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[54] **METHOD AND APPARATUS FOR LIFTING FOAMING CRUDE BY A VARIABLE RPM SUBMERSIBLE PUMP**
14 Claims, 4 Drawing Figs.

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[51] Int. Cl. E21b 43/00, E21b 47/06, F04d 27/00
[50] Field of Search 166/250, 252, 265, 314, 267, 309, 68, 53, 54, 65, 75, 104, 105, 68.5; 103/102, 35, 21, 12, 87 (E); 415/(Inquired)

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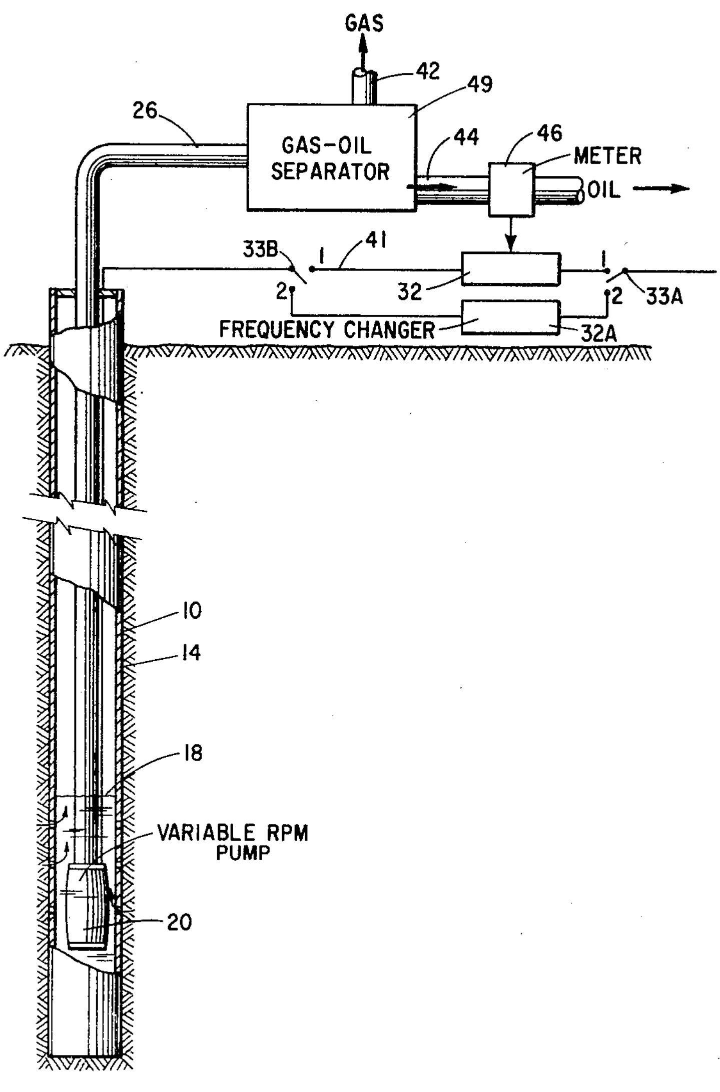
ABSTRACT: Many oil wells, especially in their latter stage of primary or secondary recovery, produce foamy crude oil. This crude oil will vary from mostly liquid to mostly foam. Pumping such a fluid is rather difficult. The main difficulty is due to reduced bulk density of the fluids. Thus, a constant r.p.m. submersible centrifugal pump has very low efficiency. This invention controls the r.p.m. as a function of the bulk density of the crude in the well bore. Various means of obtaining this are given.



