

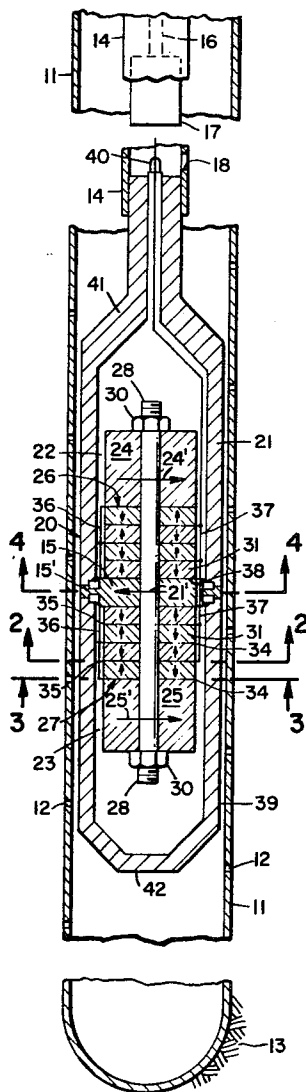
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[45] Patented **June 8, 1971**
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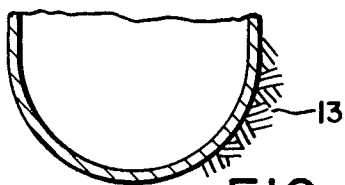
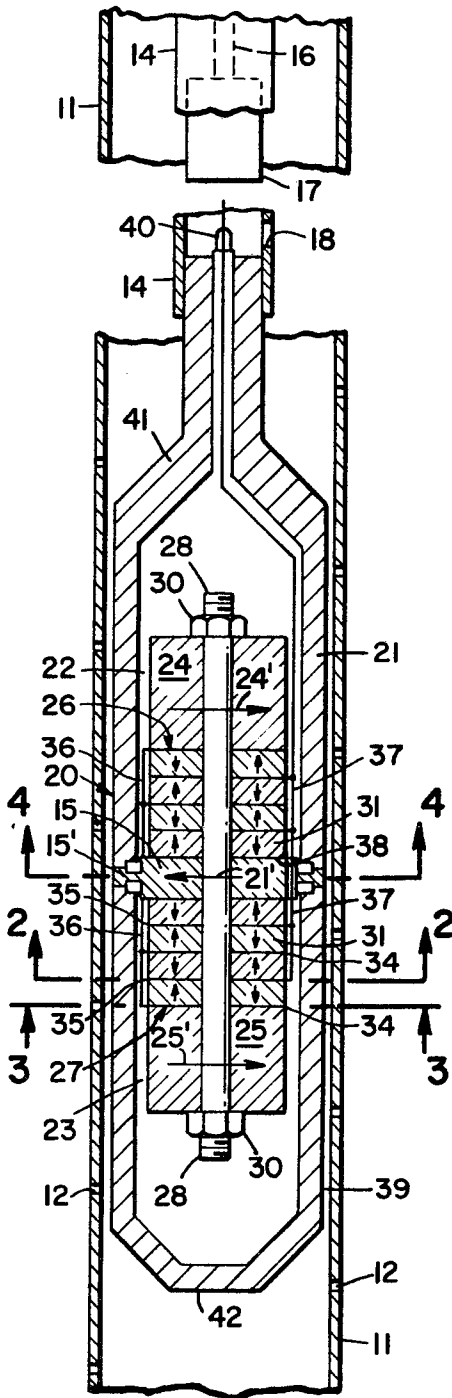
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[54] **ELECTRO-MECHANICAL TRANSDUCER FOR
SECONDARY OIL RECOVERY**
7 Claims, 5 Drawing Figs.

