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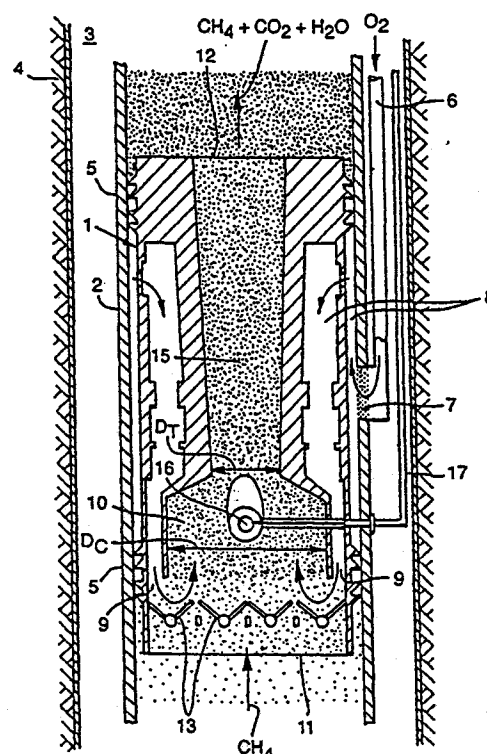
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(54) Titre : Pulsed combustion device and method.

(57) Abrégé :

A pulsed combustion device (1) for used in an underground borehole comprises a substantially tubular combustion chamber (10) and separate fuel and oxidant supply conduits (2, 6) for supplying fuel and oxidant to the combustion chamber. One of said conduits has a fluid discharge port equipped with return flow limitation means (13) located at the upstream end of the chamber and the combustion chamber is shaped as a Helmholtz resonator having a tailpipe section (15) of which the internal diameter is significantly smaller than the other parts of the combustion chamber.



PULSED COMBUSTION DEVICE AND METHOD

Background of the Invention

The invention relates to a pulsed combustion device and method of using such a device.

5 Pulsed combustion devices are known, for example from US patent Nos. 2,899,287; 2,860,484 and 5,044,930, from European patent Nos. 550401 and 636229 and from International patent application PCT/EP93/00961.

10 The known devices generally comprise a combustion chamber having an open downstream end and an upstream end which is periodically closable by a one-way valve.

15 European patent No. 636229 and International patent application PCT/EP93/00961 disclose downhole pulsed combustor devices that have cylindrical combustion chambers into which small quantities of air are periodically injected to ignite a fraction of the volume of natural gas in the chamber so as to enhance the flow of natural gas to the wellhead.

20 A disadvantage of these known devices is that they require complex procedures to start up and control the pulsed combustion process and that they have a rather low pumping efficiency.

25 The pulsed combustion device disclosed in US patent No. 2,860,484 can be used to generate driving and/or heat energy. The known device comprises a tubular combustion chamber having an upstream end which is equipped with a non-return valve and an open downstream end which defines a tailpipe section which is slightly narrower than the rest of the combustion chamber. The combustion chamber is arranged co-axially within a tube in which another non-
30 return valve is arranged upstream of the combustion chamber. The second non-return valve is closed

periodically by high pressure fronts which are reflected from the downstream end of the combustion chamber back through the annulus surrounding the chamber. The presence of two non-return valves which must open and close sequentially is not attractive for downhole use since varying wear, friction and pollution of the valves can easily result in an incorrect and out of phase opening and/or closing of the two valves which may eventually result in stalling of the device.

US patent No. 2,899,287 discloses a pulsed combustor which comprises either a single tubular combustion chamber or two parallel tubular combustion chambers. In each case each combustion chamber has an open tailpipe having a slightly smaller internal diameter than the rest of the combustion chamber and a fuel injection pump which injects accurately defined quantities of fuel into each combustion chamber to control the combustion process.