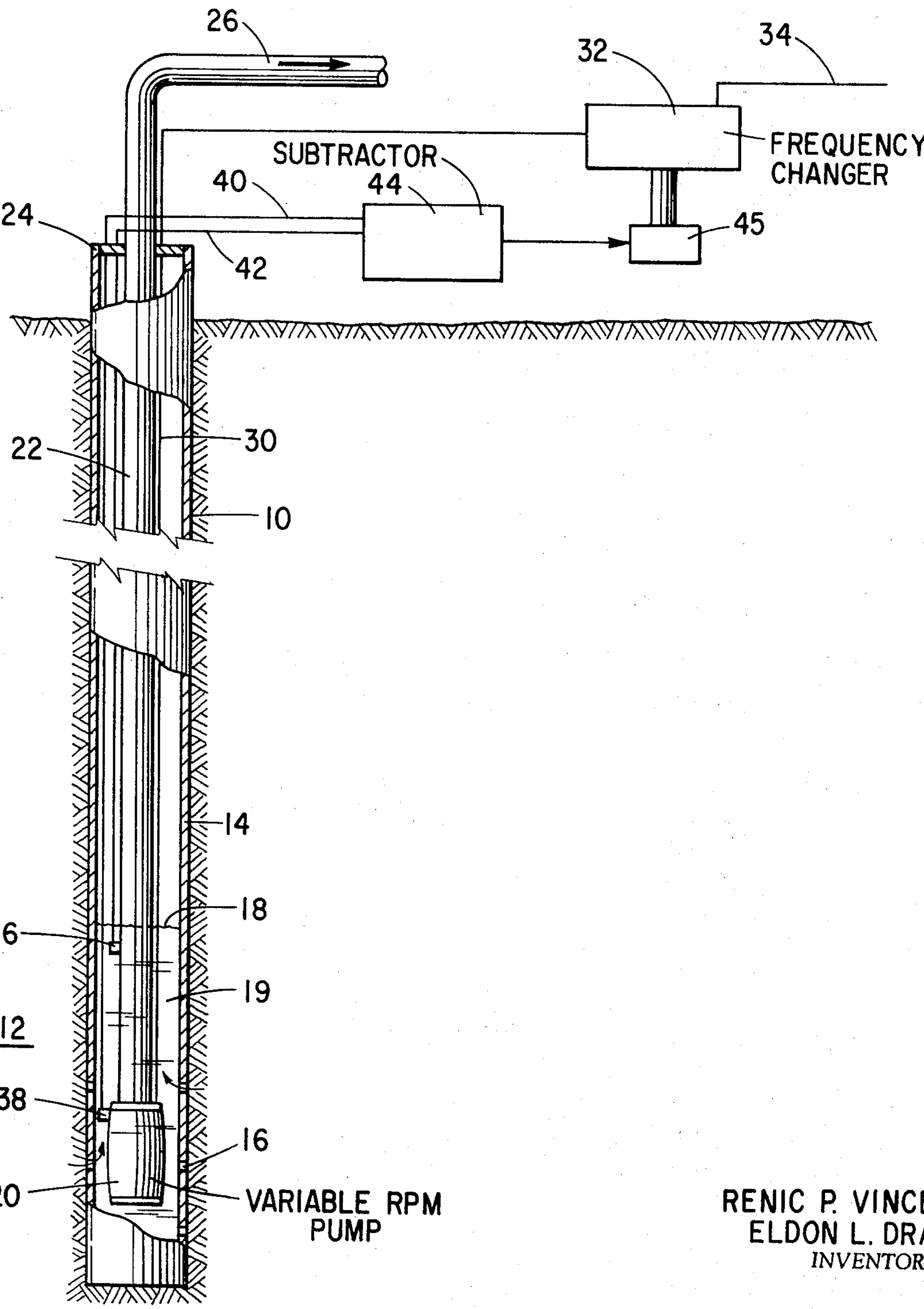


FIG. I

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