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New ways to improve the efficiency of railway transportation of viscous petroleum products

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ABSTRACT The paper proposes a new approach to solving the problem of increasing the economic efficiency of railway transportation of viscous petroleum fuels (fuel oils) at low air temperatures. The physical properties of fuel oils allow them to be obtained when poured into the tank of a tank wagon in a stratified state, when their density in the upper part of the tank is significantly less than in its lower part. This blocks the natural convection of hot fuel oil on the cold walls of the tank, and it cools only due to the molecular thermal conductivity which is very small. Upon cooling down, a relatively thin highly viscous layer forms on the inner walls of the tank of a tank wagon, which acts as a heat-insulating shell, and the bulk of it (more than 90 %) retains high temperature and fluidity throughout the period of transportation. The thermal and hydrodynamic calculations were performed using modern computer technologies (the ANSYS 5.6 software package). The results obtained show that the need to heat up the fuel oil during unloading remains, but already requires significantly less time and heat energy. The proposed energy-saving technologies for the delivery of viscous petroleum products are especially relevant in Russia with its cold continental climate, long-haul transportation, and the current structure of the country's wagon fleet. The value of the results obtained lies in the fact that the proposal can be implemented on tank wagons in circulation with minimal change to their design. The technology of operation of the drain equipment at unloading points will not change either.

KEYWORDS: railway transportation; viscous petroleum products; thermogravitational convection; stratified state; thermal insulation of the tank of a tank wagon

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Научная статья

Новые способы повышения эффективности железнодорожных перевозок вязких нефтепродуктов

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АННОТАЦИЯ Предложен новый подход к решению задачи повышения экономической эффективности железнодорожных перевозок вязких нефтяных топлив (мазутов) при низких температурах воздуха. Физические свойства мазутов позволяют получать их при наливе в котел вагона-цистерны в стратифицированном состоянии, когда их плотность в верхней части котла существенно меньше, чем в нижней. Этим блокируется естественная конвекция горячего мазута на холодных стенках котла, и он охлаждается только за счет молекулярной теплопроводности, которая очень мала. При охлаждении на внутренних стенках котла вагона-цистерны образуется сравнительно тонкий высоковязкий слой, играющий роль теплоизолирующей оболочки, основная его масса (более 90 %) сохраняет высокую температуру и текучесть за все время транспортирования.

Выполнены тепловые и гидродинамические расчеты с применением современных компьютерных технологий (пакет программ ANSYS 5.6). Полученные результаты показывают, что необходимость разогрева мазута при выгрузке остается, но требует в разы меньших затрат времени и тепловой энергии. Предложенные энергосберегающие технологии доставки вязких нефтепродуктов особенно актуальны в условиях России с ее холодным континентальным климатом, большой дальностью перевозок и сложившейся структурой вагонного парка страны.

Ценность полученных результатов заключается в том, что предложение может быть реализовано на вагонах-цистернах, находящихся в обороте при минимальных изменениях их конструкции. Технология эксплуатации сливного оборудования в пунктах выгрузки также не изменяется.

КЛЮЧЕВЫЕ СЛОВА: железнодорожные перевозки; вязкие нефтепродукты; термогравитационная конвекция; стратифицированное состояние; тепловая изоляция котла вагона-цистерны

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INTRODUCTION

The paper presents a new approach to solving the problem of increasing the economic efficiency of transport operations associated with long-distance transportation of Viscous Petroleum Products (VPP) at low air temperatures. These liquid cargoes are the most important component of freight transportation by rail transport in Russia. Their share in the total freight turnover of the country's railways, including export traffic, is approaching 18 million tonnes per year. At the same time, the main traffic flows are formed in the regions of Western Siberia, Urals, and the Far East. It is there that Russia's oil fields are in a state of initial development and at the peak of their development. The main means of delivering VPP to the centre of the country is by railway (~65 %) and river transport (~25 %). The maximum volume of transportation is accounted for by furnace fuel oils under the M100, M40 and F12 brands.

During transportation, fuel oil cools down and turns into a highly viscous state, which makes it very difficult to unload. The standard solutions used to the problem, such as insulated tank wagons and heating up of oil cargo to restore its fluidity before unloading, require a very high consumption of various types of resources. For railway transportation, these include the use of specialized wagons with a large (up to 50 %) empty return mileage, low turnover due to the duration of the heat-up period, high cost of manufacturing and operation of tank wagons, consumption of thermal energy for draining and cleaning of tank wagons from high-viscosity VPP residues.

