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ELECTROTECHNICAL MODULAR COMPLEX FOR HEATING VISCOUS LIQUIDS IN PIPELINE TRANSPORT FACILITIES

The article discusses the problem of increasing the efficiency of installations for heating viscous liquids during their transportation through pipeline systems. The posed problem is solved by intensifying the heat transfer process between heat sources and a heated liquid. Intensify the heat transfer process in heating systems by using a modular heating system. Each module consists of an induction heating section and an induction mixer. The mixer is installed at the outlet of the heating section. The process of mixing the liquid is carried out by an induction mixer of a special design. A method for calculating the temperature of the oil flow in the pipeline behind the induction heater and after the mixer is proposed. The methodology was developed on the basis of a balance of heat flows. The temperature distribution for a multi-section heater consisting of several induction modules is calculated. It is shown that the use of a modular system can significantly reduce the overall dimensions of the induction heater and reduce energy costs for transporting liquid.

В статье рассматривается проблема повышения эффективности установок для нагрева вязких жидкостей в процессе их транспортировки по трубопроводным системам. Поставленная задача решается за счет интенсификации процесса теплообмена между источниками тепла и нагреваемой жидкостью. Интенсифицировать процесс теплообмена в системах подогрева можно путем применения модульной системы нагрева. Каждый модуль состоит из индукционной нагревательной секции и индукционного смесителя. Смеситель устанавливается на выходе из нагревательной секции. Процесс перемешивания жидкости осуществляется индукционным смесителем специальной конструкции. Предложена методика расчёта температуры потока нефти в трубопроводе за индукционным нагревателем и после смесителя. Методика разработана на основе составления баланса тепловых потоков. Приведен расчет температурного распределения для многосекционного нагревателя, состоящего из нескольких индукционных модулей. Показано, что использование модульной системы позволяет существенно сократить массогабаритные показатели индукционного нагревателя и снизить энергозатраты на транспортировку жидкости.

Keywords: *pipeline transport, electricity, heater, temperature, heat transfer, power regulation, energy efficiency.*

Ключевые слова: *трубопроводный транспорт, электроэнергия, нагреватель, температура, теплообмен, регулирование мощности, энергоэффективность.*

The transportation of oil and oil products, using the pipeline system, is safer, more cost effective, and more environmentally friendly than other modes of transportation, particularly in tanks on railways. The cost gain reaches 4 times the value, including lower losses of the oil itself.

The efficiency of a pipeline system for oil, and oil products transportation, is determined by a number of factors, including the viscosity of the pumped fluid, which has a significant effect on the productivity of the pipeline system, and energy consumption for pumping [1–5]. Periodic heating of the medium pump can lower the viscosity value, thus reducing the energy consumption for pumping, and increasing the average oil velocity. Heating is performed in various ways. Electric heating is currently the most reliable and environmentally friendly way of heating high-viscosity and high pour point oils.

These works [6, 7] provide methods of calculation and technical characteristics of electric heating systems, as well as recommendations for their practical application. However, the above methods and characteristics refer to a limited class of heating devices that use special heating cables, tapes and inductive-resistive systems as heat sources.

These works [8–12] present the results of a study regarding devices for the indirect induction

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heating of viscous fluids. It has been revealed that low thermal conductivity, high oil viscosity and restrictions on the maximum heating temperature necessitate the use of multi-section induction heaters that measure 12–14 m long, with a required outlet temperature of 50–60 degrees.

The issue with increasing the efficiency of induction heating devices is urgent. This can be accomplished by intensifying the process of heat exchange between heat sources and the heated fluid. The heat transfer process can be intensified and the efficiency of the heating system can be increased either by creating flow turbulence at the expense of high velocities, or by mixing the fluid in the heated flow [13–16]. At practically implementable oil flow rates in pipeline systems, a laminar flow takes place [17]. The average flow velocity is 2.8 – 3.3 m/s, and due to high viscosity, the velocity over the flow cross section is distributed very unevenly. The high velocity in the middle of the flow decreases quickly toward the pipe walls. The wall boundary flow layers adhere to the walls, and a significant value of viscosity contributes to high shear stresses between the layers, and their deceleration. Under such conditions, it is not possible to induce turbulence. The development and application of a modular heating system, consisting of several modules connected in a series, is the most expedient option for this type of situation.