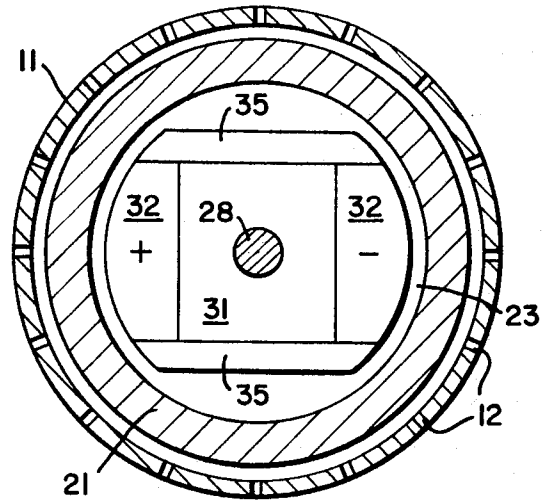
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166/177, 310/8.6, 340/10
[51] Int. Cl. **E21b 43/16,**
H04r 17/10
[50] Field of Search 259/Dig.
41, Dig. 42, Dig. 43, 1; 166/177, 249; 310/8.3, 8.5,
8.6; 340/17, 8, 10

ABSTRACT: An electromechanical transducer for use in secondary recovery in oil wells which, in effect, produces a dipole-type radiation field of increased magnitude which extends along a single axis perpendicular to the axis of the oil well. This allows the surrounding casing to vibrate in a displacement mode rather than in a circumferential expansion mode, to enable energy coupling to the surrounding oil-producing formation. In specific form of the invention, the transducer includes two resonant beams forced to vibrate at an audio or sonic frequency by piezoelectric element stacks driven by an external electrical power source and transferring energy through additive shear waves to an external body.