The paper proposes, for the first time, to make a rational use of the physical properties of the transported petroleum products themselves, such as high values of the volumetric thermal expansion coefficient, a low molecular thermal conductivity, and a sharp increase in viscosity during cooling. Giving reasonable consideration to these properties makes it possible to obtain and keep the main mass (more than 90 %) of VPP in a liquid state for a long time both in the ground storage tank and in the tank of a tank wagon. At the same time, only 5 % to 10 % of the total mass of the petroleum product located in close proximity to the inner walls of the tank passes into a highly viscous state.

A relatively thin, highly viscous layer with a low thermal conductivity is formed on them, which acts as thermal insulation of the contents of the tank from the external environment.

This provides a possibility of a sharp reduction in time and thermal energy input for unloading, which is only reduced to the dilution of this layer.

For railway transportation, the proposal can be implemented on tank wagons in circulation with minimal change in their design and maintaining the operating conditions of the drain equipment. What is to be changed is the technology of filling petroleum fuels used at a refinery.

The paper describes mathematical models of physical processes in M100 liquid furnace fuel oil in the tank of a tank wagon and the results of calculations of temperature distribution.

Options for the use of tank wagons with a steam heating casing and tanks for light general-purpose petroleum products are being considered [1–15].

PROBLEM STATEMENT AND METHODS OF ITS SOLUTION

There are a large number of development efforts aimed at accelerating the discharge of VPP and reducing the consumption of resources for the arrangement of discharge [1–3]. The flow of new papers and patent applications for inventions that has been going on for more than 50 years shows that the optimal solution to the problem has not yet been obtained.

The problem of VPP delivery is particularly typical of Russia with its cold continental climate, long duration of the cold season, a low degree of branching of the railway network in the northern and eastern regions of the country, and the established structure of its wagon fleet. Currently, fuel oil is poured into the tank of a tank wagon at a temperature close to +70 °C. These temperatures ensure a decrease in viscosity and a reduction in the VPP filling time, but heating VPP to higher temperatures is prohibited in order to preserve the performance characteristics of rubber sealing elements on the drain equipment of the tank of a tank wagon. The loss of these characteristics can cause a spill of large amounts of VPP, which will lead to large-scale environmental disasters.

Full-scale experiments to study the cooling of furnace fuel oil with an initial filling temperature T_n of +70 °C were carried out for three years and took place as early as the 1950s. They were focused on the average winter air temperature in the European part of the Soviet Union, T_g = –15 °C. From the beginning, the average value of the convective heat transfer coefficient α of 30 W/m^2 °C was also set for the heat-emitting surface of the tank of a tank wagon. The results of the experiments are shown in *Fig. 1* [5].

Fuel oils obtained from various oil fields of the Russian Federation differ by the content of paraffin fractions and have a solidification temperature range from +25 °C to +35 °C, at which they are not discharged by gravity. This temperature range is marked by a large dotted line in Figure 1, which also shows the average travel time of oil trains in the European part of Russia (~140 hours) [6] and the average time of transition of VPP to a highly viscous state (~23 hours in tank wagons without thermal insulation of the tank).

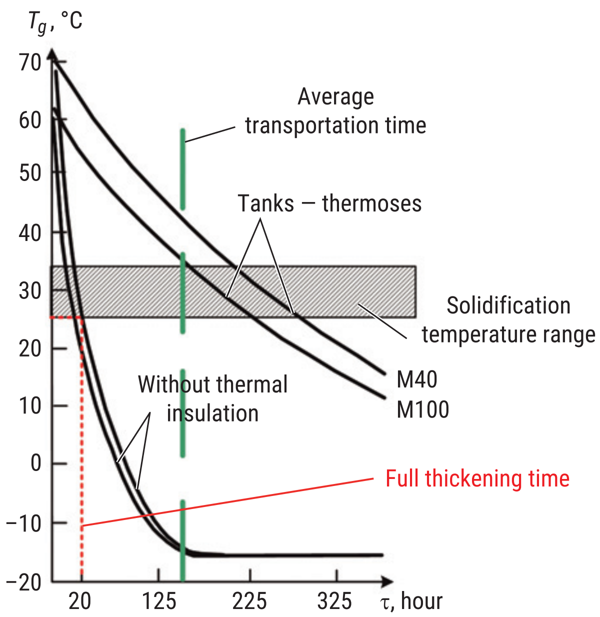


Fig. 1. Cooling of M40 and M100 fuel oils in tank wagons with and without thermal insulation of the tank [5]

Full-scale experiments have shown that after 15–20 hours of transportation at an air temperature T_g of –15 °C, the average volume temperature of VPP in a tank without thermal insulation decreased to +10 °C. At these temperatures, the viscosity of M40 and M100 fuel oils is so high that their discharge by gravity becomes impossible. In insulated tanks, it takes about 180 to 200 hours before fuel oil cools down to these temperatures.