The module consists of a solenoidal induction heater located on the pipeline. It is installed after the heater of a three-phase inductor-motor and mixer, which mixes and heats the fluid after its exit from the heating section (Fig. 1).

As a result of mixing, the temperature of the fluid over the cross section of the flow is averaged. At the inlet of the next module, the temperature of the wall boundary layer of the fluid turns out to be significantly lower than the temperature of the pipe wall. Thus, a more intense heat output for the fluid is provided. In this case, all the energy supplied to the mixer inductor is also ultimately converted into heat, providing additional heating of the fluid.

Let us consider this process using the example of oil with a substantially nonlinear temperature dependence of viscosity [3,4].

In the cross section of the pipe, the flow rate ν (*r*) is uneven and its value, in addition to viscosity, is determined by the laminar flow regime, as follows [3, 5].

$$\nu(r) = \frac{1}{\mu} R_0^2 [1 - (r / R_0)^2] \frac{\Delta P}{l}$$

Here ν (*r*) is the distribution of velocity along the radial coordinate, m/s; *l* is the length of the section under study; μ is the dynamic viscosity, Pa*s; R_0 is the inner radius of the pipe; r is the current radius along the section of the fluid flow, m; $\frac{\Delta P}{l}$ and is linear pressure loss in the oil pipe, Pa/m. The average velocity is $\nu_{av} = 0.5\nu_{max}$. The maximum velocity ν_{max} is formed on the pipe axis. Figure 2 shows the velocity diagrams of laminar

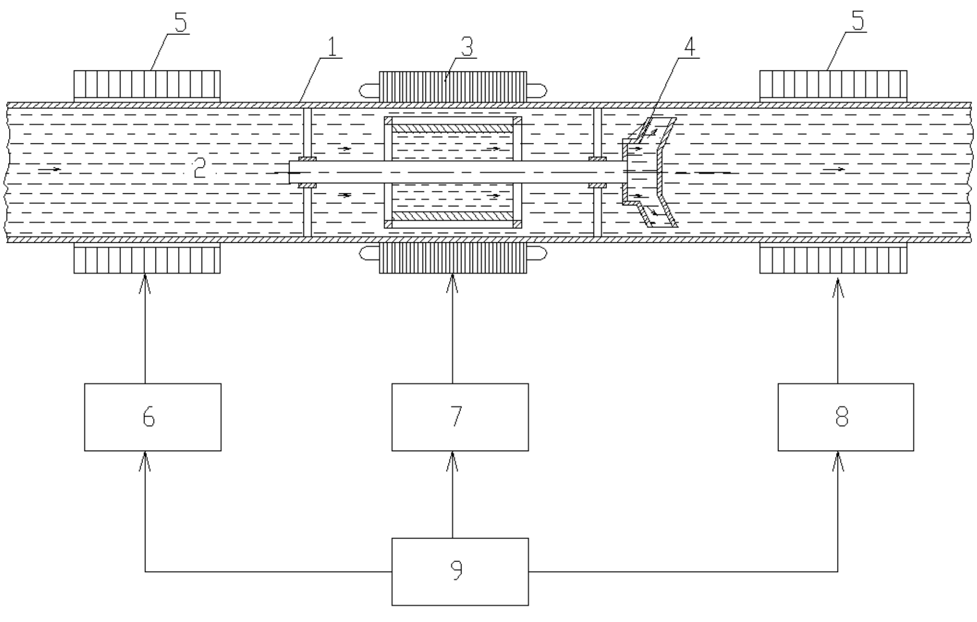

Fig. 1. Diagram of an induction module with series connection of sections
1 – pipe; 2 – heated fluid; 3 – three-phase inductor; 4 – mixer; 5 – inductor of the heating section;
6, 7, 8 – power supplies; 9 – control system

flowing oil versus temperature. The flow is heated uniformly, and has equal viscosity as a result.