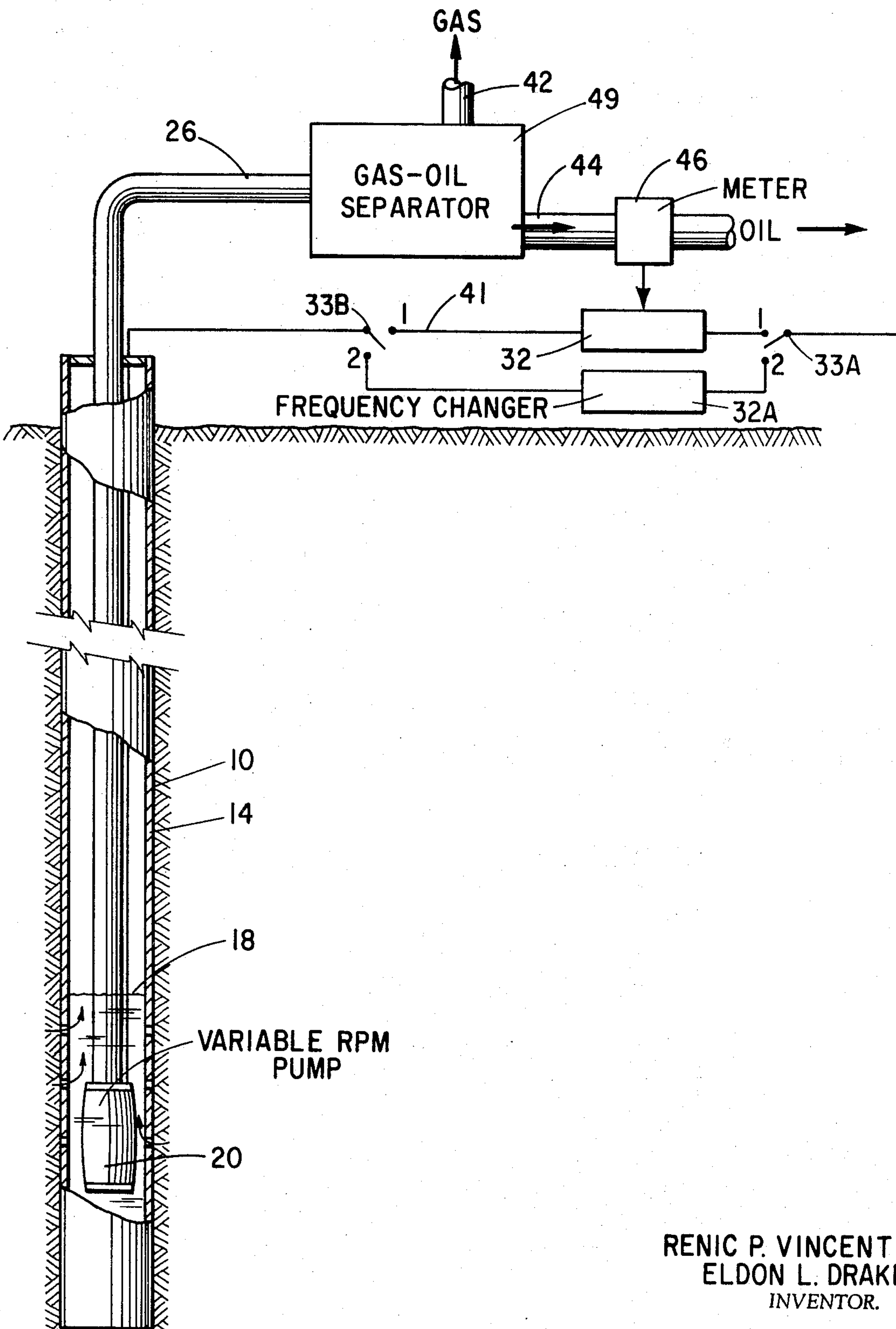

FIG. 2

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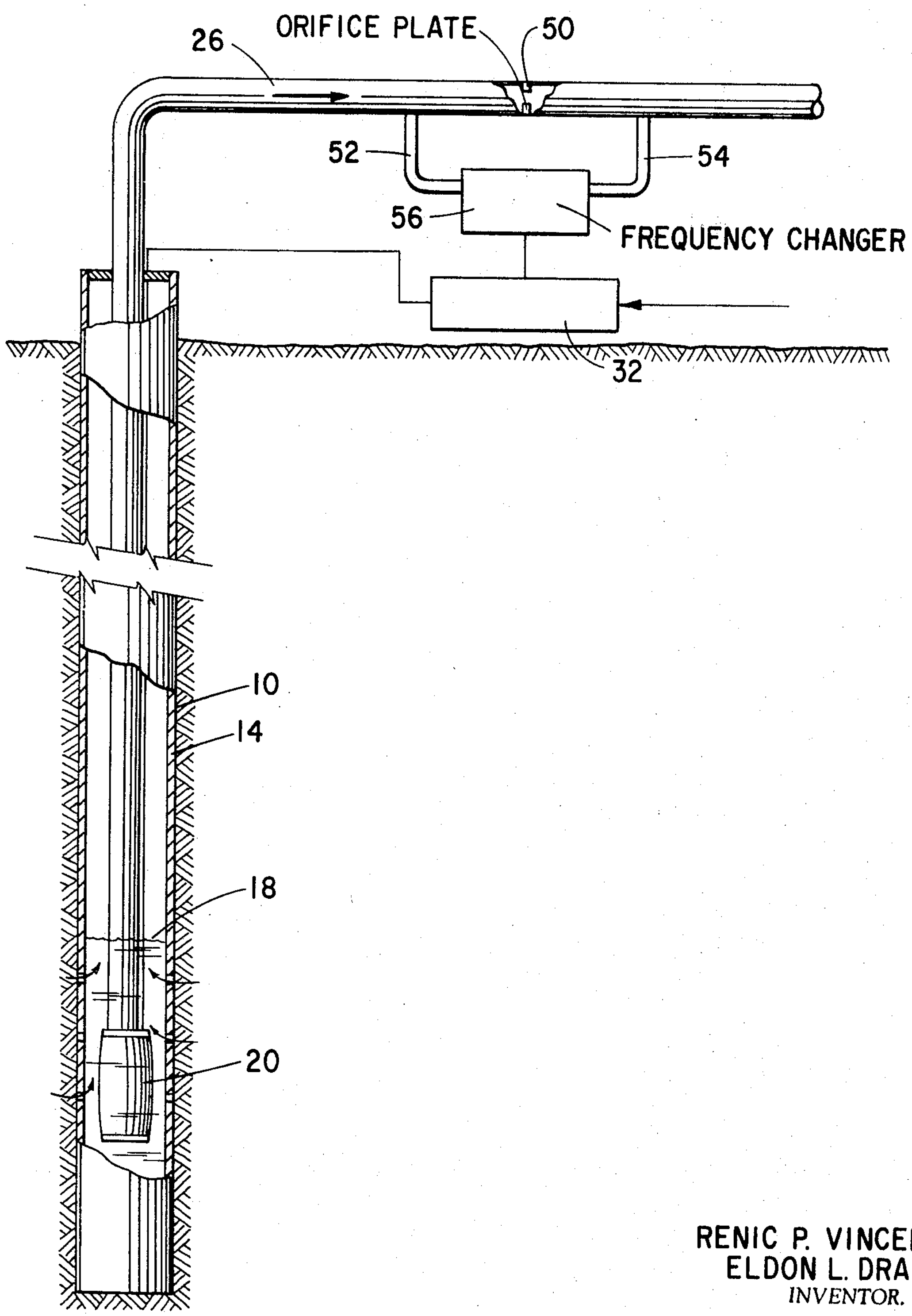