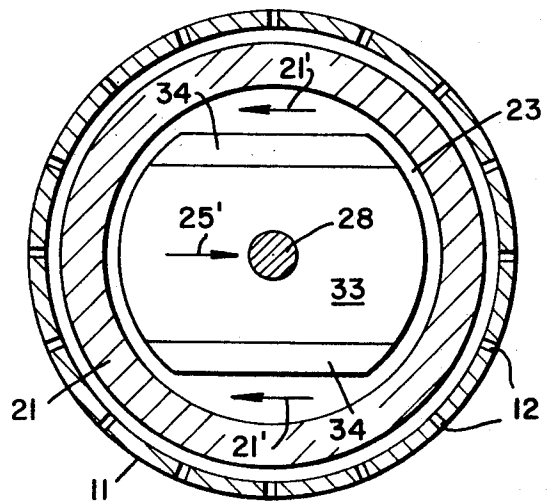




FIG_1



FIG_2

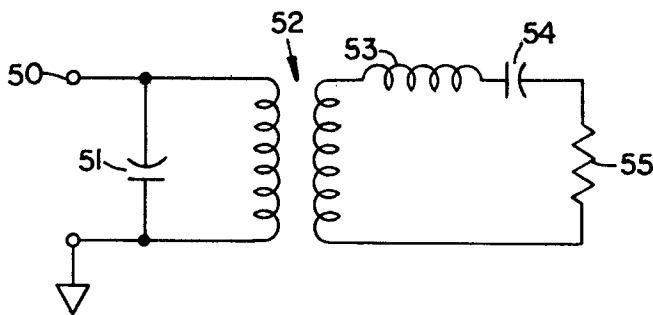
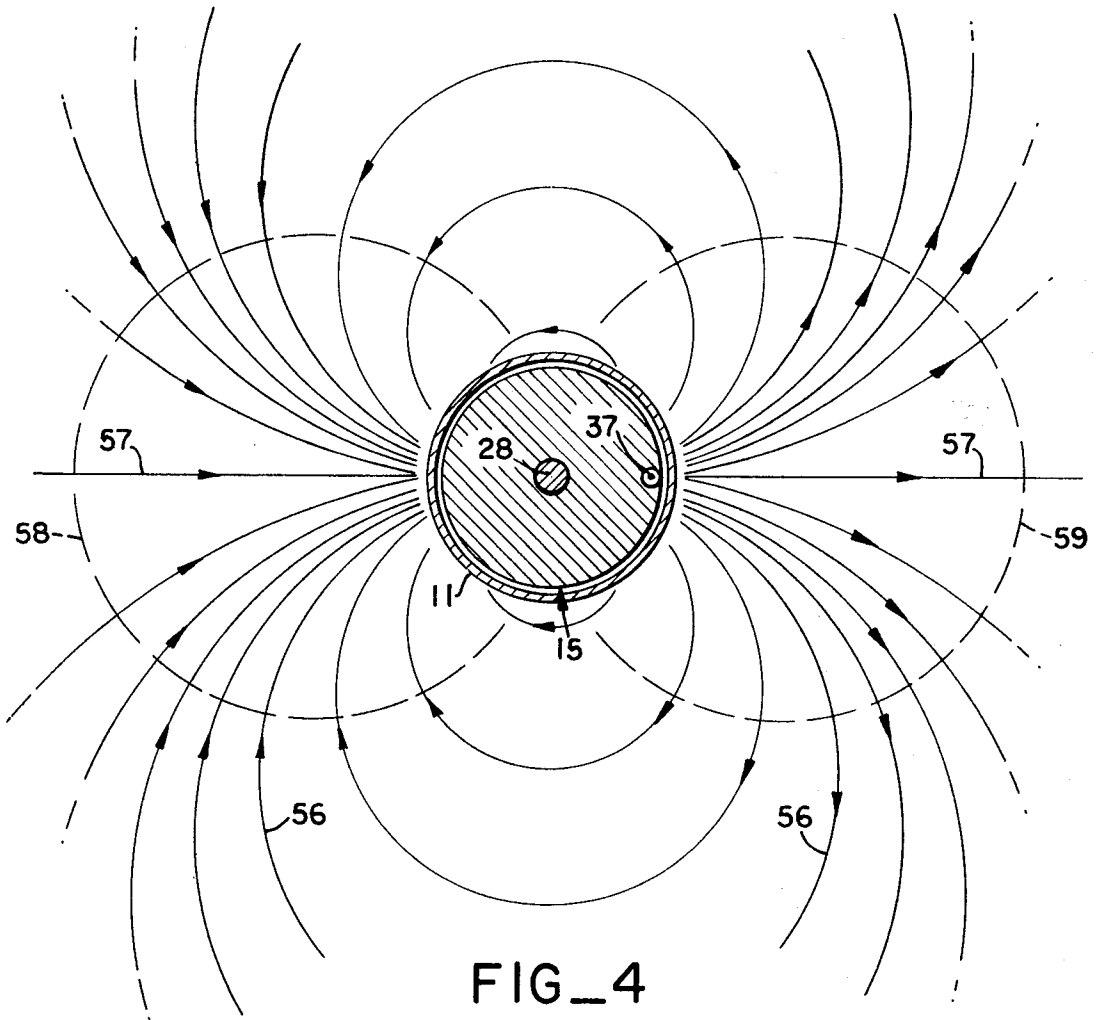


FIG_3

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ELECTRO-MECHANICAL TRANSDUCER FOR SECONDARY OIL RECOVERY

BACKGROUND OF THE INVENTION

The present invention is directed to an electromechanical transducer for secondary oil recovery and more particularly to a transducer which, because of its vibratory mode, effectively couples mechanical or sonic energy of increased magnitude to an oil-producing formation.

Underground oil is dispersed throughout the tiny pore spaces and hairline cracks of rock formations. When a well penetrates the rock, the static pressure head present in the formation drives some of the oil up the well bore. There are four types of natural recovery drives; expansion of gas dissolved in oil; pressure on the oil from expansion of a gas cap above it; force of water on the oil from below or from the edge of the field; and the weight of the oil itself in deeply dipping formations.

Sometimes these natural drives are so strong they not only move oil into the wells, but push it up to the surface. In many fields, however, the natural pressure is just enough to deliver the oil to the well bore, and it must be pumped to the surface.