Heating of the pumped oil from the pipe wall is complicated by the thermophysical properties of the flow. The wall boundary layers move at low rates.

In contrast to turbulent motion, there is no convective heat exchange in the radial direction for laminar flow. Heat is removed from the pipe walls to its axis by conduction. The coefficient of the conduction of oil (thermal conductivity, λ), fuel oil, and other viscous oil products is low [18–20].

The heat transfer from the pipe wall in the radial direction of the oil flow is insignificant due to the low thermal conductivity coefficient. As a result, the wall boundary layer of the fluid overheats. The oil vapors and its low-boiling constituents are formed in it. Uniformity and continuity of the flow is interrupted. For this reason, the pipe wall temperature is limited. It should not be higher than 100 °C. This limitation significantly affects the intensity of heat transfer, which leads to a need for increasing the heat exchange area due to the length of the heating system.

The transient process of heating a stationary, flat layer of oil in a pipe, through its walls, is described by a heat conduction equation of the following form [21, 22].

$$\frac{\partial T(X, Fo)}{\partial Fo} = a\frac{\partial^2 T(X, Fo)}{\partial X^2}$$

Here $X = \frac{x}{2R}$ is the dimensionless radial coordinate; $T(X, Fo) = \frac{t_{cm} - t}{t_{cm} - t_0}$ is the dimensionless oil temperature; t, t_{cm}, t_0 and are the oil temperatures along the coordinate X, the layer in contact with the pipe wall and the initial temperature, respectively. $Fo = \frac{a\tau}{2R}$ is the Fourier criterion and α, τ are the coefficients of thermal conductivity of oil and heating time of the layer, respectively.

Boundary conditions are $F_0 = 0$; T = 1; X = 0; X = 1; T = 0;

The problem was solved by the method of separating the Fourier variables [23].

The analytical solution obtained represents an infinite sum of an alternating decreasing series, as follows.

$$T(X, Fo) = 2\sum_{k=1}^{\infty}\left[\frac{1-\cos k\pi}{k\pi}\sin(k\pi X)\cdot\exp[-(k\pi)^2 Fo]\right]$$

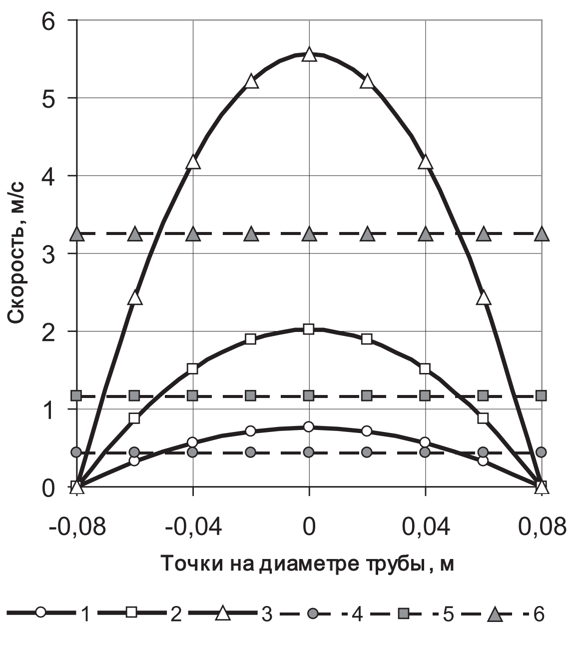

Fig. 2. Radial and average flow rates velocity diagrams: 1 – t = 20°C; 2 – t = 30°C; 3 – t = 40°C; average velocities: 4 – t = 20°C; 5 – t = 30°C; 6 – t = 40°C.

