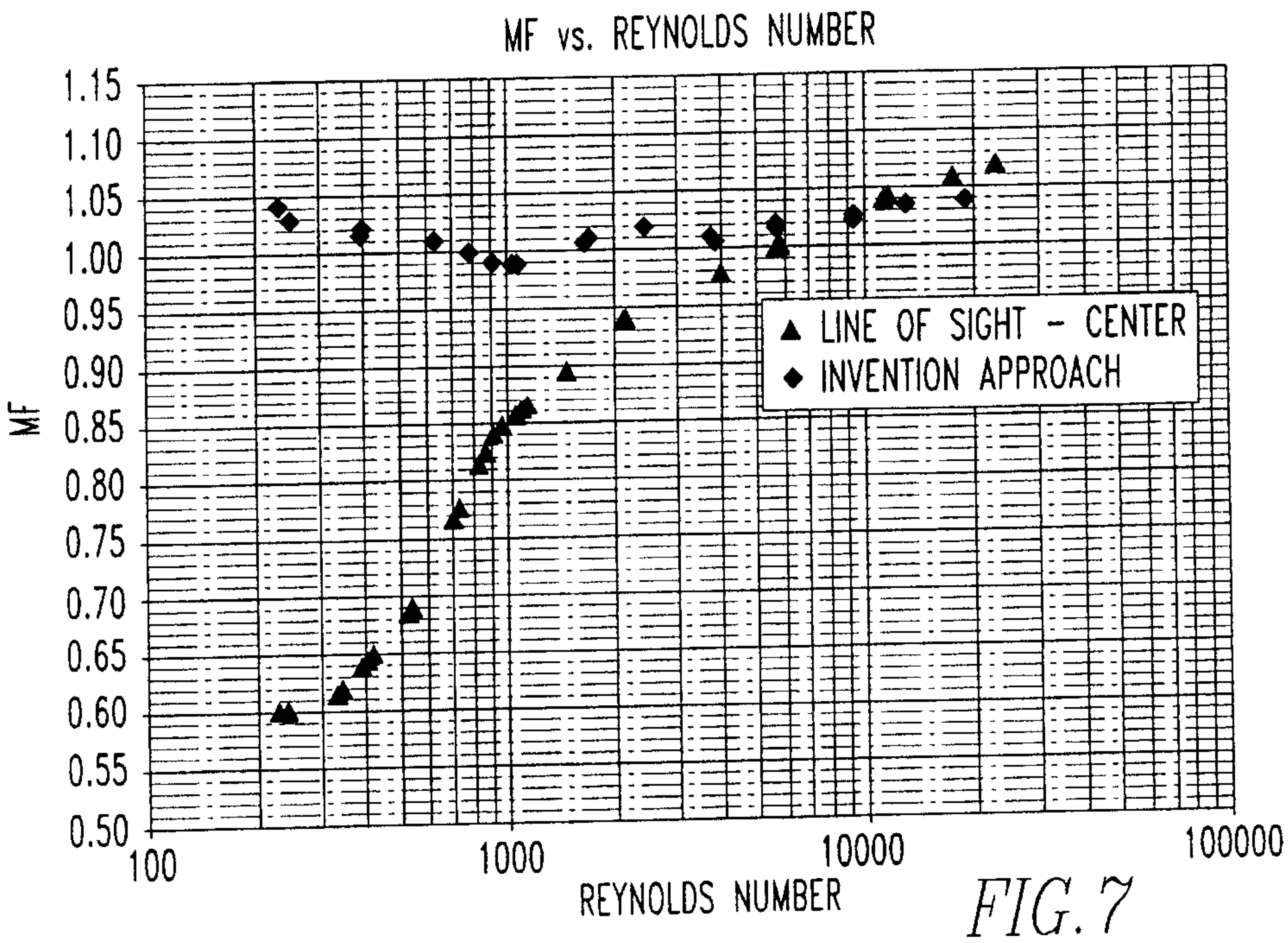
REYNOLDS NUMBER
LINE OF SIGHT - CENTER
INVENTION APPROACH

FIG.6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0.70
0.65
0.60
0.55
0.50
MF
100
1000
10000
100000
REYNOLDS NUMBER
LINE OF SIGHT - CENTER
INVENTION APPROACH

