New way to increase the profitability of railway transportation of viscous petroleum products at low air temperatures

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Abstract. The article deals with the main problems associated with the transportation and unloading of viscous petroleum products by rail at low temperatures. Taking into account the analysis of the applied technologies and modeling of the ongoing processes in the ANSYS program, a solution to the problems that arise is proposed by using a tank car with a steam-heating casing or by applying thermal insulation to the upper part of the tank. To ensure the tightness of the drain device of the tank car and to avoid the occurrence of environmental disasters, the modernization of its design is proposed.

1. Introduction
Liquid cargo is the most important component of freight transport by rail. Their share in the total freight turnover of the railways of our country exceeds 35% and is approaching 290 million tons per year. The main traffic flows are formed in the West Siberian and Ural regions, in the Far East. They are characterized by long-distance transportation and a cold continental climate with low winter air temperatures.

Among the bulk cargoes, more than 34% are dark oil products - fuel oil, cracking residues, paraffin oil, technical oils, etc. Their viscosity increases sharply with a decrease in temperature, so in the nomenclature of liquid cargo they are called viscous petroleum products (VPP).

Typical examples of VPP are boiler fuels-fuel oil M40, M100, cracking residues M200, etc. The main physical characteristics of M40 and M100 fuel oils are presented in Table 1.

| Physical characteristics | Brand of boiler fuel oil |
|--------------------------|-------------------------|
|                         | M40                     | M100                    |
| Density ρ, kg/m³         | 980                     | 980                     |
| Specific heat capacity c, J/kg°C | 1.863                  | 1.860                  |
| Temperature range, °C    | +20….+60               | +35….+60               |
| Kinematic viscosity ν·10^6, m²/s | 220…60                 | 825…193                |
| The thermal conductivity λ, W/m°C | 0.105                  | 0.105                  |
| Coefficient of thermal expansion β, (°C)^-1 | 9.31·10^-4         | 9.57·10^-4            |
| Solidification temperature T, °C | below +15            | +16…+30               |
There was a problem that during transportation oil and gas cargoes are cooled, turning into a high-viscosity state, making it impossible to unload them without prolonged and intensive heating, to restore fluidity.

Large-scale experiments to study the cooling of VPP during their railway transportation were carried out in the late 40's. At that time, two-axle 50-ton tank cars were in circulation, and the average time of oil cargo transportation in the European part of the USSR, including the Urals, was 13.5 days. The experiments were focused on the average winter air temperature of minus 15°C.

Based on the results of the experiments currently contained in the literature and shown in Figure 1, it was decided that it was not appropriate to use tank thermoses with a heat-insulating boiler shell on the Railways of the USSR. The effect of maintaining a high temperature and fluidity of VPP during transportation in the autumn-winter period was insufficient, and the costs of manufacturing and operating thermos tanks, on the contrary, were excessive. It was decided that it is more expedient to warm up the frozen oil cargo to restore fluidity before draining.

Figure 1. Results of field experiments to determine cooling rates of fuel oil during transportation in 50-ton tanks.

In the light of these decisions, in the late 50's, a tank car model 15-1566 with a steam-heating casing rigidly fixed on the lower half of the boiler was developed and found wide application [1]. It was the prototype of many engineering solutions for the creation of frame and frameless specialized tank cars for the transportation of VPP, one of the models of the last years of production is shown in Figure 2. The parameters of the boiler of the tank car model 15-1566 are presented in Table 2.

Table 2. Parameters of the boiler of the tank car model 15-1566

| Parameters                                                | Model 15-1566 |
|-----------------------------------------------------------|---------------|
| The area of the heat-transfer surface, m²                 | 110           |
| The wall thickness of the boiler, mm                     | 10            |
| Casing wall thickness, mm                                | 3             |
| Specific heat capacity of steel c, J/kg°C                | 527           |
| The thermal conductivity of steel λ, W/m°C               | 42.6          |
| The weight of the boiler with casing, kg                 | 9,087         |
| Volume of the chamber between the casing and the boiler wall, m³ | 2.8           |
As the number of discharge sites with equipment with a powerful energy supply for recirculating heating of frozen oil cargo increases, the practice of transporting VPP in General-purpose oil-gasoline tanks, in which a steam-heating casing is not structurally provided, increases. In all variants, heating the VPP is a time-consuming and lengthy operation, which causes a low turnover of tank cars, requires expensive equipment and high costs of thermal energy. According to Russian Railways, more than 600 thousand tons of conventional fuels are spent annually on draining with heating of oil cargo, while the idle time of tank cars under draining exceeds 1 million car hours.