On the average, nature provides reservoir rock and fluid conditions that allow production of only 25 percent of the oil in a reservoir, leaving 75 percent still dispersed in the rock. Techniques to recover this remaining 75 percent are known as "secondary recovery." Secondary recovery broadly includes methods of injecting liquids or gases into oil reservoirs to drive or flush additional oil from them. Injected fluid displaces oil in the reservoir in essence providing a manmade or artificial pressure head. Major types of secondary recovery include gas injection, water injection, steam injection, underground combustion, and miscible drive.

Secondary recovery is especially useful and necessary in shallow viscous type oil fields such as are found in California.

Another secondary recovery technique which has been used in conjunction with the other techniques or by itself in an attempt to remove flow-impeding materials has been vibrations using sonic wave energy. An electroacoustic or mechanical-acoustic transducer is lowered in the well which radiates sonic waves into the oil-bearing formations surrounding a well to open up blocked passages to thereby increase the flow of petroleum fluid from the formation to the well bore. While advantages of this sound energy technique have been appreciated for many years, prior attempts to generate useful energy have suffered from a condition known as insufficient "transductance." In other words, the amount of energy transferred from the transducer to the surrounding oil fluid of the oil formation and, in addition, the distance it is transferred has been severely limited. Part of the difficulty is the necessity of transferring the energy through the casing of the oil well. Calculations and theory show that in the prior art sonic energy techniques, the energy is reflected by the casing. As a result, there is insufficient "transductance." As a consequence, the sonic technique has not found wide acceptance.

In addition to secondary recovery per se, many oil fields require treatment for foreign material deposition in and immediately around the casing in the producing zone. These deposits are often rock like deposits of salts of the alkaline earth metals such as calcium and barium sulfate and carbonate. They occur predominately in the last few inches of the unfractured formation, the fractures, the perforations, and within the casing. The catalyst aiding deposition appears to be the rapid loss of fluid pressure at the last few inches of formation. Since the deposits reduce flow generally, virtually full formation pressure appears immediately outside the well bore and accentuates the rapid pressureless condition. The deposition process may in some cases be regenerative.

These deposits are normally treated by applying acid to the oil well in large quantities. The acid process is effective in removing deposits but is expensive, injurious to the metallic components of the well and often to the formation itself, and is not of a lasting nature.

SUMMARY OF THE INVENTION AND OBJECTS

Accordingly, it is a general object of the invention to provide an improved electromechanical transducer and transduction system for effectively coupling energy to a fluid medium, such as an oil-bearing formation.

It is a more specific object of the invention to provide a transducer as above which is effective in secondary oil recovery.

It is another object of the invention to provide a transducer as above which is effective both in cleaning deposits from oil well bore regions and in preventing their reaccumulation.

It is another object of the invention to provide an electromechanical transducer for use in oil wells which effectively transfers energy through the casing of the oil well to the surrounding oil formation.

It is another object of the invention to provide an improved method for secondary oil recovery with the use of the above transducer.

It is another object of the invention to provide an improved method of well bore and formation deposit cleaning with the use of the above transducer.

It is another object of the invention to provide a transducer which includes transducer stacks matched to the surrounding medium by attached vibratory beams transmitting energy by shear waves to a surrounding body in contact with said medium.

In accordance with the above objects, there is provided an electromechanical transducer for use in an oil well which extends along a predetermined axis. The transducer has a major effective radiating surface providing radiation perpendicular to the predetermined oil well axis, the major force pattern being directed along an axis perpendicular to the oil well axis.

In a more specific form the transducer itself includes moment producing vibratory element stacks with means for driving the elements. An outside body interfaces with a third medium such as oil and includes two cavities having coaxially predetermined geometrical axes. Reaction masses forming the outer ends of two vibrating beams in combination with the vibratory elements extend at least partially within the cavities. The vibratory elements provide spring like coupling to the body and couple the vibrating energy to the body through additive shear waves present during vibration.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view partially cut away of an oil well casing with an electromechanical transducer embodying the present invention inserted therein;

FIG. 2 is an enlarged cross-sectional view taken along line 2-2 of FIG. 1;

FIG. 3 is an enlarged cross-sectional view taken along line 3-3 of FIG. 1;

FIG. 4 is a cross-sectional view taken substantially along line 4-4 of FIG. 1 and illustrating the electromechanical transducer of the present invention along with lines of force indicating the path of energy transmission into the surrounding formation; and

FIG. 5 is a circuit schematic useful in understanding the invention.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is illustrated the lower end portion of an oil well showing a casing 11 having the usual perforation 12 to allow oil to flow in from the surrounding oil-bearing formation indicated at 13. Pump means are associated with the casing whereby the oil can be pumped to the surface.

