Technology and automation of low-temperature distributed induction heating in the oil and gas industry

Yu. A. Nikitin
Ufa, associate Professor of Ufa state aviation technical University, scientific adviser of LCC "Geoburservis"

nikyu@yandex.ru

Abstract. Energy efficient electrotechnologies are one of the most promising areas of development of any industry. To improve the energy efficiency of the processes of keeping up the temperatures and heating technological facilities in the oil and gas industry by reducing electricity consumption, the development and introduction of modern technologies and equipment is needed of electroheating. To such means of electroheating includes low-temperature induction heating, which provides a guaranteed increase in quantitative and qualitative production indicators, which can significantly reduce the cost of production, which is important to save energy resources especially with increased tariffs. Various aspects of the development of such induction heating systems are discussed, with a particular focus on ensuring the safety and automation of installations used in the oil and gas industry. The issues of using distributed induction heating in the oil industry are considered using the example of the induction method for oil and gas producing wells with the aim of facilitating the production of highly viscous oil, eliminating tar-tar deposits and preventing the formation of hydrate-paraffin plugs. The results of modelling the heating of the inductor - tubing system at various positions of the load-bearing and non-load-carrying cable-inductor are presented. During the simulation, data were obtained on the temperature of the oil product were obtained under various oil production conditions.

1. Introduction
Maintaining technological temperatures or heating the product in various technological devices, pipelines, tanks and containers, heat exchangers, when heating valves, water pipes and other equipment is widely used for technological purposes at the enterprises of the oil and gas industry. At the same time, such technological operations as compensation of heat losses to the environment, and directly heating the product in accordance with a given technology are characteristic. To increase the energy efficiency of these operations, the latest achievements in the field of heating electrical technology should be used.

In the case of extended pipelines, tanks or large-volume containers, usually the product heating temperature does not exceed the permissible temperature for the transported or stored product, i.e.
such heating systems belong to the class of low-temperature heating (for oil products, the surface of a heated object usually does not exceed 2500 °C). Therefore, it is advisable in this case to use heating systems distributed over the surface of the heated object. Such heating systems, in contrast to concentrated (for example, heating elements) heating systems, have a large heating area (tending to the full surface of the heated object in the limit), and, therefore, better heat transfer and a significantly lower temperature gradient for transferring thermal energy from the heater to the product.

At present, indirect electric heating using resistive [1] or self-regulating heating cables [2] is increasingly used for distributed heating systems, which replaced steam heating, which has low efficiency, but is widely used in the petrochemical industry. However, a significant disadvantage of this method of electric heating is that even with good contact of the heating cable with the heated surface of the object, it is not possible to provide low thermal resistance between the heating cable and the surface of the heated object. As a result, the heating cable in order to transfer heat to the heated object must be heated to a high temperature significantly exceeding the required surface temperature of the heated object. This imposes a restriction on the use of the heating cable in explosive areas. In addition, when using self-regulating heating cable, local overheating of the cable in loose contact with a heated surface will lead (at the expense of self-regulation) to reduce the temperature of cable (to decrease its specific capacity), and, consequently, to reduce heat transfer from the cable to the heated object, which ultimately will lead to the inability to provide specific technological regimes in certain heating zones.

An alternative to the heating cable is induction distributed heating, which, in fact, is a direct method of heating the metal surface.

2. Description of the method of distributed low-temperature induction heating of technological objects

For the first time, induction distributed heating is mentioned in [3], where the principal possibility of heating extended pipelines to maintain process temperatures is considered. It is noted that for heating pipelines, cylindrical inductors can be used from a wire with heat-resistant insulation or a single-phase cable with a large winding step. As the winding step increases in the limit, we get a two-wire line laid along the pipeline. The pipe itself can be used as a return pipe. The power is determined from the calculation of heat losses, taking into account the adopted insulation and the temperature of the pipe and the environment. Typically, the average power is a fraction of a watt per square centimeter of pipe.

