DOWNHOLE HEATING DEVICE TO REMEDIATE NEAR-WELLBORE FORMATION DAMAGE RELATED TO CLAY SWELLING AND FLUID BLOCKING

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ABSTRACT

It is a well-known fact in the petroleum industry that thermal treatment (wellbore heating) could result in significant benefits to the producing wells by remedying fluid related problems. Recently, it has been shown in the literature that thermal stimulation also improves fluid flow characteristics of the near-wellbore porous region.

To conduct wellbore and near-wellbore thermal treatments, a simple retrievable electrical downhole heating device has been designed, constructed, and tested. The downhole heating system contains a separate heating chamber, wiring chamber, and cooling chamber. The cooling chamber is inserted between the wiring chamber and the heating chamber to prevent heat propagation from heating chamber to the wiring chamber. The heating is carried out at the surface to test the heater’s capability. An inert gas at the ambient temperature condition is injected through the tubing and heated to the desirable temperature as it passes through the heater. Results indicate that by controlling the power input and the carrier gas flow various desirable temperatures can be achieved.

INTRODUCTION

Conventional hydrocarbon producing wells encounter various problems during their production life. These problems are either related to fluid characteristics or related to formation rock characteristics. Fluid related problems are primarily related to deposition of wax and asphaltene materials and creation of water-in-oil emulsion and these problems can occur in the wellbore tubulars and accessories (i.e. surface equipment, wellbore pumps, pumping rods etc.). In addition, these problems could also occur in the near wellbore regions of the rock. The reservoir rock related problems are primarily caused by fluid invasion resulting in clay swelling and fines migration.

Acid treatments are very popular in remedying the problems related to formation rock characteristics, especially, for carbonate reservoirs. However, acid treatments have had mixed success in remedying
formation rock-related problems in sandstone reservoirs.

Thermal treatment (wellbore heating) could result in significant benefits to the producing wells by remedying fluid-related problems. Recently, it has been shown in the literature that thermal stimulation also improves fluid flow characteristics of the near-wellbore porous region. The foremost application for heating a formation has been to reduce the viscosity of the oil, specifically heavy oil. A second important application for heat treatment has been the prevention or removal of waxes or asphaltenes build-up in the wellbore and near-wellbore region. Other benefits resulting from thermal treatments include clay dehydration, thermal fracturing at high temperature, prevention of thermal fracturing in water zones at low temperatures and sand consolidation in unconsolidated formation. In the case of downhole electrical heating some of the current may be diverted to prevent the corrosion of tubing, casing, pump rods and other downhole components and to prevent build-up of corrosion products.

Most downhole heating devices have been designed to apply to combustion or downhole steam generation purposes. A downhole electric heater is designed to use to ignite the in-situ fuel. The heater is removed and air is supplied to maintain a combustion front. An ohmic heating system has also been applied for an oil, which had a viscosity of 160 mPa.s. A low-frequency electric current is projected into the formation returning to the casing. The electric power caused ohmic heating which dissipated as the inverse square of the distance from the electrode.

Various downhole heating systems have been proposed in the literature. Among these heating systems, a downhole heater design which uses the casing or tubing as electrodes has been proposed in the literature. In this design, one electrode is aligned with the pay zone. The opposite electrode exists outside the pay zone and preferably at least three times the diameter of the hole away from first electrode. For current to pass from one electrode to the other it must pass through the pay zone. The current will be carried either by a conductive formation or by the water in the formation. The high resistance to current flow will result in localized heating.

A combination of downhole heater with a water pump has also been proposed earlier. In this design, if the heater is powered through pressurized water is directed through the heater and to the formation where it will cut away at the rock formation and thermally stimulate the well. If the heater is not activated then the pressurized water is to turn a turbine and assist in the downhole pumping of production fluids. The use of pressurized water also prevents the heater from overheating and burning out the elements. The method should prevent heat losses along the pipe from pumping steam from the surface.

A heating technique based on supplying electrical power at the thermal harmonic frequency of the formation is proposed by Gill and Gill. The design consists of converting the three-phase AC power to DC and then chopped to single phase AC at the harmonic frequency. The harmonic frequency heating occurs in addition to the normal ohmic heating.

A fuel-fired downhole radiant heater has been proposed by Hemsath. In this design, the well is first flooded with water from an injection well to a desired pressure then the fuel-fired heater is ignited to heat the formation and water. The heater consists of three concentric cylindrical tubes. A burner within the innermost tube ignites, and burns a source of fuel and air. Apertures are sized and positioned to develop laminar flow of the combustion products from the burner such that the heat transfer is effective along its entire length. The combustion products are removed from the annular space between the two outer tubes. The design of the heater minimizes local hot spots and should heat the reservoir evenly.