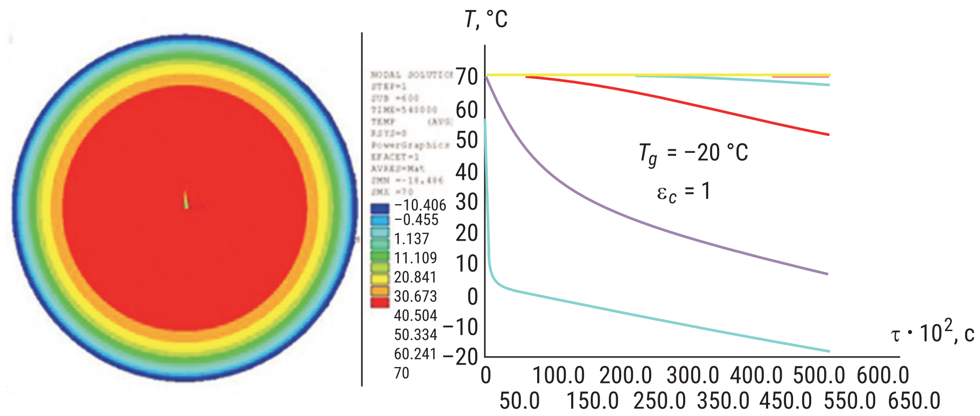
Hence, it was concluded that the heat-insulating shell of the tank does not provide the expected effect of maintaining a high temperature and fluidity of VPP necessary for draining, and it was decided that it would be more expedient to deliver petroleum fuels in a highly viscous state and warm them up before the discharge. At the same time, heating of VPP remains a laborious and lengthy operation, which causes a low turnover of tank wagons, requires expensive equipment, areas, buildings and facilities, not to mention high consumption of thermal energy. According to Russian Railways, over 660 thousand tonnes of oil equivalent are spent annually for draining and heating of oil cargoes, and the total idle time of tank wagons under draining exceeds 1 million wagon-hours, which is equivalent to about RUB 3.5 billion in monetary terms (in 2022 prices).

INNOVATION PROPOSAL

Below we propose a new and unconventional approach to solving the problem of accelerated unloading of VPP with a low energy input, even at enterprises with limited resources. It is based on the possibility of long-term maintenance of fuel oil in a ground tank or the tank of a tank wagon in a stratified state. A stratified state is a nonequilibrium, but hydrodynamically stable state of a liquid, in which its density in the lower part of the container is significantly higher than in its upper part.

Thermogravitational convection (TGC) of hot and still low-viscosity fuel oil is initially suppressed after it is poured into the tank of a tank wagon.

After the suppression of TGC, fuel oil transported in winter time does not freeze throughout the volume of the tank of a tank wagon, but it solidifies to a highly viscous state on the inner surface of its shell. The tank acquires a shell formed from the fuel oil itself with rather good thermal insulation properties. The volume of the shell is about 6 to 8 % of the internal volume of the tank. The bulk of the fuel oil (about 92 to 94 %) retains a high temperature and fluidity for a long period of time, which is sufficient for draining by gravity. The standard operation of heating the delivered fuel oil during unloading will remain necessary, but will require significantly less time and energy.



a *b*

Fig. 2. Results of calculations of temperature fields in the mass of M100 fuel oil along the section of the tank of a tank wagon in the absence of TGC: *a* — overall picture of the temperature distribution after 5.7 days of transportation at an air temperature T_g = −20 °C; *b* — curves of temperature change at different distances from the axis of the tank (model of a quasi-solid body, convection coefficient ε_c = 1)

An important point here is that fuel oil is discharged at a high temperature and fluidity. For the first time, it becomes possible to transport it through pipelines made according to temporary technological schemes, for example, when bypassing barrier sites on a destroyed railway network or when delivering fuels to watercraft without berthing.

The proposed method requires some change in the technology of filling VPP into the tank of a tank wagon carried out at a refinery, rather than in the unloading technology.

First of all, we should note the physical characteristics of petroleum fuels: bunker fuel oils (F-5), furnace fuel oils (M100), and high-viscosity cracking residues (M200). It can be seen from *Table 1* that all of them have a large coefficient of volumetric thermal expansion β_{VPP} of about 10^{-3} 1/deg (almost five times greater than that of water). They also have a low thermal conductivity λ_{VPP} ranging from 0.105 to 0.12 W/m°C, only slightly higher than that of asbestos fibre ($\lambda_{asbest} \approx$ 0.09 W/m°C), which is a typical thermal insulation material. The combination of these properties makes it possible to significantly reduce the time and consumption of heat for managing the discharge of VPP.