Thus, in a distributed induction heating on the metal surface of the heated object (technological apparatus, pipeline, container, etc.) is laid (linearly or along any given contour), a conventional mounting copper stranded cable in a shell that can withstand a given surface heating temperature (for example, in a fluoroplastic shell or a shell made of organosilicon rubber, the cable temperature can reach 180 °C). In contrast to the heating cable, a conventional mounting cable has a significantly lower cost. This cable is connected to an AC power source. Induction heating occurs as a result of the penetration of electromagnetic waves into the metal volume. Since the conducting circuit or coil through which the alternating current flows is located near the metal object of heating (through a layer of heat and electrical insulation), as a result of the penetration of the electromagnetic field into the metal, eddy currents occur in it (due to the phenomenon of electromagnetic induction), which heat the metal (Joule heat is released). Thus, heating is carried out without direct contact of the induction cable with the metal, which provides a particularly low thermal inertia and high efficiency of converting electrical energy into heat.

At an average and high operating frequency, the depth of the heated layer is small and the alignment of the thermal field in the heating object is provided only by heat conduction processes. At lower operating frequencies, the depth of penetration of the electromagnetic field increases, but the achievement of uniform heating is also achieved through the mechanisms of thermal conductivity.
Lowering the operating frequency allows you to maximize the volume of the heated area, but in some applications it is more effective to use the increased frequency of the electromagnetic field. It should be noted that the heating rate is strongly dependent on the magnetic characteristics of the heated metal. The frequency range and shape of the alternating current is selected individually in each case and can reach wide limits (from the industrial frequency-50 Hz to the ultrasonic frequency range-tens of kHz). For use in the oil industry, the frequency selection method consists not only in the correct choice of the metal heating depth, but also in some cases, the need for vibration or electromagnetic action on the petroleum product in order to meet the specified technological requirements, taking into account the necessary heat transfer in individual elements of the heating system. Therefore, the development and implementation of induction technologies in the oil and gas industry is currently an urgent and promising direction and requires appropriate development in the field of scientific and engineering practice.

3. Advantages of distributed low-temperature induction heating

A current research show [4, 5] that induction heating distributed over the surface has the following advantages compared to other types of electric heating:

- Uniform heating throughout the volume and low thermal inertia. In installations with induction heating, rapid cooling and heating of the product is possible.
- Since the thermal resistance of the walls, which must be taken into account, for example, for indirect heating, is absent, the heating temperature decreases, and the total heating efficiency increases.
- It is easy to reproduce the heating conditions of the product in accordance with the specified technological process, so the spread of product parameters is insignificant; its quality is usually stable.
- The temperature limits of heating are wide, temperature control is possible within 0-500 °C.
- Long service life and low cost of the inductive cable.
- For the operation does not require special maintenance personnel.
- Inductors and control cabinets can be explosion-proof.
- Wide possibilities for heat exchange intensification by controlling the geometric shape of the heated layer.

In addition, with induction heating, all the advantages of electric heating are preserved: good sanitary and hygienic operating conditions, the absence of special maintenance personnel (except the apparatchik himself), lower capital investment, the ability to regulate and automate the process, and save scarce primary energy resources.

As you know [5], the choice of a particular type of heating equipment for conducting a particular process is due to a number of requirements:

- The resource of work, which determines to a large extent the cost of production, the duration of operation.
- The quality of heating, on which the quality of the processed product depends (the ability to control heating, the accuracy of regulation or stabilization of temperature).
- Profitability due to the minimum consumption of energy and materials.
- Electrical, fire and explosion safety.
- Constructive perfection of the equipment: minimum weight and dimensions, manufacturability of the design, ease of use, ease of installation and dismantling, ease of maintenance, etc. This requirement is relevant, since devices with heating contain technological and electrical elements, i.e. obviously quite complicated.
- The minimum cost of equipment.
- Good sanitary and hygienic working conditions and compliance with environmental requirements.
Induction heating satisfies all the above requirements.