FIG. 3

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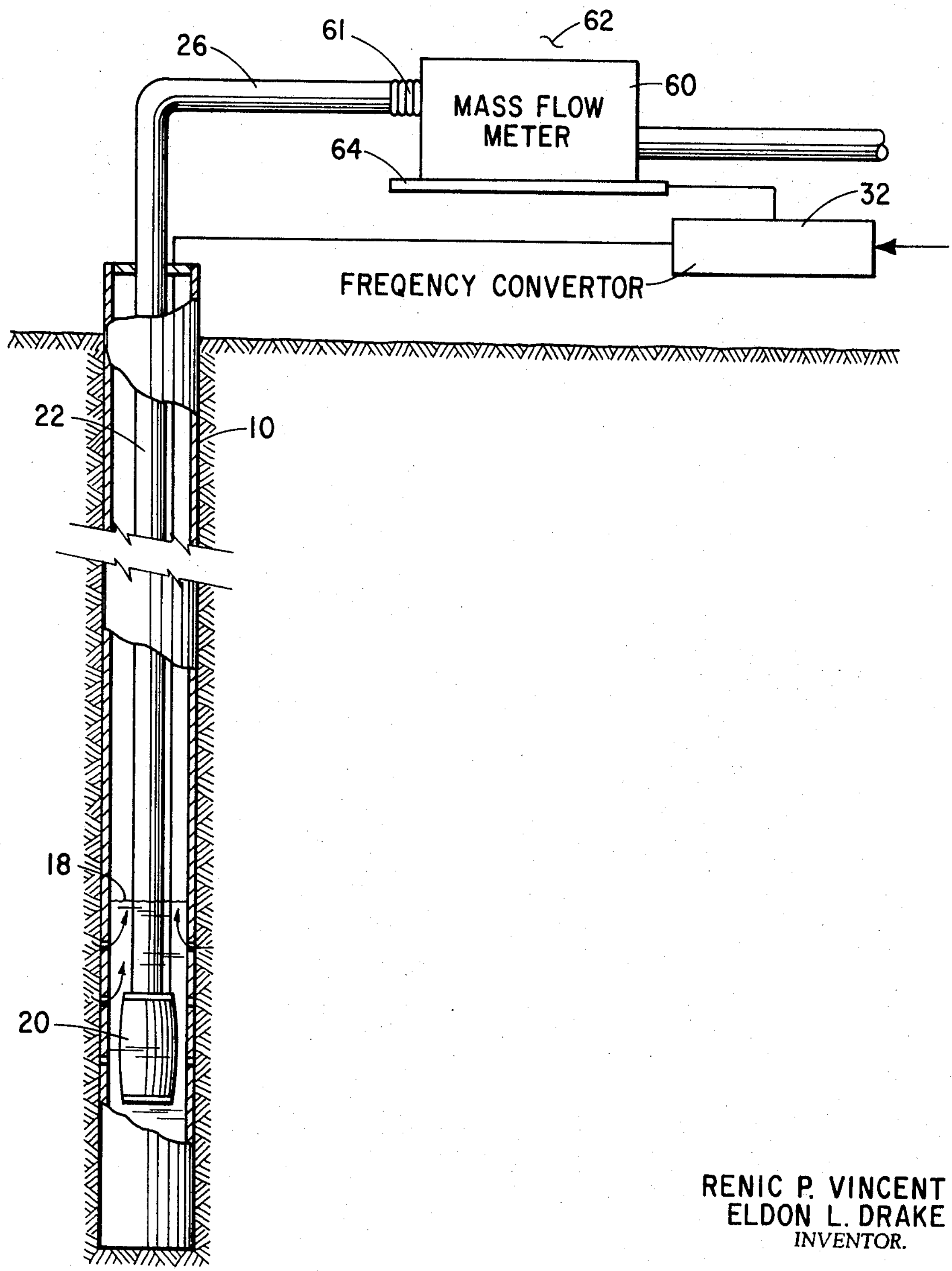