If the known device has a single combustion chamber then it is equipped with a mechanical non-return valve and if it has two parallel combustion chambers then it is equipped with a pair of aerodynamic non-return valves. These aerodynamic valves comprise U-shaped regenerative tube systems, which have an inlet close to the downstream end of the combustion chamber and which convey combustion gas pressure pulses back to the inlet and which tend to adjust themselves into phase-opposition.

A disadvantage of the pulsed combustor known from US patent 2,899,287 is that it is not suitable for downhole use since it is not feasible to install downhole a fuel injection pump which remains stable over a period of several years and there is no room available to install two parallel combustion chambers with associated non-return valves and a U-shaped regenerative tube system.

French patent No. 1252585 discloses another oscillating heating device with a Helmholtz oscillator and a U-shaped regenerative tube between the downstream and the upstream end of the combustion chamber, which is not suitable for use in a well because of the lack of space available for such a U-shaped regenerative tube.

It is an object of the present invention to provide a pulsed combustion device and method which are able to operate safely and efficiently under varying downhole conditions and which comprise a minimum of wear prone components so that only minimal maintenance and inspection is required.

Summary of the Invention

The pulsed combustion device according to the invention thereto comprises a substantially tubular combustion chamber having an upstream and a downstream end, separate fuel and oxidant supply conduits for supplying fuel and oxidant to the combustion chamber, one of said conduits having a fluid discharge port debouching into the combustion chamber between the upstream and downstream ends thereof, the other of said conduits having a fluid discharge port located at the upstream end of the chamber which discharge port is equipped with return flow limitation means which limit flow of combustion fluids from the combustion chamber into the fluid supply conduit and wherein the combustion chamber is shaped as a Helmholtz resonator having a tailpipe section near the downstream end of which the smallest cross-sectional area is between 0.15 and 0.30 times the average cross-sectional area of the other parts of the combustion chamber.

It has been found that by properly shaping the combustion chamber as a Helmholtz resonator the pulsed combustor device becomes self-aspiring and discharging without requiring a U-shaped regenerative tube.

Preferably the tailpipe and the other parts of the combustion chamber have a cylindrical or conical shape.

Experiments revealed that the above combustion chamber geometry is optimal since it transmits a significant part of the pressure fluctuations from inside the combustion chamber to the outlet of the tailpipe without destroying the pulse combustion process.

If the pulsed combustor according to the invention is used to compress natural gas downhole in a gas production well then it preferably is installed inside a production tubing by means of a pair of expandable packers and air or another oxidant such as oxygen is fed to the device via a supply conduit in the casing-tubing annulus, which conduit is connected to an orifice in the production tubing which is located between the two packers. The air or oxidant is then allowed to flow into the combustion chamber from the annular space between the packers via an oxidant supply port which debouches into the combustion chamber between the upstream and downstream end thereof.

In that case it is preferred that the return flow limitation means comprise one or more flapper-type discharge or non-return valves.

Alternatively, the pulsed combustor device according to the invention is used to heat the underground formation which surrounds the wellbore in which one or more pulsed combustion devices are operated.

In that case the method according to the invention comprises feeding fuel and oxidant to each pulsed combustor device via fuel and oxidant supply conduits which extend from the wellhead into the well and repeatedly allowing in each pulsed combustor device the

oxidant to react with a fraction of the fuel fed into the combustion chamber thereby generating a high pressure wave front which is inhibited at the upstream end of each combustion chamber by the return flow limitation means and which is enhanced at the downstream end of said chamber by the tailpipe section. At the downstream end of the tailpipe section the high pressure wave front is reflected and followed by a low pressure wave front which induces oxidant and fuel to flow into the combustion chamber.

It is preferred that the return flow limitation means of the heater device comprise one or more aerovalves which do not comprise any movable parts or a regenerative tube system extending between the downstream and upstream ends of the combustion chamber.

Preferably a string of pulsed combustor devices is suspended from the wellhead from the oxidant and fuel supply conduits such that the devices are axially spaced in the well.