Точки на диаметре трубы, м	Points on the pipe diameter, m
Скорость, м/с	Velocity, m/s

The graphs in Fig. 3 present the solution result.

At the end of the first second of heating oil with an initial temperature (t of 20 °C) at a constant temperature (tst of 100 °C) of the pipe wall, the adjacent fixed layer is heated to a depth of 0.005 m with the pipe diameter of 0.16 m. The central part

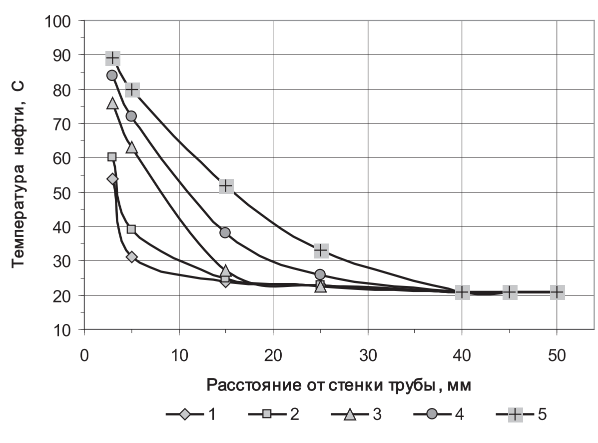

Fig. 3. Temperature distribution in the wall boundary oil layer heated evenly up to 20 degrees.
1 – 1 sec; 2 – 1 min; 3 – 0.125 h; 4 – 0.25 h; 5 – 0.5 h.

Расстояние от стенки трубы, мм	Distance from the pipe wall, mm
Температура нефти, С	Oil temperature, C

of the flow, the core, will remain cold with a high viscosity value.

The temperature distributions obtained are used to plot the velocity field in the pipeline located directly behind the heater (Fig. 4). Here graphs 1 and 2 represent the velocity field and the average velocity when oil is heated from the pipe walls, respectively. Graphs 3 and 4 are the velocity field and the average velocity of oil heated uniformly, up to 20 °C, respectively.

Graph 1 shows that oil heated from the pipe walls has the same velocity in the central part of the flow as cold oil.

The fields of velocities of flows 1 and 3 coincide over almost the entire section of the pipe. Velocity

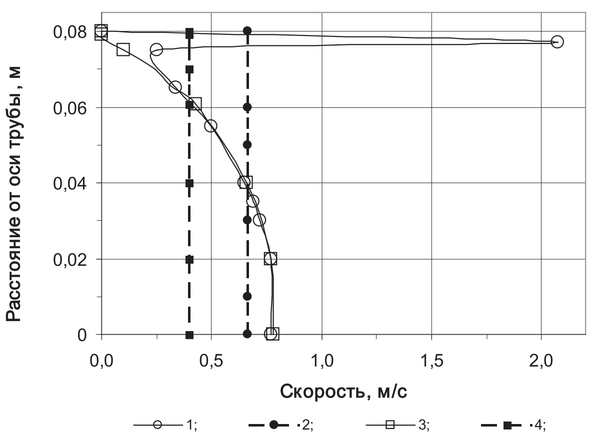

Fig. 4. Oil velocity distribution in the pipe behind the heater:
1 – heating from the pipe wall; 3 – t = 20°C; average velocities, 2 – heating from the pipe wall; 4 – t = 20°C;

Расстояние от оси трубы, м	Distance from the pipe axis, m
Скорость, м/с	Velocity, m/s

increases significantly only at the pipe wall, due to oil heating from the pipe walls (Graph 1). The maximum velocity at the pipe wall is 2.1 m/s. This significant difference is due to a great decrease in viscosity near the pipe wall. The analysis of the graphs, and the calculations performed, revealed more information about oil heating. Due to the heat generated in the pipe wall from the vortex currents, induced by the electromagnetic field, the oil heating provides an average flow rate (2), which exceeds the average flow rate (4) of oil heated uniformly to a temperature of 20 °C. At the same time, the amount of heat spent on heating oil from the pipe walls is much less than it is for heating the flow over the entire section. This circumstance confirms the advisability of using heating for the oil boundary layer. So, with equal oil consumption, surface heating (with the use of induction heaters) consumes 3.5 times less energy for heating compared to uniformly heating oil over the entire cross section.