FIG. 4

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METHOD AND APPARATUS FOR LIFTING FOAMING CRUDE BY A VARIABLE RPM SUBMERSIBLE PUMP

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to the pumping of foamy crude oil. A foamy crude oil contains gas in the form of bubbles; thus, the bulk density is low. This invention relates especially to a means of varying the r.p.m. of a submersible pump used in pumping such foamy fluids as a function of the bulk density of the fluid being pumped.

2. Setting of the Invention

The production of oil from oil wells drilled into a subterranean deposit goes through three stages:

Primary recovery where the oil flows into the well of its own energy and then is removed from the well by its own energy or a pump. Foamy crudes often accumulate in the well bore in the latter stages of primary recovery.

b. Secondary recovery is production after most of the original fluid producing energy is depleted and in which a liquid or a gas is injected into the formation to give the oil the energy or the viscosity it needs to flow into the well bore. This includes the injection of a liquid such as water into one well to drive formation fluids into an output well bore from whence crude oil is produced. Foamy crude is frequently accumulated in the well bore in secondary recovery operation.

c. The third stage is called tertiary and includes some exotic type recovery, but ordinarily this third stage is not involved to any large degree in the problem of the subject invention at the present time.

Foamy crude oil ordinarily is a crude in which gas forms bubbles within the crude so that the bulk density of the fluid is low. This is frequently caused by natural gas present in the formation breaking out of solution. There is ordinarily natural gas in solution in the oil when found in the reservoir. However, for this oil to stay in solution form it must have at least a certain pressure. When the fluid decreases below this pressure, which sometimes is called the bubble point, the gas comes out of the solution and takes the form of bubbles. Sometimes the problem is brought on by the injection of gas as in a gas drive recovery program.

Case histories of wells have shown that foamy crudes are ordinarily no problem in the first part of primary production. However, as the well is produced, the bottom hole pressure decreases and the bulk volume needed to be produced increases. The apparent specific gravity of the fluid decreases, thus reducing the volumetric efficiency of the ordinary pump. As mentioned, in trying to pump such foamy oil, the volumetric efficiency of the pump goes way down. Some have attributed this to gas locking. However, gas locking is ordinarily not the cause of the problem and efforts to improve pump volumetric efficiency by attacking the problem as being one of gas locking have been unsuccessful. Gas locking generally occurs where free, or lightly entrained, gas breaks out readily. In a tight emulsion (as a foam) where the finely entrained gas does not readily break out, gas locking becomes a lesser factor, or relatively nonexistent as the foam tends to be stable.

BRIEF SUMMARY OF THE INVENTION

This invention relates to an improved system for pumping foamy crude oils. A variable speed submersible pump is supported in the lower portion of a well bore and is submerged in the foamy crude to be pumped. The outlet of the pump is connected to a tubular member which extends to storage and processing facilities on the surface of the earth. Measuring means are provided to obtain a parameter which is a function of the density of the fluid being pumped. The speed of the pump is adjusted inversely to the parameter thus measured within the limits of the pump, e.g., as the density decreases, the speed of the pump is increased.

In an especially preferred embodiment, means are provided to obtain the pressure of the foamy crude at two vertically spaced points in the vicinity of the submersible pump. The difference in pressure is a function of the density of the fluid. This difference in pressure is converted to an electrical or mechanical signal, which signals are used to control variations in the speed of the submersible pump.