It should be noted that the problem of cooling a cylinder streamlined by an air flow from the outside is one of the canonical problems of mathematical physics which was solved back in the nineteenth century. The necessary analytical expressions, tables and graphs are available in the literature [8, 9]. Based on this, let us imagine fuel oil in a tank wagon with a tank diameter *D* of 3 m as a quasi-solid body with a thermal conductivity λ_{VPP} of 0.105 W/m°C and an initial temperature of +70 °C. Let us assess its cooling time to the discharge temperature of +40 °C.

To solve this problem, computer calculations were performed showing the radial temperature distribution; the calculation results obtained using the ANSYS 5.6 software package are shown in *Fig. 2*.

These give a picture of the temperature distribution over the section of the tank of a tank wagon that is streamlined by an air flow with a temperature T_g of –20 °C and a velocity u_g of about 20 m/s. As you can see, after 140 hours (~6 days) of transportation, the bulk of M100 fuel oil (highlighted in red, orange, yellow and green colours) will retains a high temperature and fluidity sufficient for unloading, and only a thin layer at the very walls of the tank will solidify

Table 1

Physical characteristics of petroleum fuels (fuel oils) [4]

Petroleum fuel	Density, ρ_0, kg/m³	Specific heat capacity, *C*, J/kg°C	Kinematic viscosity in the temperature range +40...60 °C, $\nu \cdot 10^6$, m²/s	Coefficient of thermal conductivity, λ, W/m²°C	Coefficient of thermal expansion, β, °C⁻¹	Temperature of unloading (by gravity), *T*, °C
F-5, F-12 bunker fuel oils	900–950	1880	96–43	0,120	$9{,}31 \cdot 10^{-4}$	+30...+40
M100 furnace fuel oil	970–984	1860	825–400	0,105	$9{,}57 \cdot 10^{-4}$	+50...+60
M200 fuel oil	998–1010	1848	3674–668	0,102	$9{,}57 \cdot 10^{-4}$	higher +60

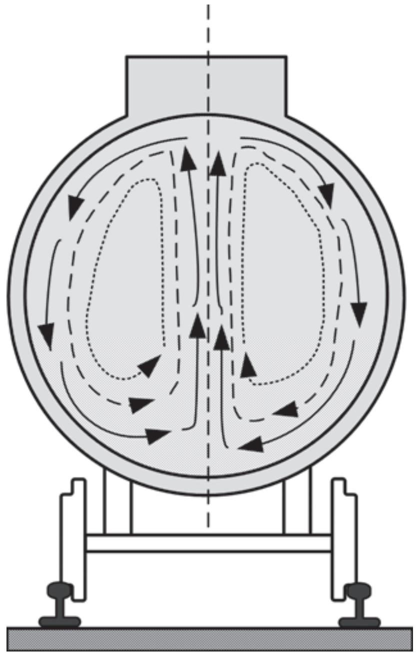


Fig. 3. Schematic representation of liquid currents inside a tank wagon during thermogravitational convection and symmetrical cooling of the walls

(highlighted in turquoise, light blue and dark blue colours).

The graphs show the curves that characterize the change in fuel oil temperature over time at various distances from the axis of the tank of a tank wagon.

This result is in sharp contradiction with the data of field experiments shown in *Fig. 1*. Consequently, the model of the medium as a quasi-solid body turned out to be erroneous. In reality, there are internal movements of low-viscosity VPP, which can be considered as mixed natural and forced convection.

Being an integral part of it, thermogravitational convection (TGC) occurs when the wall layers of the liquid are cooled by the cold walls of the tank, accompanied by an increase in the density of VPP.

The cooled wall layers of the liquid move downward, displacing the liquid upward in the central areas of the tank. A diagram of the currents of the circulating fluid movement in a horizontal cylinder at TGC is shown in *Fig. 3*; the arrows indicate the directions of the currents, and the density of the lines shows the areas with the highest speed of movement [22].

Being the second component of the process, forced convection is a secondary factor. This is observed only when the tank wagon is moving and only in the upper layers of petroleum products, and since the tank of a tank wagon is usually filled to 90 to 95 %, the air layer above the free surface of the liquid, where waves develop, turns out to be too thin to cause intense mixing of the liquid [28].