In the example shown, the pump means includes a pump tube 14 which extends downwardly from the surface along the interior of the casing 11. An actuating rod 16 is located in the interior of the pump tube 14. The rod is coupled to a pump schematically shown at block 17. The inlet of the pump is shown at 18. Up and down movement of actuating rod 16 causes suc-

tion to be created at 18 to allow entry of any available fluid or oil at inlet 18 to be pumped to the surface through tube 14. Pump 17 would normally be contained within the diameter of the pump tube.

An electromechanical transducer 20 is supported at the bottom of the pump tube 14 in proximity to the oil-bearing formation 13. It is apparent that the output power to the formation 13 may be increased proportionate to the number of transducers serially connected to the bottom of the pump tube 14.

It should be appreciated at this point that although a pump assembly 16, 17, 18 has been illustrated, in flowing wells, where there is sufficient natural pressure, the pump is not required. Also, for other applications where pressure is applied, for example, by a water flood method or gas infusion, the pump may not be required.

The construction of the electromechanical transducer is illustrated in FIG. 1. The transducer is composed of an elongated cylindrical housing 21 which includes coaxial cavities 22 and 23 separated by an integrated web 15. Web 15 is supported in housing 21 by a thin flange portion 15'. The flange is made integral to the housing beam welding two halves of the housing to the flange. Reaction masses 24 and 25 are inserted within cavities 22 and 23 respectively and assembled compressively with vibratory piezoelectric element stacks 26 and 27, by stud 28 and nuts 30. Each stack contains multiple elements 31 polarized in one direction (marked +) at one end, and in the other direction (marked -) at the other end as shown in FIG. 2. Each element has two metallic coatings 32 on one side and one metallic coating 33 on the other side, as in FIG. 3, to enable the bidirectional polarization and to enable electrical connection within the transducer. The piezoelectric elements are mounted in facing pairs as indicated by the small arrow directions in FIG. 1 and the inversely facing elements of FIG. 2 and FIG. 3. Compliant metallic plates 34 and 35 are compressed between elements 31 as shown. Ground wires 36 connect plates 35 and therefore four of coatings 33 to ground (body) potential. Lead wire 37 is connected to each of plates 34 and therefore to each of the eight sets of coatings 32. Similar plates 38 are installed at the remaining joints between the stacks 26 and 27 and center web 15.

All the piezoelectric elements 31 and therefore stacks 26 and 27 are driven in synchronous and mirror image movement producing modes by the application of alternating voltage to the lead wire 37 since all positive polarized ends and all negative polarized ends are each exclusively axially colinear. Thus, the left side of the stacks expand while the right sides contract for one line voltage polarity and then mutually invert state for the opposite polarity. Generally the combinations of reaction mass 24 and stack 26 and reaction mass 25 and stack 27 form continuous cantilevered beams. Each beam assembly is forced to vibrate laterally with masses 24 and 25 moving as indicated by the arrows 24' and 25' thereby creating bending moments and shear forces at the beam assembly center section 15 boundaries as indicated by arrow 21'. The housing 21 suffers no direct reaction due to the moments because their simultaneous mirror image application results in mutual cancellation. This is further ensured by the presence of thin web flange 15' which isolates the outer portion of housing 21 from any residual asymmetrical vibration pattern. This in turn assures that there will be only one resonant beam frequency since both are therefore able to vibrate in a single free-free beam mode. Therefore, the shear wave reactions sum to yield body motion as shown by the arrow 21' in center area 15.