Figure 5 presents a schematic model of an induction mixer.

On pipe 1, there is a three-phase inductor (2), constructed according to the principle of an asynchronous electric motor with a hollow rotor. A paddle mixer (6) installed on the rotor shaft divides the flow into three parts. The cold core of the flow (5) enters the mixer window, and along the paddles located at an angle to the pipe axis, it enters the heated wall boundary layer (3). Flows 7 are mixed, and the temperature of the wall

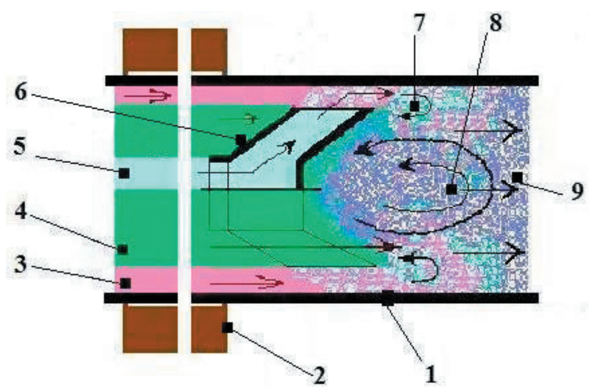

Fig. 5. Diagram of fluid flows in the pipe behind the mixer.
1 – pipe, 2 – three-phase inductor, 3 – wall boundary part of the flow, 4 – the central part of the flow, 5 – the core of the cold stream, 6 – mixer, 7 – mixing of the core and wall boundary flow, 8 – secondary mixing, 9 – oil flow after mixing.

boundary layer decreases. The central part of the flow (4) moves around the inclined rotor blades from the outside. Behind the blades, in the astern zone behind the rotor, the central part (8) of the flow is combined with the newly formed mixture in the wall boundary region.

Oil with an average temperature, due to mixing of three flows, moves to the next heater. The resulting temperature (in the fluid flow behind the rotor) depends on the ratio of flow rates and temperatures, along the three separate flows in front of the rotor. The size of the wall boundary layer (ring 3) is determined by the depth of the conductive heating of oil, and it amounts to 0.01 m for the structure under consideration.

The size of the layer in the flow core (5) depends on the radius of the rotor inlet window. Studies have shown that the optimal radius of the rotor inlet window should be at least 0.25 of the pipe radius, i.e. 0.02 m.

The calculation of the average temperature, of oil flow in the pipeline after the mixer, is based on creating the heat flow balance.

The mass flow rates, for each of the sections of the flow, are determined by the velocity and cross-sectional area. In proportion to the three flow sections, the oil mass flow rate $G_{тр}$ in the pipeline was divided into three values:

$$G_{тр} = G_{ст} + G_{я} + G_{к},\ kg/s.$$

Heat balance of oil flow in a pipe is as follows.

$$G_{тр} \cdot c_p \cdot t_i = G_{ст} \cdot c_p \cdot t_{ст} + G_{я} \cdot c_p \cdot t_{я} + G_{к} \cdot c_p \cdot t_{к},\ kJ/s.$$

The average temperature ti of the oil mass, after the mixer is determined, is based on the balance.