Such a string of axially spaced pulsed combustion devices is particularly suitable to heat underground shale or heavy oil reservoirs such that the reservoir temperature in the region of the wellbore is between 600 and 800 K.

Experiments have revealed that the pulsed combustor device is able to operate in a stable manner at such high temperatures over periods of many years and provides a cost-effective alternative to existing electrical and catalytic flameless combustion downhole heating devices.

Brief description of the drawings

The invention will be described in more detail with reference to the accompanying drawings in which:

Fig. 1 is a longitudinal sectional view of a pulsed combustor device according to the invention in a production tubing of a natural gas production well;

Fig. 2 is a longitudinal sectional view of two pulsed combustor devices according to the invention which are used to heat an underground formation; and

5 Fig. 3 is a graph in which the fraction of combusted methane is plotted against the ratio A_T/A_C between the minimum cross-sectional areas of the tail pipe and other parts of the combustion chamber.

Detailed Description of the Invention

10 Referring to Fig. 1 there is shown a pulsed combustor device 1 which is located in a production tubing 2 in a natural gas production well 3 which traverses an underground formation 4.

15 The pulsed combustor device 1 is sealingly secured inside the production tubing 2 by means of a pair of expandable packers 5.

20 Air or another oxidant, represented in the drawing as O_2 , is fed to the device 1 via an air supply tube 6 which extends from the wellhead (not shown) through the tubing/casing annulus to an orifice 7 in the tubing 2 between the packers 5.

25 The air flows from the orifice 7 via annular spaces 8 to a series of air discharge ports 9 which debouch into a combustion chamber 10 of the device 1 at a location between an upstream end 11 and a downstream end 12 of said chamber 10.

30 A series of flapper-type discharge or non-return valves 13 is arranged at the upstream end 11 of the combustion chamber 10 which valves allow natural gas, represented in the drawing as CH_4 , to flow from the production tubing 2 below the device into the combustion chamber 10, but which prevent natural gas and/or combustion products, represented in the drawing as $CO_2 + H_2O$ to flow back from the combustion chamber 10 into the production tubing 2 below the device 1.

In accordance with the present invention the combustion chamber 10 is shaped as a Helmholtz resonator wherein the chamber 10 is provided with a narrow and elongated tailpipe 15 which has a smallest diameter D_T , which preferably is between 0.3 and 0.5 times the average diameter D_C of the cylindrical lower part of the combustion chamber. Experiments and computer calculations have indicated that this D_T/D_C ratio is optimal since the highest pressure fluctuations and the highest massflow of natural gas through the device 1 are achieved at lowest fuel consumption as will be explained in more detail with reference to Fig. 3.

The device 1 of Fig. 1 is equipped with a glow plug 16 to which electrical power is supplied via a power cable 17. The glow plug 16 is continuously activated during operation of the device 1 and is generally not switched off when the device 1 has reached its normal operating temperature since if the device 1 is used as a downhole gas compressor its operating temperature is maintained at such a low level that there is no spontaneous combustion of the natural gas.

During normal operation of the device 1 pulsed combustion takes place in the combustion chamber 10.

The frequency of the pulsed combustion process is dictated by the Helmholtz effect and is typically between 10 and 50 cycles per second.

During each cycle a high pressure wave front is generated which is followed by a low pressure wave front. Both wavefronts are enhanced by the Helmholtz effect so that a maximum amount of natural gas is sucked into the chamber 10 when the low pressure wave front reaches the upstream end thereof and also a maximum amount of natural gas and combustion gases are pressed via the tailpipe 15 through the downstream end of the chamber 10 as a result of the high pressure wave front. The divergent shape of

the tailpipe 15 further enhances the mass flow through the combustion chamber.

5 If the device 1 is used as a downhole compressor in a natural gas production well only a relatively small amount of air or other oxidant, such as pure oxygen, is supplied to the combustion chamber such that less than 10% of the natural gas flowing through the production tubing 2 is combusted. The presence of a small fraction of combustion gases only provides insignificant pollution of the produced natural gas.