FIG.7

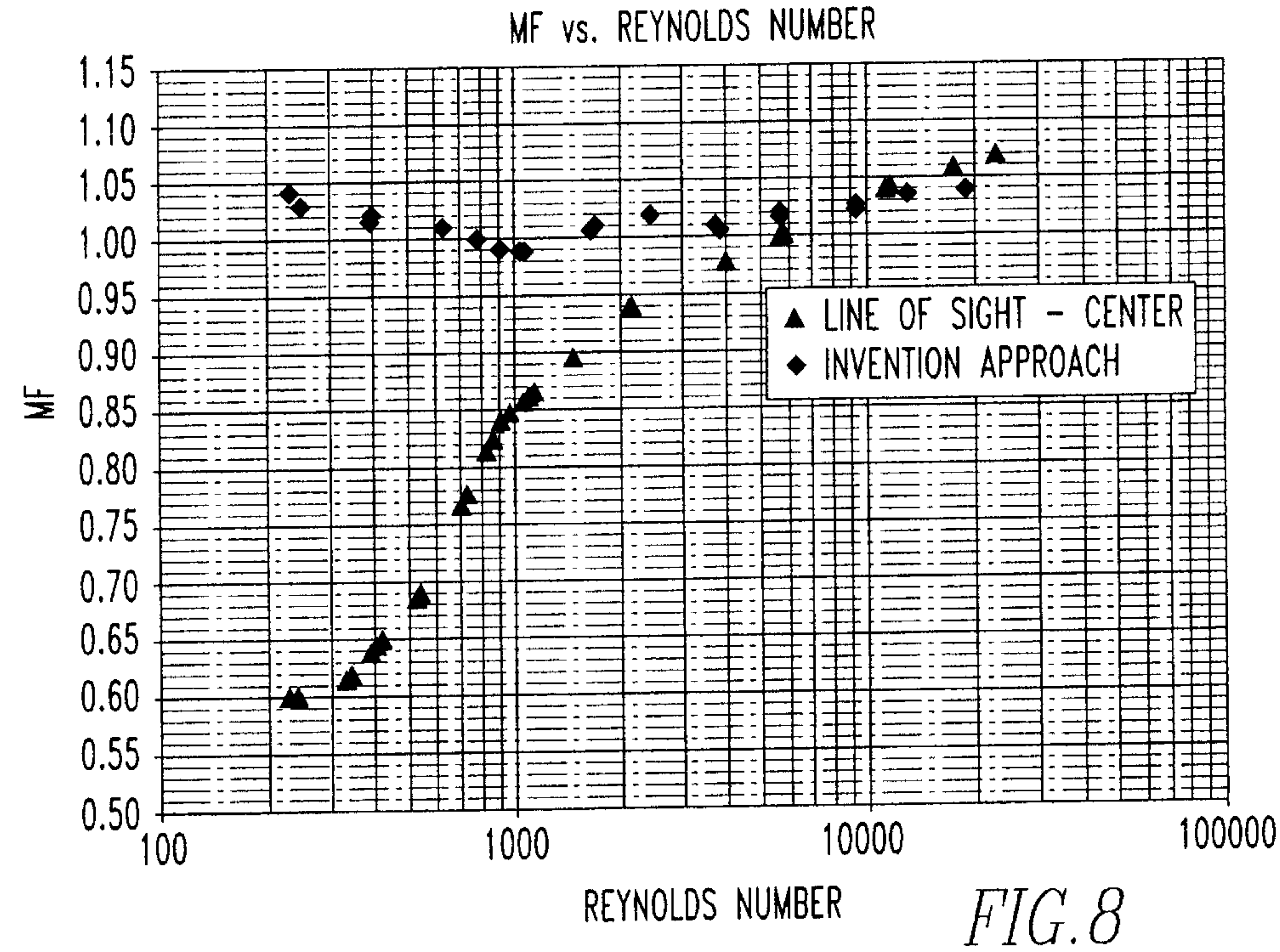


FIG.8

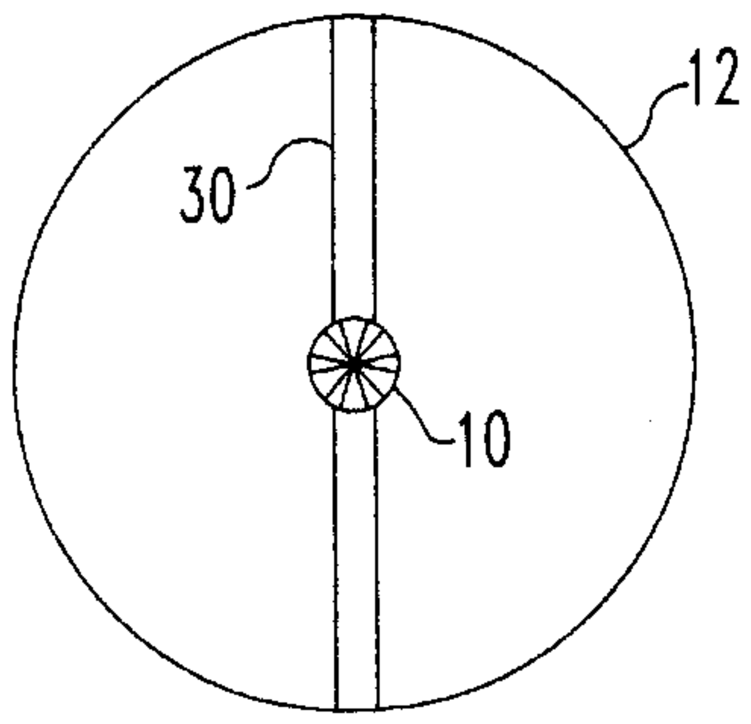