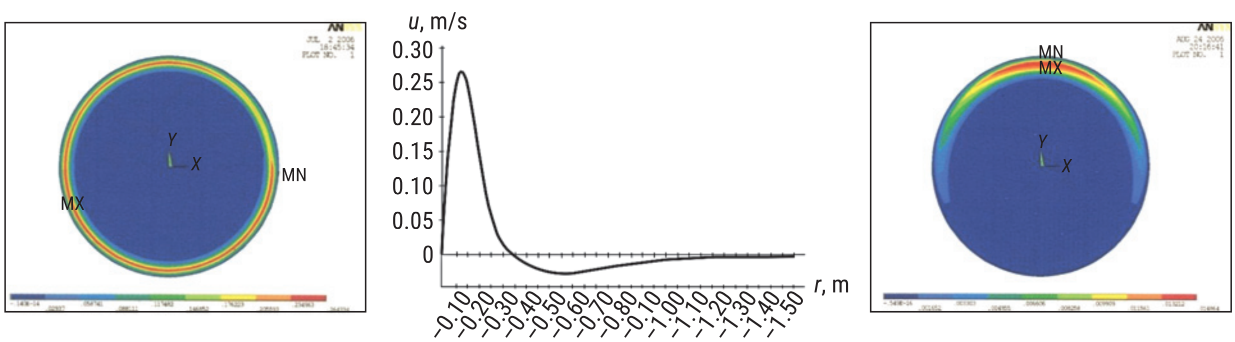
EVALUATION OF THE RESULTS OF HYDRODYNAMIC CALCULATIONS

All works on TGC note that the most intense currents occur in a thin, near-wall layer of liquid [10], as shown in *Fig. 3*. Therefore, TGC is described using the laminar boundary layer model [10]. This model was also used in the calculations for M100 fuel oil. The equations of hydrodynamics and convective heat transfer [26] were solved by the finite element method using the ANSYS 5.6 software package.

When performing the calculations, the following conditions were set:

- when poured, M100 fuel oil had an initial temperature Tn of +70 °C;
- the outside air had a temperature T_g of –20 °C;
- the external heat transfer coefficient α was 15 W/m²°C;
- filling of the tank lasted 45 minutes, taking into account the transition to a steady state of internal currents in VPP.

The images shown in *Fig. 4*, *a*, *b* show the thickness of the laminar flow descending along the tank wall δ_{max}



a *b* *c*

Fig. 4. Distribution of velocities of the circulating movement of M100 fuel oil during thermogravitational convection inside the tank of a tank wagon: *a*, *b* — during the first 45 minutes after filling the tank wagon; *c* — 360 minutes after pouring VPP into the tank

of about 0.30 m, with the highest flow velocity u_{max} of about 0.27 m/s observed at a distance δ of about 0.13 m from the tank wall. At a distance *r* of more than 0.3 m, countercurrents rising upwards are formed, closing the circulation vortices schematically shown in *Fig. 4*, *b*. In the centre of the tank, at distances *r* exceeding 1 m from its wall, a fixed core is formed, where the liquid remains motionless.

It follows that at the flow rates u_{max} of about 0.27 m/s, TGC is the main reason for the rapid cooling down of fuel oil in the entire volume of the tank of a tank wagon, which confirms the results of field experiments shown in *Fig. 1*. A sharp decrease in the rate of cooling of the oil cargo 20 to 23 hours after it is poured into the tank is also understandable. It can be seen from *Fig. 4*, *a* and *b* that in the first 45 minutes TGC is observed throughout the entire section of the tank, and then, as can be seen from *Fig. 4*, *b*, after 360 minutes the process noticeably shifts upwards. It can be expected that after 20 hours of cooling, the increase in the viscosity of VPP will completely extinguish TGC, and this will fully confirm the course of the experimental curve shown in *Fig. 1*.

It can be concluded that when TGC is suppressed, a liquid petroleum product will cool down as a quasi-solid body by molecular thermal conductivity at λ_{VPP} of about 0.12 W/m°C, and the temperature distribution in it will correspond to the picture shown in *Fig. 2* [16–27].

OBTAINING THE STRATIFIED STATE OF LIQUID PETROLEUM FUELS

Let us look at several ways to delaminate hot liquid petroleum products and obtain a temporary thermal insulation shell of a tank, specifically for the tank of a tank wagon, from a highly viscous oil product itself [17]. (Compare with a layer of ice on the surface of a reservoir that thermally insulates liquid water located under it).

The first method is implemented in a specialized tank wagon, model 15-1566, for viscous liquid cargoes with a steam heating casing rigidly mounted on the bottom of the tank [7, 19, 20, 24]. The model was developed back in the 1960s, has been modernized many times, and is now widely used (*Fig. 5*). The parameters of the tank of the tank wagon are given in *Table 2*.

Fig. 5. Tank wagon with a steam heating casing, model 15-1566: 1 — tank of the tank wagon; 2 — steam heating casing of the tank

The model has a chamber of about 2.8 m^3 in volume between the walls of the tank and the casing; the thickness of the chamber is about $4.5 \cdot 10^{-2}$ m.