10 Referring to Fig. 2 there is shown a heat injection well 20 which traverses an underground shale or heavy oil bearing formation 21.

15 In the well 20 a string of pulsed combustion devices 22 according to the invention is suspended.

20 The devices 22 are suspended from a central methane injection tube 23 which passes through the centre of each of the devices 22. An air injection tube 24 is connected to an air inlet chamber 25 of each device 22 via an orifice 26.

25 The air inlet chamber 25 is connected to the combustion chamber 27 via a number of aerovalves 28, which allow air to flow up from the air inlet into the combustion chamber but which inhibit combustion gas to flow back from the combustion into the air inlet chamber.

30 During normal operation of the devices 22 methane (CH_4) or another fuel is injected via the methane injection tube 23 and a series of methane discharge ports 29 into the combustion chambers 27. At the same time air is injected into the chambers 27 via the aerovalves 28 which causes at the elevated temperature in the combustion chambers 27 a pulsed combustion process to take place.

35 If the devices 22 are used as heaters the combustion process is only assisted by a glow plug (not shown)

during start-up, whereas during normal operation spontaneous combustion of the methane occurs in the combustion chambers as a result of the prevailing pressure and temperature in the chambers 27.

5 During each combustion cycle high and low pressure wave fronts develop in the combustion chambers 22 at a frequency which is dictated by the Helmholtz effect, which is induced by the presence of a tailpipe 30 at the downstream end 31 of each combustion chamber which is
10 relatively narrow compared to the upstream part 32 of each combustion chamber.

 In the example shown the cross-sectional area of the tailpipe is represented as A_T and the cross-sectional area of the upstream part 32 of the combustion chamber as
15 A_C .

 It will be understood that the cross-sectional area A_M of the methane injection tube 23 at the centre of the devices 22 does not count as part of the cross-sectional areas A_T and A_C of the tail pipes and upstream parts 32
20 of the combustion chambers 22. In the example shown the ratio A_T/A_C is selected between 0.15 and 0.25 on the basis of the following analysis.

 Experiments revealed that the onset of thermo-acoustical pulsations in a pulse combustor may be studied
25 by linear analysis of the one-dimensional conservation equations for mass, momentum and energy. It was found that the pulsations get the more damped,

a) the larger the gas velocity through the combustion chamber 27 is;

30 b) the shorter the upstream part 32 of the combustion chamber is relative to the length of the tail pipe 30;

c) the smaller the diameter of the tail pipe 30 is relative to that of the upstream part 32 of the combustion chamber.

On the other hand it has been found that the pressure build up in the combustion chamber 27 is the larger, the more closed-off the combustion chamber 27 is. So there must be an optimum tail pipe diameter at which the highest pressure fluctuations are achieved.

The standard geometry ratio between the cross-sectional areas of the tail pipe and the other parts of the combustion chamber deviates from common dimensions of pulse combustors in industrial and scientific applications. A set of computer simulations has been done to investigate whether a change in the cross-sectional area ratio A_T/A_C can improve the performance of the pulse combustor. The minimum tail pipe diameter is the only parameter that is changed in these simulations.

The results of these computer simulations and experiments are shown in Fig. 3.

Fig. 3 shows that an optimal tail pipe cross-sectional area does indeed exist for a given compression ratio at which the combusted fraction of methane is minimal. A minimal methane combustion at a given compression rate is a clear indication that the pulsed combustion process performs in an optimal manner. Fig. 3 indicates that an optimum A_T/A_C ratio is between 0.15 and 0.25. If the tailpipe and other parts of the combustion chamber are tubular and have an open centre as shown in Fig. 1. then the ratio between their diameters D_T/D_C should be between 0.3 and 0.5. The chosen diameter for the standard geometry is in both cases reasonably close to the optimal diameter. Nevertheless, for a compression ratio of 1.15 the massflow can be increased by 20% by choosing a somewhat broader tail pipe.