The distributed effective spring constant and mass determine the resonant frequency of beams 24, 26 and 25, 27. This frequency may be determined by the Timoshenko theory of thick resonant beams which takes shear deformation and section moment of inertia into account in its eigenvalue solution. The resonant frequency is chosen so that it is resonant with the resonant cavity formed by the oil-filled circumferential gap 39 defined by the outer surface of cylindrical housing 21 and the inside surface of the well casing 11. The resonant frequency of the transducer is determined by the mean cir-

cumference of the gap. The resonant wavelength λ , which determines the frequency of operation, equals the circumference. It is, of course, apparent that there will be resonances at harmonic frequencies of the fundamental.

When the transducer is operated at resonance, the housing 21 and reaction masses 24 and 25 move in opposite directions as indicated by arrows 21', 25' and 24' (see also FIG. 3). This, in turn, causes the transducer assembly to move back and forth in a direction substantially perpendicular to its longitudinal axis. The energy is transferred through the oil in the cavity, through the casing 11 and into the formation where it radiates outwardly in a dipole pattern as will be more fully explained below.

The lead wire 37 is also attached to connector 40, which is hermetically sealed to fitting end 41. Plain end 42 is fitted at the bottom although a second fitting end could be used if it is desired to make connection to the bottom end to accommodate other transducers below the transducer assembly 20. The entire body 21 is hermetically sealed by electron beam welds and is thus compatible with rough oil field use.

In operation, the motion of reaction masses 24 and 25 is built up until the spring reaction force drives the body 21 with enough amplitude against the impressed load of the cavity-formation system to consume the applied power in sound power transmitted to the formation. Sound power is transferred to the surrounding formation by a combination of the RMS values of the factors of velocity of movement of the casing multiplied by the force of such movement. The sound power may be further described as the formation acoustic impedance times the total transducer plan area times the square of the casing RMS velocity or also as the product of the plan area times the sound RMS pressure squared divided by the acoustic impedance. This power or work rate must, of course, equal the electrical energy coupled into the system from the power source.

It has been observed that when the system comes into full operation with the masses vibrating at their normal amplitude and driving the resonant cavity at resonance, the applied current from the power source substantially comes into phase with the applied voltage thus indicating an efficient transfer of electrical energy to the mechanical energy form which is in the form of sonic energy to the surrounding oil formation.

The present assembly is more efficient than that described in patent application, Ser. No. 761,139, now U.S. Pat. No. 3,527,300 filed Sept. 20, 1968 with the present inventor and entitled "Electro-Mechanical Transducer for Secondary Oil Recovery and Method Therefore." This may be seen by referring to the equivalent circuit shown in FIG. 5. Alternating electrical voltage is applied to lead 50 (equivalent to lead wire 37) to transformer 52 (equivalent to the electromechanical coupling of piezoelectric elements 31) and shunted by the actual parallel plate capacitance 51 of the elements 26, 27. The transformer load is the series combination of inductor 53 (equivalent to the effective resonant mass), capacitor 54 (equivalent to the effective spring compliance $1/k$), and resistor 55 (equivalent to the acoustic load). Because resonant

frequency is $f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$. Because of the use of a bending

mode rather than an extensional one, k has been reduced. Therefore the mass, m , is also reduced. The mechanical im-

pedance is $z_m = \sqrt{km}$. Since the acoustic load resistance is proportional to zm , the load reflected back through transformer 52 is of lower impedance. Therefore more output

power is available to the load since $P = \frac{v^2}{R_{\text{effective}}}$

As thus far described, it is believed that the energy distribution of the transducer element is best illustrated by a radiation pattern indicated by the lines 56 in FIG. 4 where the greatest density of the lines occurs along an axis 57 which extends through bolt 28. In other words, in a two-dimensional aspect

the vibratory radiation from the transducer forms a major transmission pattern which is directed along a single axis 57 which is perpendicular to the vertical axis of the oil well. This, of course, means that it is also perpendicular to the axis of the casing 11.

The radiation field pattern 56 can be roughly analogized to the radiation pattern of a dipole antenna where the antenna has a double-lobe energy distribution pattern illustrated in dashed lines at 58 and 59.