When unloading VPP, steam is supplied to the chamber to heat up the tank walls and a relatively thin layer of solidified petroleum product which is in thermal contact with them. The layer melts, dramatically reducing its viscosity, and the entire bulk of VPP with a low temperature and high viscosity slides over this layer and is poured into a receiving pit below ground level.

Next, the tank wagon leaves the discharge facility, and heating and sending the drained petroleum product to storage becomes a responsibility of ground services.

The idea is good, but the fuel oil facilities of an enterprise receiving VPP should have expensive and energy-consuming equipment (heated fuel oil pipelines of great length). This means that the problem of heating up VPP during the discharge and distribution to ground storage and associated resource costs remain unresolved.

According to the proposed new technology, before being poured into the tank of a tank wagon, fuel oil must have a temperature exceeding the boiling point of water (100 °C). The above mentioned difficulties related to maintaining the performance of the rubber sealing collar on the drain device shown in *Fig. 6* can be resolved by a simple act [12, 13].

Table 2

Parameters of the tank of a tank wagon, model 15-1566 [11]

Area of the heat-emitting surface, m^2	Tank wall thickness, m	Thickness of the casing walls, m	Specific heat capacity of steel, J/kg °C	Heat capacity of steel λ, W/m°C	Tank weight with the casing, kg	Increase in the weight of the container, kg	Volume of the chamber under the casing, m^3
110	10–2	$3 \cdot 10^{-3}$	527	42.6	9,087	1,630	2.8

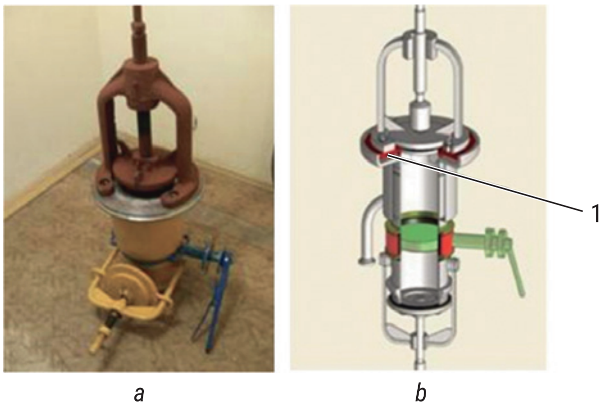


Fig. 6. Tank wagon's drain device: *a* — general view; *b* — axonometric view of the device; 1 — rubber sealing collar [29]

Fig. 7. Application of thermal insulation from rigid polyurethane foam [23]

Before filling the tank of a tank wagon with hot fuel oil, process water with a temperature of about plus 50 °C is supplied to the chamber. (At very low air temperatures (minus 50 °C), it provides preheating of the empty tank to temperatures of the order of plus 5 to 10 °C, which solves the problem of thermal stresses in the tank welds). An extension pipe with a length of 0.10 m to 0.15 m is attached to the tank of the tank wagon, and a flange with a bolted connection to the flange on the drain device is welded to its free end. When pouring hot VPP, the first masses of the product are spread over the cold bottom of the tank and cooled down on it. The extension pipe with an internal volume of about 3 litres is filled with already cooled fuel oil. But as it has a low thermal conductivity (*Table 1*), it will create thermal insulation of the rubber sealing collar from the hot VPP inside the tank of the tank wagon. Filling becomes possible at a temperature of fuel oil T_{VPP} of about +120 °C to +150 °C, i.e. exceeding the boiling point of water. When fuel oil with such a temperature is poured into the tank of the tank wagon, the water under the steam heating casing will heat up and boil, with the water mass m_W being 2,800 kg.

This requires a lot of heat, which leads to a sharp cooling of the fuel oil in the lower part of the tank.

The amount of cooling water is estimated from the heat balance equation. Let us assume that in the lower part of the tank, the mass of fuel oil (m_{VPP}) being cooled down from the initial temperature $T_{VPP.0}$ of +150 °C to T_{VPP} of +100 °C when the boiling of water stops is 30 tonnes. However, the water under the casing is additionally cooled down to the temperature of the water drain T_W of +30 °C. The thermophysical properties of water in liquid and gaseous states are shown in *Table 3*.

Using the values indicated in *Table 1* and *Table 3*, we obtain the heat balance equation as follows

$$\Delta T = \frac{(r_W + C_W 70) \cdot m_W}{C_{VPP} m_{VPP}} =$$

$$= \frac{(2238 + 4,2 \cdot 2,8 \cdot 70) \cdot 2800}{1,86 \cdot 30 \cdot 10^3} \approx 122\,°\text{C}.$$

It follows that the transfer of heat to 2.8 tonnes of water in the chamber under the casing will cause cooling of 30 tonnes of fuel oil in the lower half of the tank of a tank wagon by 122 °C. At the same time, the average temperature of the fuel oil in the upper half of the tank $T_{VPP.1}$ will remain equal to about 150 °C, and the temperature in the lower half $T_{VPP.2}$ will drop to about 28 °C, i.e. the difference of temperatures of VPP in the upper and lower halves of the tank (ΔT) will be about 120 °C.