In contrast to the considered distributed induction heating, the method of concentrated induction heating using an inductor coil is very widely used in mechanical engineering in induction furnaces for melting metal, when heating work pieces for forging, quenching [3]. A special feature and main advantage of concentrated induction heating is that it is heated to high temperatures (local heating). Currently, semiconductor frequency converters are increasingly used as power sources for inductors (generators) operating at frequencies higher than industrial frequency. The efficiency of using a particular class of converters for local induction heating, used in the engineering industry, is a well-studied issue and there are appropriate engineering methods for choosing a particular type of converters [6]. The circuitry of the power part and the control circuit of these converters is based mainly on ensuring safe switching of power semiconductors using an oscillating circuit that is the load of the Converter and an additional resonant circuit formed by the inductor and a compensating capacitance connected in parallel or in series with the inductor. This type of induction heater is characterized by heating the metal above the Curie point, which consequently leads to a sharp change in the magnetic properties of the latter (the magnetic permeability drops and becomes in some cases at the level of the magnetic permeability of the air). The consequence of such a sharp change in the physical properties of the metal is a significant detuning of the resonant circuit, which is the load of the semiconductor converter. Therefore, controlling the operation of such a Converter is quite a complex task and requires the mandatory use of phase-locked frequency in control systems.

With distributed induction heating, the temperature usually does not reach the Curie point, so there is no detuning of the resonant circuit and the requirements for Converter control systems are significantly reduced. As a result of the research and design work [4, 7], simple technical solutions were proposed for implementing algorithms and circuit solutions for controlling the power part of induction heaters using frequency-pulse modulation. It is shown that energy-efficient (high efficiency, ensuring the safe operation of power switches and drivers in a wide range of power control in the load and other indicators of the efficiency of the power supply) is the use of quasi-resonant circuits in of the power part of the converters [7], which reduces the cost of induction distributed heating systems in general.

4. Various aspects of development of distributed low-temperature induction heating systems

At the present stage of development of distributed induction heating systems due to only optimization of the design of converters and induction cables, it is quite difficult to substantially improve the technical characteristics of the heating system. Further research is required to identify the regularities of induction distributed heating systems in order to ensure their more economical, reliable, and safe operation (especially in high explosive conditions at oil and gas industry facilities), as well as ensuring coordination of their interaction with the work of existing automation systems for technological processes and production, which requires the use of more advanced in terms of integration of electronic control and management systems. Most often, various safety systems are connected to distributed heating systems, which (in automatic or semi-automatic mode) monitor the performance of devices, prevent the occurrence of emergency situations, protect converter equipment from damage, which leads to the need to develop:

- alarm devices that indicate an unauthorized stop of the heating system or the operation of the Converter in emergency mode;
- devices for protecting heating systems from short-circuiting the inducing cable to the metal surface of the heating object (short-circuiting the inductor to the ground in case of accidental mechanical damage to the latter);
- inducing cable protection devices that disable the Converter when the temperature rises above a certain value.
Also, devices that automatically turn on or turn off the heating system in a particular situation, for example, various sensors and actuators, can be connected to the system [8]:
- relays that turn the heating system on and off at certain times of the day;
- devices that automatically turn on the heating system after interruptions in the operation of the power supply network;
- devices that control several heating objects, including one or more generators and, for example, switch inducing cables at certain intervals;
- pressure and temperature sensors;
- interfaces allowing to connect external control and monitoring tools to heating systems;
- other electronic devices.

When choosing automation, it is necessary to take into account the power, type and number of semiconductor converters of the induction distributed heating system, the number and type of the induction cable used, on which the heating system can work. Since, in heating systems, the operation of the generator and induction cable is often tightly connected with the operation of the pump, moreover, both the heating system and the pump are controlled by the automation of the heating system.

Often, various control and monitoring systems of induction distributed heating systems are combined into sufficiently powerful multi-channel programmable electronic units that control not only the heating system directly, pumps, but also the corresponding shut-off valves.