Various objects and a better understanding of the invention can be had from the following description.

DRAWINGS

FIG. 1 is a schematic drawing of a pump submerged in a well bore and whose speed is controlled by the difference in pressure between two vertically spaced points in the vicinity of the pump.

FIG. 2 is a schematic view of a variable speed submersible pump submerged in the liquid in a borehole and including means for varying the speed of the pump in accordance with the liquid produced and also including means for varying the speed of the pump manually.

FIG. 3 is a schematic view of a variable speed pump submerged in a liquid in a borehole and including means to vary the speed in accordance with the pressure drop across an orifice and the pump discharge line.

FIG. 4 is still another embodiment and is a schematic view of a variable speed pump submerged in a liquid in a borehole and including means to vary the speed of the pump inversely as the mass of the fluid pumped.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Attention is now directed to the drawing in FIG. 1. Shown thereon is a well bore **10** drilled in the earth and completed in a productive zone **12**. Borehole **10** is normally provided with a casing **14** set in the borehole and cemented therein and having perforations **16** through which fluid flows into the well bore. Fluid **19** flows into the well bore from productive zone **12** and rises to a level indicated at **18**. Submerged in the liquid **19** in well gore **10** is a variable speed centrifugal pump **20**. The outlet of this pump is connected through a vertical tubing **22**, through a conventional well head assembly **24** in the top of casing **14**. Discharge line **22** extends laterally out of the well head as discharge conduit **26**. Details of the sealing means, etc. are not shown as they are well-known.

We shall now consider the means for supplying power to pump **20**. Typically, pump **20** is an assembly which includes both a submersible centrifugal pump and an electric motor. Energy for the motor is passed from any suitable unit at the surface over electrical conductors within cable **30**. Pump assembly **20** includes a motor of the type in which the rotational speed varies as a function of the frequency of the applied voltage. This energizing voltage is received over the conductors within power cable **30** which is connected at the surface to a frequency changer **32**. Such a frequency changer, or frequency converter, is commercially available from many sources such as the Borg-Warner Controls Division of Borg-Warner Corporation in Santa Ana, California. A suitable frequency changer is designated by Borg-Warner Corporation as "Solid-State Adjustable Frequency Drives." The frequency changer may include a rectifier for converting received AC voltage to a DC voltage, an inverter with a frequency control for producing an AC output voltage of a desired frequency, and a transformer, or other voltage amplitude regulating unit, to afford regulation of the amplitude of the inverter AC output voltage. The inverter frequency can be regulated by hand, such as a knob which regulates the effective value of a component in an oscillator circuit, or the frequency can be adjusted automatically in response to variation in one characteristic of an electrical signal received from a unit such as subtractor **44**. By way of example, such frequency changers are readily available to provide an output frequency of from 0 to 200 Hz. when energized by commercially available power sources. A cable **34** is coupled to the input side of frequency changer **32** to apply such energy from a commercial source (not shown) to the frequency changer. This changer or frequency converter **32** has upper and lower limit sets so that the pump **20** will operate with its prescribed operational limitations.

We shall now consider the measurements required to modify the setting on the frequency changer **32**. It will be recalled that we have previously taught herein that the r.p.m. of pump **20** is to be modified as an inverse function of the change in density. For example, if the density decreases, then the speed should increase. Typically, this increase will be linear. To obtain a measure of the density of the fluid **19** within the well bore in the embodiment of FIG. **1**, we have an upper pressure sensor **36** and a lower pressure sensor **38**. These pressure sensors each have an output electrical signal which is a function of the pressure. Pressure sensors **36** and **38** are connected by conductors represented by lines **40** and **42** to a subtracting unit **44**. The signals from the pressure sensor are transmitted to subtractor **44** which provides an output signal which is proportional or indicative of the difference in pressure as measured by pressure sensors **36** and **38**. This output signal is amplified as necessary and is used to adjust frequency setting on the frequency changer **32**. The feature can be built into the frequency changer or means can be provided to adjust the setting on the frequency changer. For example, the output signal from subtractor **44** can be fed to a drive means **45** which may be a potentiometer whose shaft position is a function of the input signal. The shaft then adjusts the setting of frequency changer **32**. In the other FIGS. of the drawing, the electrical signal indicative of the measured parameter is usually shown as being connected directly to the frequency converter for controlling the frequency of the output power voltage.