Since the force field of the present invention is similar to the dipole antenna, it is believed that certain precautions as to the design of the transducer with respect to the frequency used must be taken. It has been found that the circumferential distance around the outer periphery of body 21 should be substantially equal to or greater than one wavelength in free liquid. If it is less than this, the sonic vibrations in one direction might tend to cancel those being produced on the other side of the transducer. For this reason, it is important to avoid too low a frequency since the effective gap between the two sides of the transducer along the axis 57 will have the appearance of a leak path and lower the efficiency of the transducer.

From yet another aspect, although a type of dipole radiation field is created, the medium itself, i.e., the oil bearing formation loss media, is not the same as that with a dipole antenna loss media. More specifically, the wavelength of sound in the medium, for example, oil, is the same order of magnitude as the flow path length of the oil. Thus, there may be preferred motion paths. Secondly, the medium is lossy from a sonic energy standpoint and thus the flow field has circulation and does not follow LaPlace's Theorem. Lastly, there will normally be a considerable energy scattering effect since there are particles and discontinuities present in the medium.

A transducer assembly was constructed and tested. The transducer assembly comprised a body 21 $4\frac{1}{2}$ inches OD having 3 $\frac{1}{16}$ inch, ID cylindrical bores 4 inches deep. The body was 10 inches long with a $\frac{3}{4}$ -inch thick center web with $\frac{1}{2}$ -inch thick insulation. The piezoelectric elements 31 were 2 $\frac{1}{4}$ inches long by 1 $\frac{1}{8}$ inches wide by $\frac{3}{8}$ inch thick. The reaction masses 24 and 25 were 1 $\frac{1}{8}$ inches thick to account for a cantilever beam length of 3 $\frac{3}{8}$ inches. The transducer assembly was placed in a casing having a 5 $\frac{1}{2}$ inch OD and a 4.9 inch ID. The pump inlet 18 was approximately 30 feet above the transducer assembly to ensure sufficient liquid pressure about the transducer to eliminate cavitation.

Thus, the present invention provides an improved transducer for secondary oil recovery which is highly efficient. The

invention is particularly useful in eliminating foreign material deposition.

I claim:

1. An electromechanical transducer for coupling energy to a fluid medium comprising, a body elongated along a predetermined axis having first and second coaxial cavities separated by web means integral to said body, first and second vibratory means at least partially within said respective cavities and having first ends mounted to said web means to place said vibratory means in coaxial relationship, reaction means coupled to the other ends of said first and second vibratory means, said vibratory means having a mode of vibration to move said reaction means in planes substantially perpendicular to said axis of said body, and means for placing said first and second vibratory means in synchronous vibration.

2. An electromechanical transducer as in claim 1 where said cavities are sealed to exclude said fluid medium.

3. An electromechanical transducer as in claim 1 where each of said vibratory means includes a stack of piezoelectric elements having a bidirectional polarization.

4. An electromechanical transducer as in claim 1 where said means for placing said vibratory means in synchronous vibration includes a source of alternating voltage.

5. An electromechanical transducer as in claim 1 where the mechanical impedance of said transducer is $\sqrt{km}$, where k is the effective spring compliance of the transducer and m the mass of the transducer and where k is primarily determined by the bending mode of said transducer.

6. An electromechanical transducer adapted to be disposed in a well casing to couple energy to the fluid and formation surrounding said casing comprising, a body elongated along a predetermined axis having first and second coaxial cavities separated by web means integral to said body, first and second vibrating means respectively cantilevered on said web means, each of said vibrating means including vibratory elements and a reaction mass, said vibrating elements in combination with said reaction mass forming cantilevered beams having an axis substantially coincident with said predetermined axis, means for placing said vibratory elements in synchronous vibration whereby vibrating energy is coupled to said body through additive shear waves produced by said beams vibrating in a free-free mode.

7. An electromechanical transducer as in claim 6 where said web means includes a relatively thin flange portion coupling said web means to said body.