Of great importance in an induction distributed heating system is the estimation of the cost of the "generator - induction cable" system, which is quite difficult to implement, since it depends on a variety of parameters and the mode of operation of the system. At the same time, despite the relatively high cost of powerful industrial converters, they pay off quickly. Moreover, since converters of induction distributed heating systems are necessarily equipped with soft start and soft stop devices, their use avoids sudden changes in the power consumed from the network, which in turn increases the service life of both the converter itself and induction cable. In contrast to the use of traditional resistive heating cables, the overall efficiency of the heating system increases, since the heating cable is characterized by the presence of significant starting currents until the cable and the heating object itself are warmed to the nominal temperature. With the help of modern semiconductor converters, can not only control the operation of the inducing cable and the heating system as a whole, but also monitor their main parameters in real time. The most advanced models can capture and transmit up to several dozen operating parameters of the heating system in real time. Processing this information allows you to perform deep diagnostics of equipment and prevent the occurrence of emergency situations.

5. Application of distributed induction heating in the oil industry as an example of induction effects on oil and gas wells
As an example of the use of distributed induction heating in the oil industry, we consider the method of induction impact on oil and gas wells in order to facilitate the production of high-viscosity oil, eliminate asphaltene, wax deposits and prevent the formation of hydrate and paraffin plugs [9, 10]. The method of induction impact on the well includes:
- Induction heating of the geophysical cable in metal armor, which is immersed either directly into the pump-tubing of an oil and gas well through a lubricator, or in the tube space between the pump-tubing and the casing of the well, and maintaining the temperatures in the wells, as well as additional heating by the well of the liquid from the heated geophysical cable.
- Ultrasonic vibration effect on downhole fluid and oil plates.
- Additional electromagnetic effects on the borehole fluid.

In the case of using geophysical cable with an outer shell of polypropylene or fluoropolymer, while passing high frequency current through the veins of the geophysical cable thermal, vibrational,
acoustic and electromagnetic field is formed directly in a conducting body [11] (production string and tungsten hanger) and on bottom-hole formation zone and the downhole fluid, respectively, without heating the cable itself (the cable should have proper insulation and mechanical strength to hold it well).

Method of induction impact on the well [10] (Fig. 1) ensures the safety of work, reducing the time spent on the elimination of asphaltene and paraffin deposits in the inter-pipe and internal space of the tubing and, accordingly, the time of preventive treatment without stopping the well operation, high efficiency and, as a result, low operating costs. Work is carried out without involving repair teams. During preventive work, complete cleaning of the inner column space from paraffin is provided, the interprophilactic period of well treatment is significantly increased, and the power consumption during preventive work is usually no more than 25 kW.

For fig.2 shows the appearance of the control station for induction processing, which contains a high-voltage high-frequency transformer and a power converter on IGBT transistors, made according to the bridge scheme, and also shows how the geophysical cable is immersed in a well with a rod pump. The geophysical cable is located on the winch and is smoothly fed through the lubricator into the well into the inter-tube space between the casing and the tubing.

Fig. 1 Composition of equipment for induction effects on the well: 1 - high-frequency high-voltage transformer; 2 - geophysical cable; 3 - control station; 4 - a drum with a geophysical cable; 5 - tubing (a pump-compressor pipe, pump-tubing); 6 - casing string.
Fig. 2 Control station (left) and immersion of the geophysical cable into the well (right).

In all types of wells, the cable-inductor can be installed by hanging the cable at the mouth: in wells with an electric pump through the lubricator, in wells with a rod or screw deep pump through the gland device into the inter-tube space (the cable is lowered and lifted by a standard geophysical winch without stopping the well pump).

To model the phenomena occurring during the induction action on the tubing, consider a heating system consisting of an inductor – 2 and a pump-compressor pipe – 5 (Fig. 1) [12]. The heating system is placed in the casing 6. The pump power cable is located in the inter-tube space. The length of the inductor cable must be greater than the zone of formation of asphaltene and paraffin deposits in the tubing (usually no more than 1000 m).