It is known that density of fuel oils of various grades is temperature dependent as follows [14]

$$\rho(T) = \frac{\rho_{20}}{1 + 0,0023(T - 20)},$$

where ρ_{20} is the density of fuel oil at temperature T = +20 °C, and T is the temperature of fuel oil, °C.

By using this equality, it is easy to establish that the density of fuel oil in the upper half of the tank of a tank wagon turns out to be almost 8 % lower than that in its lower part. This must be the reason for blocking TGC. The results of computer calculations and the dynamics of cooling down of M100 fuel oil in a stratified state are shown in *Fig. 8, b, d*.

For the second option of VPP stratification, a general purpose tank without a steam heating casing can also be used [5, 16]. A polyurethane foam shell with a thickness of 0.03 m to 0.05 m is applied to the upper

Table 3

Physical properties of water

Boiling point T_b, °C	Specific heat of water vaporization r_w, kJ/kg	Specific heat capacity, C_w, kJ/kg °C	Specific heat sink from oil cargo when filling the tank, kJ/kg
+100	2,238	4.2	3,000

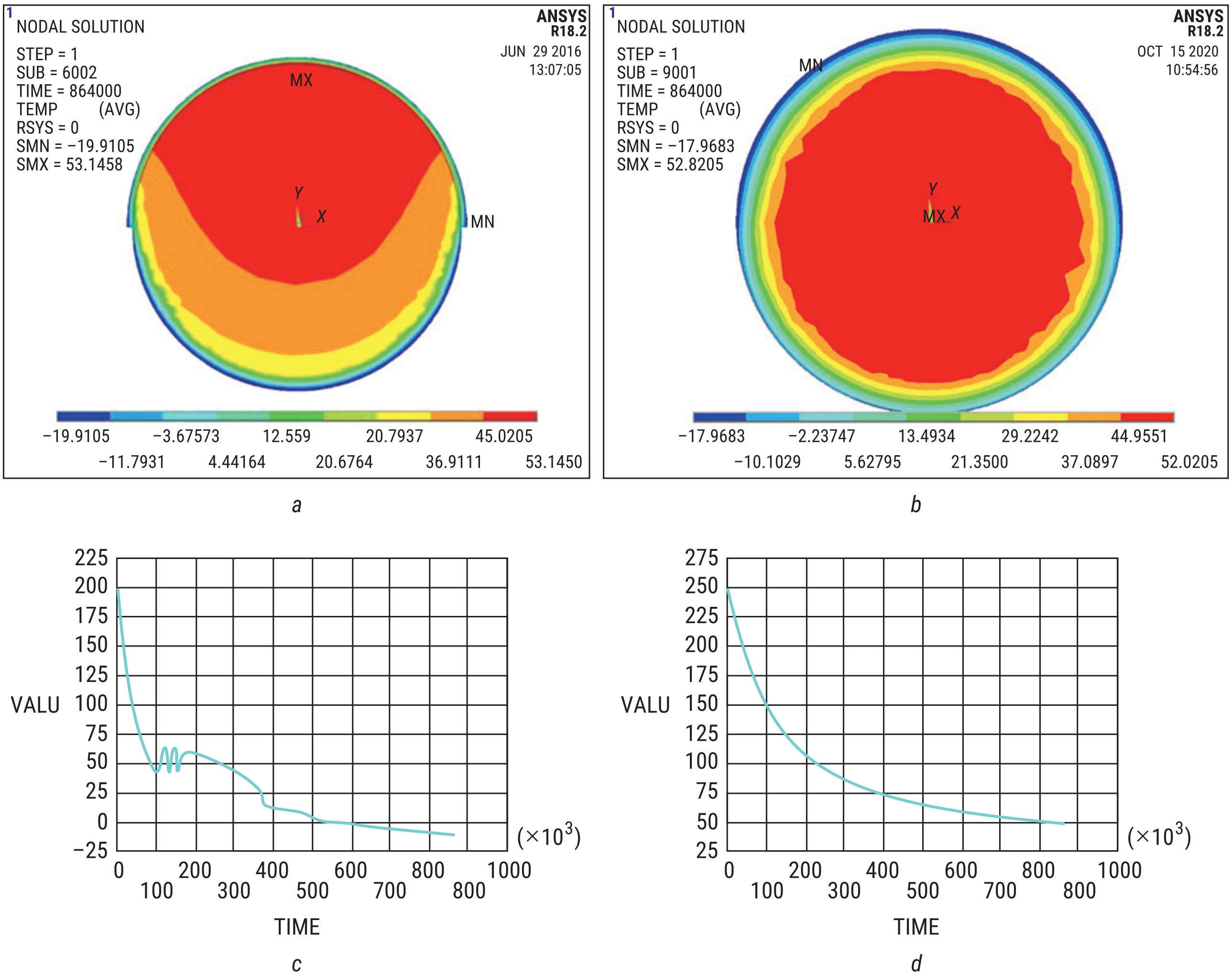


Fig. 8. Temperature distribution in stratified M100 fuel oil (transportation at an initial temperature of VPP T_0 = +150 °C, air temperature T_g = –20 °C, and the external heat transfer coefficient α_{ex} = 15 W/m^2°C: *a* — when transported in a general-purpose tank wagon with the thermal insulation of the upper half; *b* — when transported in a tank wagon with a steam heating casing; *c* — cooling curve for fuel oil in the lower part of the tank in the area of the drain pipe; *d* — cooling curve for fuel oil in the central part of the tank

part of the tank. It is created by mixing two polyurethane components that are supplied under pressure to a dispersing nozzle (*Fig. 8*). When they are mixed, polyurethane foams to form an integral structure without joints and seams, regardless of the complexity of its shape.

Practice has proven that the effectiveness of the rigid polyurethane foam shell continues for up to 10 years. At the same time, the shell is easily removed mechanically (with a scraper) as necessary due to wear or according to individual requirements, for example, when necessary to control the strength characteristics of the tank walls by ultrasonic methods.

The thermal insulation can be applied and removed in a depot environment. The application time of the shell by a single worker is about two hours. The cost of the thermal insulation shell material is about RUB 50 thousand per tank.

The change in the technology of filling petroleum products boils down to the following.

Currently, the filling of VPP is carried out from one container, where the fuel oil is at a temperature of +70 °C. According to the new technology, the tank of a tank wagon is filled in series and from two containers: one third of the tank is filled with fuel oil with a temperature of +50 °C, and the remaining two thirds are filled with fuel oil with a temperature of +100 °C to +110 °C. Higher temperatures are not allowed, since polyurethane foam melts at temperatures from +130 °C to +150 °C. Melting causes deformation and shrinkage of the shell. The specified temperature difference of 30 to 40 °C provides the stratification of hot fuel oil.