Using the above dependences, with a known restriction on the pipe wall temperature, the temperature distribution in the oil flow for a heater (consisting of several modules) was calculated. The constant temperature of 100 °C for the pipe wall is maintained. The average oil temperature, required by the technology at the outlet from the heater, should be 50 ÷ 60 °C. Figure 6 shows the results of calculation, using the above method of temperature distributions during oil heating in a multi-section induction heater. Here are the graphs of the temperature of the boundary layer (1), the average temperature of the wall boundary layer (2), and the average temperature (3), when the oil is heated to the maximum permissible temperature of 95 °C, respectively. The abscissa of the graph at points 0 – 1 shows cold oil in the pipeline in front of the heater, where point 1 is the heater inlet. Points 2, 3.5, 5, 6.5, 8, 9.5, 11, and 12.5 correspond to the outputs from the heater inductors. Points 2.5, 4, 5.5, 7, 8.5, 10, 11.5 and 13 correspond to the mixer outputs. The temperature of the oil flow, the individual layers which are mixed, is indicated by the bold line with the squares of the points calculated. Sinus-shaped lines with circles of the calculated temperature values (at the points of abscissa 2, 3.5, 5, 6.5, 8, 9.5, 11, and 12.5) describe the behavior of the oil temperature at the point corresponding to the radius of the surface layer, after passing the inductors and before entering the mixers. Dotted line (2), with triangles of points, shows the average temperature of the wall boundary oil layer behind the inductors.

The increasing part of graph 1 characterizes the heating intensity of the boundary layer of oil when passing through the induction heater. The minimum point on the descending part of graph 1 represents the average temperature, after mixing the boundary layer and the flow core. Graph 3 characterizes the average oil temperature as the flow passes through the multi-section heater. As follows, from the results obtained, the use of induction mixers enables a reduction in the number of sections and the length of the heating system by 15–20%.

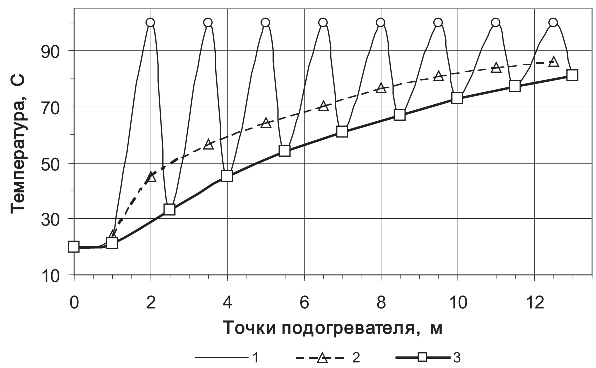

Fig. 6. Temperature distribution
in the oil flow along the heater length
1 – on the boundary with the pipe wall;
2 – average temperature of the wall boundary layer;
3 – average flow temperature.

Температура, С	Temperature, C
Точки подогревателя, м	Heater points, m

Conclusions

The proposed technique was used to study thermohydraulic processes in a heating module consisting of an induction heater and an induction mixer. The obtained calculations of the temperature and velocity fields (in the flow of a viscous fluid) showed, that due to the high viscosity and low thermal conductivity of oil (with a strict limitation of the coolant temperature), the heating depth of the oil flow is insignificant. To increase the efficiency of heat transfer in subsequent sections of the heater, the temperature of the wall boundary layer (of the oil flow) needs to be maintained at a minimum level at the inlet to each subsequent heating section. This can be done by moving the inner, cold layer in the fluid flow to the outer, wall boundary layer, which leads to a decrease in the temperature of the fluid, at the entry to the next heating section. As a consequence, it also leads to an increase in the temperature head. For this purpose, a specially designed mixer is installed at the outlet of the heating section, which moves the cold central part of the flow to the heater wall. It was revealed that the use of a three-phase induction device, based on an asynchronous electric motor, is the most effective because it combines the functions of the rotor rotation drive of the mixer and the heater. The presented results of calculating temperature distributions during oil heating in a multi-section induction heater (containing several induction modules confirm the expediency of using the modular system proposed in this work.

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