FIG.9

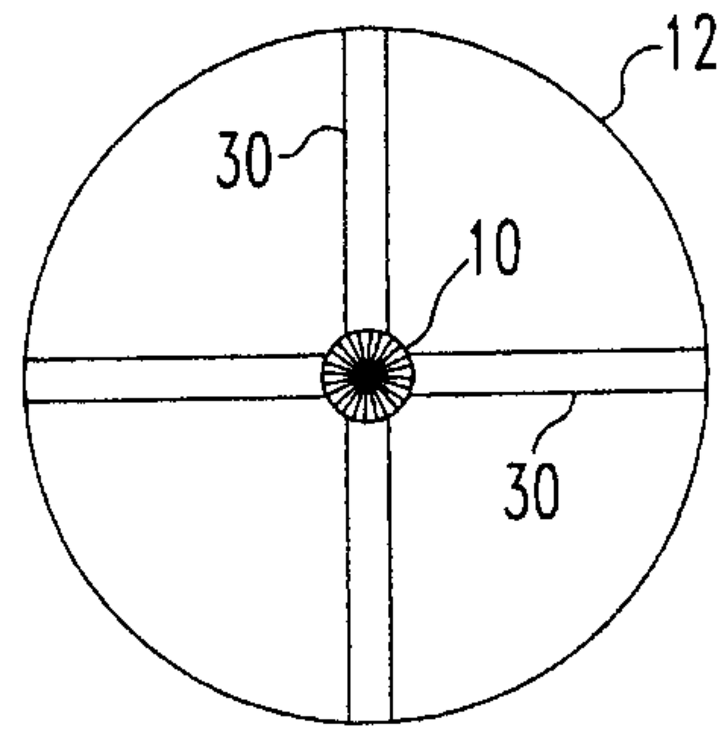


FIG.10

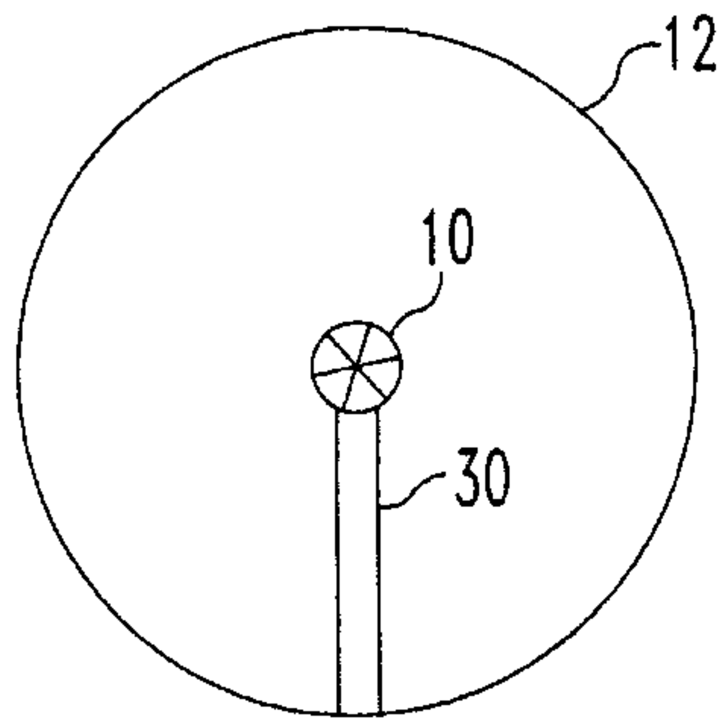