Modeling of electromagnetic and thermal processes in the inductor-tubing system was carried out in the COMSOL Multiphysics application package [13]. In the model creation wizard, we step by step define the model's design area, enter the model's geometric parameters, select materials for each geometry object, select AC/DC (Magnetic Fields) and Heat Transfer (Heat Transfer in Solids) physics, the Frequency-domain solver, and the required type of study, such as Temperature. The considered model of tubing with an inductor placed in it is shown in Fig.3.

Fig. 3 Tubing model in COMSOL Multiphysics

The simulation was performed under the condition that the cable-inductor is either adjacent to the inner surface of the tubing, or is located in the center of the tubing. During the simulation, tubing with an average nominal diameter of 73 mm was selected. Single-core load-carrying and non-load-carrying cables were considered as an inductor. The following simplifications are introduced into the model: the current-conducting cores of the inductor are represented as a single conductor with an equivalent cross-section area, the inner and outer layer of the load-carrying cable's armor is represented as a single shell made of galvanized steel. Physical characteristics of the model are as follows: inductor length – 0.3 m, conductor diameter – 11.38 mm for load-carrying cable, 5.64 mm for non-load-carrying cable, cable insulation thickness – 1.6 mm, armor thickness of the load-carrying cable – 2.4 mm, tubing diameter-73 mm, tubing wall thickness-5.5 mm, frequency of current passed through the veins of the cable-inductor -20 kHz, cable-inductor current-10 A, materials-iron, copper, fluoroplast, oil.

When oil production 1-20 m$/\text{day}$ flow rate of oil in the tubing will be respectively equal to 0.23 m$/\text{min}$ 4.6 m$/\text{min}$. The length of the inductor is equal to 1000 m choose To simplify the construction of models and presentation of modeling of processes of heating wells, we consider only the part of the inductor, which is many times smaller than the heated portion of the tubing (Fig. 3). This assumption is correct, since the induction heating of the tubing has a uniform increase in the temperature of the
tubing surface under the condition of mixing the oil in the tubing. Based on this, knowing the speed of the oil flow in the tubing, we can determine the time during which the oil will rise to the surface from a depth of 1000 m. All this time, the oil will be heated inside the tubing under the action of the heated inductor shell. The lifting time of oil in the tubing, respectively, is from 217.4 minutes to 4347.8 minutes.

When using a non-load-carrying inductor, the tubing in well is heated by eddy currents. In turn, the tubing surface in contact with the oil heats it and, accordingly, the tubing surface is cleaned of asphaltene and paraffin deposits. Some results of modeling of oil heating under induction influence on the well by load-bearing and non-load-bearing cables with production of 1 m³/day are presented in Fig.4 with oil temperature indicators.

When modeling oil heating, when the non-load-carrying inductor was adjacent to the tubing surface, the required temperature was reached after 1050 minutes (17.5 hours) of inductor operation. When the required temperature is reached, the device turns off the current supply to the inductor, and the temperature increase stops. The current supply will resume when the oil temperature set for a particular well is reached. In the oil heating model with a non-load-carrying inductor located in the center of the tubing, the required temperature was reached after 2300 minutes (38.3 hours) of inductor operation.

When using a load-carrying inductor, oil is heated from the surface of the armor heated by eddy currents. It took 350 minutes (5.8 hours) for the inductor to heat to the required temperature. With the central position of the inductor, the required temperature was reached after 250 minutes (4.2 hours) of operation of the inductor.

Similarly, the heating of oil was considered under the induction effect on a well with a production of 20 m³/day. During the time required to rise to the mouth well, the oil was heated only to a temperature of 47–48 °C. When simulating heating with a non-load-carrying cable in the center of the tubing during production of 20 m³/day, the average oil temperature was 43 °C. As a result of the simulation, during the time necessary for the ascent to the mouth, the oil was heated mainly to a temperature of 65–67 °C. When simulating heating with a load- carrying cable in the center of the tubing during production of 20 m³/day, the average oil temperature was 75–85 °C.