Also for the heater assembly shown in Fig. 2 it is important to have an optimal compression ratio since this ensures a stable operation of the device 22.

The string of devices 22 may extend along the entire depth of the shale oil formation. If required the heat injection well 20 may be inclined or horizontal and may be an open or a cased hole.

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C L A I M S

5 1. A pulsed combustion device (1,22) for use in an
underground borehole (3,20), the device comprising a
substantially tubular combustion chamber (10,27) having
an upstream (11) and a downstream end (12), separate fuel
and oxidant supply conduits (2,23,6,24) for supplying
fuel and oxidant to the combustion chamber, one of said
conduits having a fluid discharge port (9,29) debouching
into the combustion chamber between the upstream and
downstream ends (11,12) thereof, the other of said
10 conduits (2,24) having a fluid discharge port located at
the upstream end (11) of the chamber (10,27), which
discharge port is equipped with return flow limitation
means (13,28) which limit flow of combustion fluids from
the combustion chamber (10,27) into the fluid supply
15 conduit (2,24) and wherein the combustion chamber is
shaped as a Helmholtz resonator having a tailpipe section
(15,30) near the downstream end (12) of which the
smallest cross-sectional area is between 0.15 and
0.30 times the average cross-sectional area of the other
20 parts of the combustion chamber (10,27).

2. The pulsed combustion device of claim 1 wherein the
tailpipe (15,30) and the other parts of the combustion
chamber (10,27) have a cylindrical or conical shape.

25 3. The pulsed combustor device of claim 2 wherein the
tailpipe (15,30) has a tapered divergent conical shape
and the other parts of the combustion chamber (10,27)
have a substantially cylindrical shape.

30 4. The pulsed combustor device of claim 1 wherein the
return flow limitation means comprise one or more
discharge or non-return valves (13).

5. The pulsed combustor device of claim 1 wherein the return flow limitation means comprise one or more aerovalves (28) which do not have movable parts.

5 6. A method of enhancing fluid flow in a natural gas production well (3), the method comprising installing a pulsed combustor device (1) according to claim 4 in the well production tubing (2) such that a seal (5) is created between the outer surface of the combustion chamber (10) and the inner surface of the production tubing (2), injecting an oxidant through the supply conduit (6) which has a fluid discharge port (9) which debouches into the combustion chamber (10) between the upstream and downstream ends (11,12) thereof, allowing the oxidant to react with a fraction of the natural gas present in the combustion chamber (10) thereby generating a high pressure wave front which is inhibited at the upstream end of the combustion chamber by the return flow limitation means (13) and which is enhanced at the downstream end (12) of the combustion chamber by the tailpipe section (15) thereby inducing the mixture and combustion gases to flow up through the production tubing (2), which high pressure wave front is followed by a low pressure wave front which induces natural gas to flow into the combustion chamber via the return flow limitation means (13).

15 7. A method of heating an underground formation, the method comprising lowering into a well (30) traversing the formation (21) at least one pulsed combustor device (22) according to claim 1 into the well, feeding fuel and oxidant to each pulsed combustor device via fuel and oxidant supply conduits (23,24) which extend from the wellhead into the well and repeatedly allowing in each pulsed combustor device (23,24) the oxidant to react with a fraction of the fuel fed into the combustion chamber (27) thereby generating a high pressure wave

front which is inhibited at the upstream end of each combustion chamber by the return flow limitation means (28) and which is enhanced at the downstream end of said chamber by the tailpipe section (30), which high pressure wave front is followed by a low pressure wave front which induces oxidant and fuel to flow into the combustion chamber (27).

8. The method of claim 7 wherein a string of pulsed combustor devices (22) is suspended from the wellhead from the oxidant and fuel supply conduits (23,24) such that the devices (22) are axially spaced in the well (20).