A downhole steam generator involving combusting a fuel downhole is described by Meeks and Rhodes. The heat generated during combustion heats an array of water tubes converting the water to steam. The steam is injected downwardly into the borehole. The combustion products are retrieved from the annulus between the heater and the casing. A packer forces the steam into the formation preventing it from mixing with the combustion products.

A downhole steam generator specifically designed for horizontal wells has been described by Meshekov. A chamber having water in the bottom is heated with electrodes to form steam above the water. The steam is discharged into the formation.
An apparatus for use in a horizontal well but for producing tar sands has been discussed by Mims. The first step involves a preheating period to get the bitumen to such a temperature that it will flow. Then steam is injected through perforations at the toe of the horizontal well only. The steam will gravitate upwards and towards the perforations in the production (heel) end of the horizontal well. The injection and production sections of the horizontal well are separated from each other by a packer. As the toe end becomes depleted the packer can be moved toward the well head to stimulate additional sections of the reservoir.

A downhole packed-bed electric heater has been described by Nenninger. The heater comprises two electrode which are displaced from each other. The gap is filled with conductive balls. Resistive heating occurs when current is passed through the heater. The multiple paths of current flow through the heater prevent failure of the heater due to element burnout. The heater provides a large surface area for heating while maintaining a low pressure drop between the inlet and outlet of the heater. The length and diameter can be easily adjusted to satisfy well design and heating requirements. Formation heating is achieved by passing a solvent through the heater which is heated up, passes into the formation and transfers the heat to the formation.

Rice et al. describe the process required to heat up a reservoir slowly to avoid hot spots and material problems. They ran a slotted fiberglass liner (rated to 150 °C) with a 5m long steel electrode such that the electrode terminated opposite the producing zone. Electric power at a frequency of 27 Hz and maximum current of 400 A was conducted through an armour insulated 1"-diameter copper cable. Power losses in the cable were estimated to be in the range of 10-20%. A downhole electric heater has been used by Stahl et al to covert hot water to steam. Instead of producing steam on the surface and pumping it downhole, they suggest heating water on the surface, pump this downhole where an electric heater converts the hot water to steam. The electric heater is a series of U-tubes disposed circumferentially around the water injection tube. Each U-tube can be individually controlled. The injection tube is closed at the bottom with orifices placed radially. Water flows out the injection tube and past the heater tubes where it is vaporized. Electric power is supplied via a three-phase grounded neutral "Y" system with one end of each of heater elements being common and neutral. They also supplied DC current to the heater.

Van Egmond advises using a copper-nickel alloy core cable for downhole heating. This 6% by weight nickel alloy is less prone to failure because it has a low temperature coefficient of resistance. It maintains the low resistance of copper. The cable is capable of withstanding temperatures to 1000°C and utilizing voltages to 1000 volts. The cable is especially useful for heating long intervals. Van Egmond describes a heater using this material which is cemented into an uncased borehole. The savings on casing stable to high-temperature corrosion would reduce the cost of installation considerably. The heater can provide heat to about 250 watts per foot of length.

The present design is concerned with an electrical downhole heating system for formation heat treatment. The heater contains separate wiring chamber, heating chamber, and cooling chamber, the latter being inserted between the wiring chamber and the heating chamber. The heat treatment is carried out by inserting the heater in a borehole to be treated. A gas, preferably nitrogen or air, is brought to the heater with a hose or tube. The gas goes through the wiring chamber and cooling chamber, and is heated by following a tortuous path in the heating chamber before it is expelled from the heater.

**FORMATION HEAT TREATMENT CONCEPT**

The formation heat treatment (FHT) process involves the application of heat for the treatment of near-wellbore damage. The FHT process consists of exposing the formation to an elevated temperature to cause:

- vaporization of blocked water,
- dehydration of the clay structure,
- partial destruction of the clay minerals, and
- possibly, micro-fracture of the formation in the near-wellbore area due to thermal induced stresses.

The dehydration and vaporization of bound and blocked water occur at temperatures higher than the saturation temperature corresponding to the reservoir pressure. The extent of clay destruction also depends on the heating temperature.
The electric downhole heating system designed for the FHT process is particularly suitable for stimulating the production of oil and gas formations containing clay materials and those formations that are susceptible to fluid blockage. Other uses include in situ steam generation, initiating in situ combustion, near-wellbore heating for heavy oil viscosity reduction, stimulation of water injection well, near-wellbore emulsion breakings etc.