Thus, using the developed models, information was obtained on the nature of heating the tubing with a non-load- carrying and load- carrying geophysical cable used as an inductor at their various positions inside the tubing. When modeling electromagnetic and thermal processes in a well, oil temperatures were obtained under various production conditions.
6. Conclusions
The use of low-temperature distributed induction heating in the oil and gas industry helps to reduce the cost of production and increase the quantitative and qualitative indicators of production. Information is provided on the development of such induction heating systems that ensure the safety and automation of installations.

With distributed induction heating, the temperature of the metal surface of the heating object is significantly lower than the Curie point, so there is no mismatch in the load loop of power converters and the requirements for their control systems are significantly reduced.

Modeling of electromagnetic and thermal processes using COMSOL Multiphysics shows that the downhole temperature regime for distributed induction heating of well pipelines satisfies the conditions under which asphaltene and paraffin deposits in the well are removed, which facilitates the production of high-viscosity oil.

References
[1] Fonarev Z. I. Electric Heating of pipelines, reservoirs and process equipment in the oil industry. – Leningrad: Nedra, 1984. – 148.
[2] Strupinsky M. L. Design and operation of electric heating systems in the oil industry: reference book / M. L. Strupinsky, N. N. Khrenkov, A. B. Kuvaldin. – Moscow: Infra-Engineering, 2015. – 272 p.
[3] Induction heating installations: A textbook for universities/ A. E. Slushotsky, V. S. Nemkov, N. A. Bamuner; edited by A. E. Slushotsky – L.: Energoizdat, 1981. – 224 p.
[4] Makulov I. A., Nikitin Yu. A. Equipment and features of application of induction heating in the oil and gas industry. - Moscow: Industrial electric heating and electric heating. 2014. No. 3. Pp. 50-53.
[5] Nikitin Yu. A. Technology and automation of low-temperature induction distributed heating. - Automation and management of technological and production processes: Materials of the all-Russian scientific and practical conference (Ufa state aviation technical University. – Ufa: USATU, 2011. – Pp. 226-231.
[6] Development and design of thyristor frequency converters /A. K. Belkin, S. A. Gorbatkov, Yu. m. Gusev, I. I. Parfenov, A. A. Shulyak-M.: Energoatomizdat, 1994. – 272 p.
[7] Nikitin Yu. a. Transistor converters of constant voltage of class E. / / Kand. thesis. - MAI, 1990. - 225 p.
[8] Nikitin Yu. a. Technical means of automation and quality management systems: A textbook for students of higher educational institutions studying in the direction of training "Automated technologies and production" / Yu. a. Nikitin; Federal Agency for education, State educational institution of higher education. Prof. of education Ufa state aviation technical University-T. Ufa, 2008. – 223 p.
[9] Makulov I. A., Nikitin Yu. A., Nikitin A. Yu., Makulov R. I. Method of destruction and prevention of formation of deposits and traffic jams in oil and gas wells and device for its implementation. - Patent for invention RU no. 2503797. Registered in the State register of inventions of the Russian Federation. - Byul. No. 14. Published on 10.01.2014.
[10] Nikitin Yu. a., Osipov V. V., Nikitin A. Yu. Method of elimination, prevention of formation of deposits and intensification of oil production in oil and gas wells and device for its implementation. - Patent for invention RU No. 2630018. Registered in the State register of inventions of the Russian Federation. - Byul. No. 25. Published on: 05.09.2017.
[11] Makulov I. A., Nikitin Yu. a., Nikitin A. Yu., Makulov R. I. Method of transportation and discharge of high-viscosity fluids. - Patent for invention RU No. 2568084. Registered in the State register of inventions of the Russian Federation. - Byul. No. 31. Published on: 10.11.2015.
[12] Nikitin Yu. a. Modeling and calculation of the inductor-pump-compressor pipe system. – In the collection: machine tool Construction and innovative engineering. problems and points of growth: Materials of the all-Russian scientific and technical conference. Ufa, 2018. Pp. 170-175.

[13] Pracht V. A., Dmitrievsky V. A., Sarapulov F. N. Modeling of thermal and electromagnetic processes in electrical installations. Comsol program: Textbook / Edited by F. N. Sarapulov-M.: Sputnik + publishing House, 2011. - 158 p.