9. The method of claim 8 wherein fuel in the form of methane is fed to each of the devices via a methane supply conduit (23) which passes through the centre of the combustion chamber (27) and tailpipe (30) of at least one pulsed combustor device (22) and methane is injected into the combustion chamber of each device via a methane discharge port (29) located between the upstream and downstream ends of the chamber (27) whereas oxidant is supplied via an oxidant discharge port (26) at the upstream end of the combustion chamber (27).

10. The method of claim 7 wherein the underground formation (21) contains shale oil and the pulsed combustor devices (22) are operated such that the shale oil containing formation (21) in the region of the well (20) is between 600 and 800 K.

Fig.1.

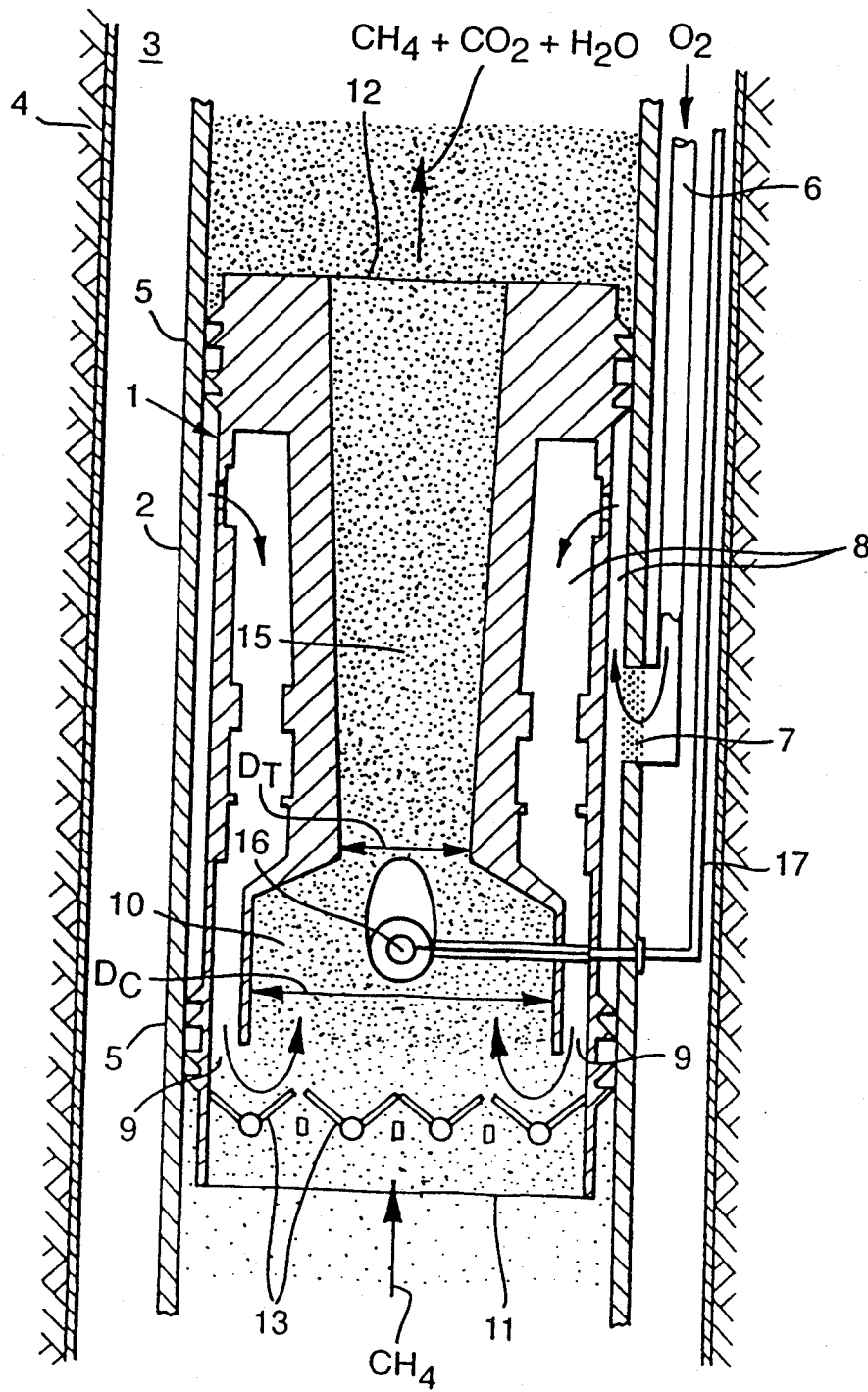
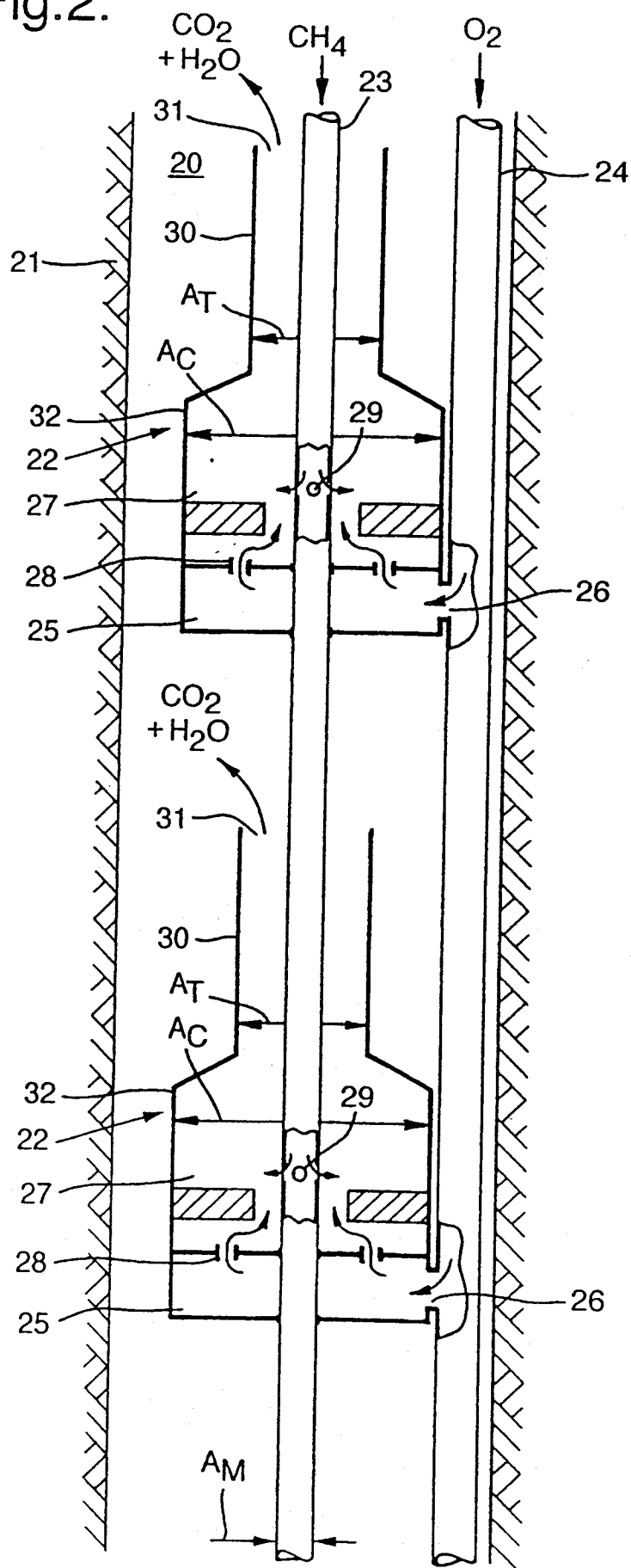


Fig.2.



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Fig.3.