The main advantages of the method are the possibility of transporting VPP in non-specialized general-purpose tank wagons. They have a significantly lower empty mileage than specialized rolling stock, a lower tare weight, and lower cost of manufacture and operation.

The results of computer calculations of temperature fields in the bulk of fuel oil transported in a stratified state shown in *Fig. 8* show that the layers of VPP adjacent to the shell of the tank cool down the fastest with the transition to a highly viscous state. These layers cool down when passing into a highly viscous state, but at the same time they form a heat-insulating shell of the tank that emerges spontaneously from the transported petroleum product itself. The thickness of solidified layers of VPP that form the shell depends on the ambient temperature and, under severe winter conditions, does not exceed 10 cm, and their weight does not exceed 15 tonnes, i.e. no more than 20 % of the contents of a 65-tonne tank wagon. The major portion of the transported VPP (highlighted in red, orange and yellow) with a total weight of up to 50–55 tonnes will retain a high temperature and fluidity throughout the transportation time [28].

Unloading of the delivered VPP from the tank of a tank wagon is carried out by the method currently in use. Steam is supplied to the chamber through the inlet fitting on the steam heating casing to heat up and melt the layer of thickened petroleum product forming a heat-insulating shell; the rest of its mass has a temperature sufficient to discharge by gravity.

The discharge of M100 fuel oil from a general-purpose tank wagon can also be carried out by recirculation. It can be seen from *Fig. 8, a* that it remains necessary to dilute not the entire contents of the tank, but a relatively thin solidified layer formed in the lower part of the tank [28, 29].

CONCLUSIONS

We have proposed a new method of transporting viscous petroleum products at low air temperatures by their pre-conversion to a stratified state. The achieved positive effects from the use of the declared technical proposal are summarized below:

- a sharp reduction in the time and input of thermal energy required for heating when unloading VPP from a tank wagon by reducing the oil product cooling rate during transportation and maintaining fluidity of more than 80 to 90 % of its total mass in the tank of a tank wagon;
- when unloading a petroleum product, only a thickened layer which is less than 20 % of its total mass in the tank wagon needs to be thinned;
- reduction in the amount of thermal energy for additional heating of petroleum products in aboveground pipelines that provide their transportation to storage facilities.

The method can be implemented by using rolling stock in circulation.

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