DETAILED DESCRIPTION OF THE DOWNHOLE HEATING DEVICE

A schematic diagram of the downhole heating device is presented in Figure 1. As seen in Figure 1, the downhole heater having a wiring chamber, a cooling chamber and a heating chamber, contained in an outer shell. The chambers are threaded for joining them together. The heater is closed at one end with a cap and is provided with a connector at the opposite end, for connection with any conventional tubing means, including coiled tubing, used in the oil and gas industry. The connector has a centered channel extending throughout its length and emerging into production tube, which is inserted in heater and extends through the wiring chamber, the section of the pipe in the cooling chamber being cut and removed.

The heating chamber is comprised of three concentric pipes. The central pipe is open at both ends and the intermediate pipe is closed at the bottom end and connected to the metal block separating the heating chamber from the cooling chamber. Slots are cut in the upper part of the intermediate tube for gas to flow through. The outer tube is the continuous shell that extends from the wiring chamber to the heating chamber. The bottom part of the outer shell is closed and slots are cut at the bottom of the outer shell for the hot gas to exit the heater.

Conventional heating elements are briefly described as follows: Each comprises a first section made of two wires of nickel extending from the wiring chamber through the cooling chamber. The second section is in the heating chamber and comprises two wires of INCONEL electrically connected to the wires of nickel. Both sections are contained in a casing filled with a dielectric material like magnesium oxide. The result is that little heat is generated in the cooling chamber because of the nickel wires, while the INCONEL wires, which are resistive, converts electricity to heat in the heating chamber.

Each heating element is inserted in a tube, which is connected to a heater extension with bolts. The heater extension is also made of dielectric material, so that very little heat, if any, is transferred from heating chamber or heating element to cooling chamber and wiring chamber. The heater extensions are combined by groups of three in wiring chamber to form three wires which are connected to an appropriate power source at the surface.

The heating elements are connected to the outer surface of the intermediate tubing. The heating chamber is equipped with a thermocouple to monitor the temperature at each end of each chamber.

A closer look at the heating chamber shows that the intermediate tube has one end closed while the other end is also closed by the metal slab that connects the heating chamber to the cooling chamber. However, just below the upper connection, slots are being cut to allow the passage of gas from the first annular space to the second annular space. To insure that the gas is uniformly dispersed, the slots should be distributed at regular intervals at the same end around the intermediate tubing. The outer shell also has slots to allow even distribution of hot gas radially from the heater to the sandface. Spacers are placed in between the innermost tubing and the intermediate tubing and also between the intermediate tubing and the outer shell. Spacers maintain the pipes in place.

In operation, as illustrated in Figure 2, the heater is lowered in wellbore provided with a conventional internal metal casing, in the area of the zone of interest, heating elements are heated and the hot gas, preferably nitrogen, is injected from the surface, generally a nitrogen truck if the gas is nitrogen, in the production tube. Since the section of pipe has been removed from cooling chamber, the gas is allowed to flow freely therein and act as a coolant. As the gas enters the heating chamber, its temperature starts to increase because of the presence of heating elements on the surface of the intermediate pipe. The gas follows the tortuous path indicated by the arrows before being expelled from the heater through the openings at the outer shell at the desired temperature. Such tortuous path provides adequate residence time for the gas to heat up at the desired temperature. The ability to manipulate
the gas flow rate at the surface also allows flexibility of the gas residence time within the heating chamber. It should also be noted that nitrogen is also injected through the tubing-casing annulus to maintain a positive pressure downward, so that the heated gas is concentrated in the zone of interest, thus reducing the heat losses to the top of the zone (Figure 2).

Each heating element has a power of 7.2 kW. In the heater, 9 heating elements are used, therefore allowing a total power of the equipment of 65 kW. The heating elements are connected by groups of three in parallel connections, so that if one group fails, the heater will still be able to operate with six elements.

Gases suitable for injection in the above heater include air, oxygen, methane, steam, inert gases and the like. Inert gases are preferred, nitrogen being the most preferred. The flow rate of gas may vary from 5000 m³/day to 57,000, or higher, m³/day (standard conditions of 15°C and 1 atm). Accordingly, a 65 kW power and a nitrogen flow rate of about 10,000 m³/day would correspond to a temperature increase of up to 800°C. A temperature above 600°C is generally sufficient for the applications of the present electric heating system. It is thus possible to control the temperature both by varying the flow rate of gas, or by regulating the power output.