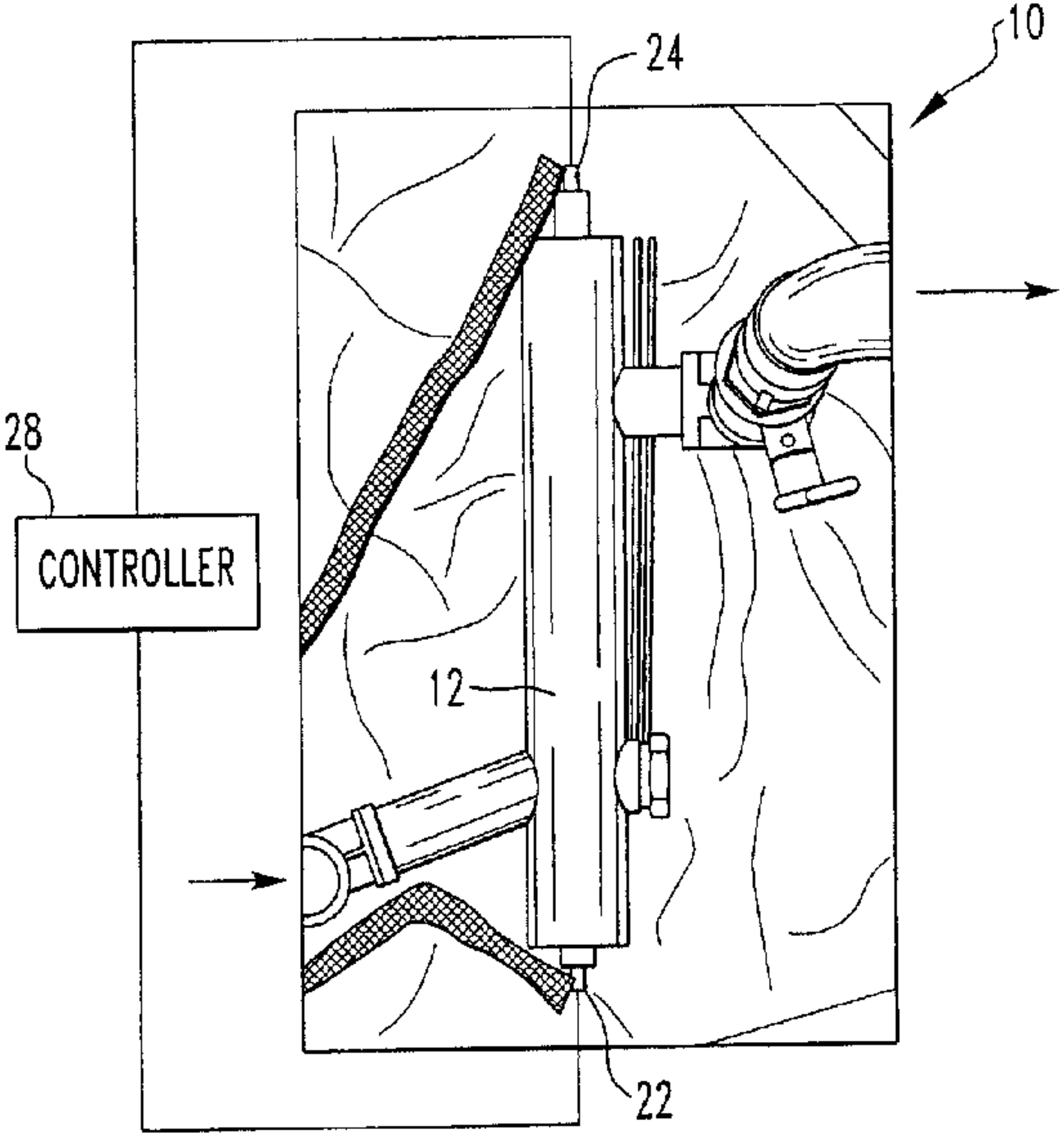


FIG.11


10
24
28
CONTROLLER
12
22