The rotational speed of a centrifugal pump driven by an AC motor varies directly with the change in frequency or cycles per second. For example, the normal 60 cycles input to a two-pole, electric motor produces a rotational synchronous speed of 3,600r.p.m. Reducing the input frequency to one-half, or 30 cycles per second, reduces the rotational speed to one-half synchronous speed or 1,800r.p.m. Conversely, increasing the input frequency two times, or 120 cycles per second, increases the rotational speed two times the synchronous speed or 7,200r.p.m. Any intermediate level of frequency setting produces a proportionate change in rotational speed.

Pump performance or the pump output is affected by changes in rotational speed. When speed "*N*" is change, flow "*Q*" varies directly as the speed.

$$\frac{Q_1}{Q_2}=\frac{N_1}{N_2}$$

When speed is changed, the head "*H*" varies directly as the square of the speed.

$$\frac{H_1}{H_2}=\left(\frac{N_1}{N_2}\right)^2$$

When speed is changed, the brake horsepower "*BHP*" varies directly as the cube of the speed.

$$\frac{BHP_1}{BHP_2}=\left(\frac{N_1}{N_2}\right)^3$$

Motor characteristics are affected by changes in frequency or cycles per second. Three parameters are used in predicting motor performance at frequencies other than the normal 60-cycle input.

When frequency "*F*" is changed, speed "*N*" varies directly as the frequency.

$$\frac{N_1}{N_2}=\frac{F_1}{F_2}$$

When frequency is changed, brake horsepower output "BHP" varies directly as the frequency.

$$\frac{BHP_1}{BHP_2}=\frac{F_1}{F_2}$$

When frequency is changed, the required voltage input "*V*" varies directly as the frequency.

$$\frac{V_1}{V_2}=\frac{F_1}{F_2}$$

When the measurement of the density such as reflected by the measurements of pressure sensors **36** and **38** dictates a change in r.p.m., the frequency setting on the frequency changer **32** is adjusted to give the proper frequency of the output power. The changer **32** also adjusts the amplitude of the output voltage.

Attention is next directed to FIG. **2** which shows a modification of the device in FIG. **1**. Instead of using pressure sensors in the well bore, we determine the rate of flow of the liquid. The amount of liquid pumped is a function of the density. In FIG. **2**, discharge conduit **26** is connected to a gas-oil separator **49**. The gas goes out upper outlet **43** and the liquid out a lower outlet **47**. The gas-oil separator is preferably one such as the gas powered heater. Additives known as defoaming agents are added to the separator in order to accelerate the separation of the gas from the oil and thus break down the foam which has been pumped. The liquid output goes through a meter **46** to storage facilities not shown. Meter **46** provides an output signal on line **48** which is indicative of the oil being produced. If the rate of the oil produced decreases, then the signal increases and increases the output frequency of changer **32**. This in turn increases the output of the subsurface pump until the prescribed or preset volume of liquid is produced. Obviously, there must be upper limits set on the pump r.p.m. which take over in the event that the well is incapable of producing the preset volume of liquid.

In FIG. **2**, a power source is connected through switch **33A**, when in its No. **1** position, to frequency converter **32**. The output from converter **32** is conducted through switch **33B**, when in its No. **1** position, to the power cable connected to pump **20**. This is the position of the switches when it is desired to have automatic control of pump **20**.

It is sometimes desirable to provide means whereby the spped of pump **20** can be varied manually. This can be accomplished by the system of FIG. **2** by placing switches **33A** and **33B** in their No. **2** position. This connects the power input source to a manually operated frequency converter **32A**. Frequency changer **32A** is the same as changer **32** except that for changer **32A**, it is essential to have a manually adjustable control. When the switches are each in their No. **2** position, power controller **32** is out of the power circuit. Speed of the pump **20** is then operated manually.

Attention is now directed to FIG. **3** which shows another embodiment of this invention. Here, instead of having the pressure sensors at the bottom as in FIG. **1**, we measure the pressure drop across the orifice in orifice plate **50** in outlet **26**. Pressure lines **52** and **54** on either side of orifice plate **50** are connected to a differential pressure measuring divice **56**. In this embodiment, output of the differential pressure measuring device is an electrical signal which varies as a function of the differential pressure. This electrical signal is applied over line **58** to frequency changer **32**. The pressure drop across orifice plate **50** is a function of the density of the fluid going therethrough. Thus, the speed of pump **20** is controlled as a function of the density of the pumped fluid.