Before reaching the heating chamber, the injected gas is at ambient temperature, and cools the wiring chamber and the cooling chamber, thus avoiding undesirable overheating in these chambers. The wiring chamber is also preferably fluid sealed to permit the application of the heater in any environment in the wellbore, such as water, oil, gas and mixtures. For material safety issue, the heater should include an automatic shutoff system to cut the power off and prevent overheating of the cooling and wiring chambers.

The total length of an electric heater according to the present design and illustrated in Figure 1 is about 462 cm (182"), 3/4 of which being the length of the heating chamber, and the wiring and cooling chamber each representing 1/8 of the length of the heater. As the diameter of deep wellbores generally does not exceed 12 cm (5"), the diameter of the heater should be around 8-9 cm (3.5") to facilitate its introduction and positioning.

The design of the present electric heater has several advantages:

If one heating element fails, the heater may still be operated at lower power; there is therefore no need to retrieve it from the wellbore.

It may be used in harsh wellbores, which contain brine, oil and gas.

All the pieces of the present heater are made of stainless steel, except for the heating elements and the heating extensions, which are sealed in INCONEL 600 sheets.

SURFACE TESTING OF THE DOWNHOLE ELECTRICAL HEATING DEVICE

The electrical downhole heater design presented in this paper was constructed and tested on the surface several times. To emulate the field condition during the surface testing, the heater was hoisted vertically and placed inside a 12.7 cm (5") casing. Several thermocouples were attached to the heater to monitor the heat transfer characteristics. The thermocouple locations are indicated by numbers in Figure 1. Several thermocouples were also attached to the enclosing casing to monitor the heat distribution around the outer surface of the heater. Nitrogen gas was used to flow through the heater and also through the heater-casing annulus.

During the surface testing, the heater was powered up slowly inorder not to provide a sudden electrical shock to the heating elements. The power up sequence is presented in Figure 3. As seen in the figure, initially, the power was controlled by variac. After reaching about 90 kW power the power control was switched to automatic Halmar controller and sequentially power was increased to about 45 kW. This power corresponds to a current of 42 Amps and a voltage of 630 Volts.

The temperature of the gas exiting the heater is presented in Figure 4. As seen in the figure, the exit gas temperature increased slowly as the power was increased slowly. The heater temperature reached the highest temperature of 720°C corresponding to a power of 45 kW and a total nitrogen flow rate of 3.0 m³/min at around 180 minutes after the experiments started. Subsequently, the power was cut off and the nitrogen flow rate was increased to cool the heater quickly. The average exit gas temperature was calculated using the average gas properties and the calculation indicates that...
the exist gas temperature should have been 748°C. As expected, the measured exit gas temperature was lower than the calculated value and this is because of the heat losses. Thermocouple #14 (shown in Figure 4) was located at the inner side of the casing opposite the exit gas appature of the heater.

Temperatures of junction box (thermocouple #1), cold box (thermocouple #2), outside of the junction box (thermocouple #8), and thermocouple #12 which was located across the cold box are presented in Figure 5. As seen in the figure, the temperatures in these thermocouples did not increase over 50°C.

Temperatures in the heating chambers at various locations are presented in Figure 6. As seen in the figure, gas temperature at the top of the heating element is low in the second annular space. This is because of the fact that thermocouple #3 was closed to the cold gas entry to the heater. It is also interesting to note that as the gas goes down the second annular space, it reaches higher temperatures (thermocouple #5) and slightly cools down at the close to the exit (thermocouple #6). This is also because the bottom part of the heating element directly contacts the cold gas entry from the first tubing to the first annular space.

REFERENCES


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SUMMARY

To conduct wellbore and near-wellbore thermal treatments, a simple retrievable electrical downhole heating device has been designed, constructed, and tested. The downhole heating system contains a separate heating chamber, wiring chamber, and cooling chamber. The cooling chamber is inserted between the wiring chamber and the heating chamber to prevent heat propagation from heating chamber to the wiring chamber. The heating is carried out at the surface to test the heater's capability. An inert gas at the ambient temperature condition is injected through the tubing and heated to the desirable temperature as it passes through the heater. Results indicate that by controlling the power input and the carrier gas flow various desirable temperatures can be achieved.


Figure 1: Schematic diagram of the electrical downhole heater
Figure 2: Schematic diagram of the field logistics
Figure 4: Measured exit gas temperature of the heater
Figure 6: Measured gas temperature in the heating chamber