Attention is next directed to FIG. **4** which shows still another embodiment of this invention. In this embodiment the speed of the motor of submerged pump assembly **20** is determined by a measurement of the mass of the discharge fluid. The discharge from line **26** goes to a mass flow meter **60** which has an output signal which varies as a function of the mass. This output signal controls the frequency changer **32**. The frequency of the output of frequency changer **32** varies inversely as the mass of the fluid flowing through discharge line **26**. As the mass decreases, the frequency increases so that pump **20** is turned at a higher r.p.m. Mass flow meter **60** can be any of the commercially available flow meters which determine and record the mass of the fluid flowing through a line rather than mere volume. The mass flow meter can also take the form of a tank **62** supported by scales **64**. Conduit **26** is connected to tank **62** by a flexible connector **61**. As the mass flowing through tank **62** varies, the weight determined by scale **64** varies accordingly. The output from scale **64** can be in the form of an electrical signal or a mechanical linkage to vary the setting on frequency changer **32**.

While the above invention has been described with a great deal of detail, various modifications thereto can be made without departing from the spirit or scope of the invention.

We claim:

1. A method of producing a foamy petroleum fluid from a well bore with a variable speed speed pump, which comprises:
measuring a parameter which is a function of the density of the fluid being pumped; and
adjusting the speed of said pump in accordance with the parameter thus measured.

2. A method of producing a foamy petroleum fluid from a well bore with a variable speed, centrifugal pump which comprises:
measuring a parameter of the fluid in said well bore; and
controlling the revolutions per minute of said centrifugal pump according to the parameter measured.

3. A method as defined in claim **2** in which the parameter measured is a measure of the density of the fluid in the well bore.

4. A method as defined in claim **2** in which the parameter measured is a measure of the difference in pressure at two vertically spaced points in said well bore.

5. A method of producing foamy petroleum fluid from a well bore with a variable speed pump, which comprises:
producing the foamy petroleum fluid through an oil-gas separator to separate the oil from the gas;
measuring the rate of the flow of oil from said separator; and
varying the rate of speed of said pump inversely to the rate of oil produced downstream from said separator.

6. An apparatus for producing a foamy petroleum fluid from a well bore, which comprises:
a variable speed, centrifugal pump located in said well bore;
conduit means extending from said pump to the surface;
means for measuring a parameter of the fluid in the well bore; and
means responsive to the parameter thus measured for controlling the revolutions per minute of said centrifugal pump.

7. An apparatus as defined in claim **6** in which the means for measuring a parameter includes density measuring means.

8. An apparatus as defined in claim **6** in which the means for measuring the parameter includes two vertically spaced apart pressure sensors positioned in the petroleum fluid in the well bore and means for obtaining the differential pressure between the two pressure sensors.

9. An apparatus for producing foamy petroleum fluid from a well bore, which comprises:
a variable speed pump suspended in said well bore;
an oil-gas separator located on the surface;
conduit means connecting the discharge of said pump to said oil-gas separator;
second conduit means for removing the oil from said separator;
means for measuring the rate of flow of oil through said second conduit; and
means for varying the speed of said pump inversely to the rate of oil thus measured in said second conduit.

10. An apparatus for producing a foamy petroleum fluid from a well bore, which comprises:
a variable speed, electrically driven, centrifugal pump supported in said foamy fluid in said well bore, the speed of said pump being dependent on the frequency of the electrical current supplied thereto;
an AC electrical power source;
a frequency changer electrically connected to said power source, the output of said converter electrically connected to said pump;
measuring means for obtaining a parameter which is a function of the density of the fluid being pumped;
means connecting the measuring means to said frequency changer for adjusting the output frequency as an inverse function of the parameter obtained by said measuring means; and
a fluid-carrying conduit extending from said pump to the surface. representing

11. An apparatus as defined in claim **10** in which said measuring means includes two vertically spaced pressure sensors submerged in the fluid signal within said well bore in the vicinity of said pump, and means using a signal representing the difference in pressure between said pressure sensors to control the frequency output of said frequency changer.

12. An apparatus as defined in claim **10** in which said measuring means includes a discharge conduit connected to said fluid-carrying conduit, an orifice plate having an orifice therein and placed within said discharge conduit; and Δp means measuring the pressure drop across said orifice plate, said Δp means including means to adjust the frequency output of said frequency changer as an inverse function of the pressure drop across said orifice plate.

13. An apparatus as defined in claim **10** in which said measuring means includes a mass flow meter fluidly connected to said fluid-carrying conduit.

14. An apparatus for producing foamy petroleum crude from a well bore comprising a variable speed centrifugal pump, first means for measuring a parameter of the well fluid indicative of the density of the fluid, and means connected to said pump for varying said speed thereof in response to the parameter measured by said first means.