2. Physical justifications of the new approach

Below we consider a new, non-traditional approach to solving the problem of increasing the economic efficiency and productivity of labour for the organization of transportation of VPP in winter with cash rolling stock in circulation. It is aimed at reducing the time and energy costs for unloading oil cargo. The proposal boils down to the fact that the hot oil product is still at the stage of filling into the tank is transferred to a stable stratified state, in which its density in the lower part of the boiler of the tank car is initially created and maintained all the time greater than in its upper part.

We will first focus on the physics of the process. Table 1 shows that VPP have a low thermal conductivity $\lambda_{\text{VPP}} = 0.105 \text{ W/m}\cdot\text{°C}$, only slightly higher than the thermal conductivity of asbestos fiber $\lambda_{\text{asbestos}} \approx 0.09 \text{ W/m}\cdot\text{°C}$, known as a typical thermal insulation material, while the coefficient of volumetric thermal expansion of VPP is very large $\beta \approx 10^{-3} \text{ (°C)}^{-1}$, it is almost five times greater than that of water and only 3.7 times less than that of gases.

The equations describing the cooling of an unbounded cylinder are well known and described in numerous works on the theory of heat conductivity and heat transfer [2]. If we imagine the fuel oil in the tank as a quasi-solid body with a thermal conductivity $\lambda_{\text{VPP}} = 0.105 \text{ W/m}\cdot\text{°C}$, filling the entire volume of the boiler with an initial temperature equal to the filling temperature plus 80 °C, then it will take a very long time to cool down to the freezing temperature, at which the discharge by gravity is difficult to perform.

Performed computer calculations using the software package ANSYS 5.6 shows a picture of the temperature distribution over the cross-section of the boiler of a tank car, streamlined by an air flow with a temperature of - 20 °C, with an external heat transfer coefficient $\alpha = 15 \text{ W/m}^2\cdot\text{°C}$, corresponding to a flow rate close to 20 m/s. This picture is shown in Figure 3.
Figure 3. Results of calculations on the distribution of temperatures in the GNP over the cross-section of the boiler of a tank car in the absence of internal convection movements (quasi-solid body model): a) General picture of the temperature field after 5.7 days of transportation; b) Curves of temperature changes at different distances from the boiler axis.
It turns out that after 5.75 days of transportation (5×10^5 sec, end of count) at an air temperature of minus 20 °C, the main volume of oil product, highlighted in red, orange, yellow and green colors, retained a high temperature exceeding plus 30 °C, sufficient for self-discharge. From the picture in Figure 3a it can be seen that only a thin layer of petroleum product adjacent to the walls of the boiler, highlighted in turquoise, blue and blue colors, has cooled to the temperature of transition to a high-viscosity state.

Figure 3b shows curves that determine the temperature change of fuel oil over time at different distances from the boiler axis of the tank car. This result is in sharp contradiction with the data of full-scale experiments shown in Figure 1. They indicate that, after 25 hours of transportation under milder external conditions (at an air temperature of minus 15 °C), the VPP temperature, the average volume of the boiler without thermal insulation, dropped to plus 10 °C. At this temperature, the viscosity of M40 and M100 fuel oils is already very high.

Therefore, the model of the medium as a quasi-solid body is erroneous. In fact, there are internal fluid movements that can be considered as mixed, free-forced convection.

Forced convection, as one of the components of the process, is observed only when the car is moving. The tank car is filled with a maximum of 95% VPP, and there is a free liquid surface inside it, and a layer of air above it. With fluctuations and changes in the speed of the moving car, waves arise on the free surface of the liquid VPP, causing mixing of at least the upper layers of the liquid.

Free convection is caused by the cooling of the wall layers of the liquid by the cold walls of the boiler, and the resulting increase in the density of VPP. As the density increases, the cooled areas of the liquid begin to move down in the wall area, displacing the liquid up in the Central areas of the boiler. There is a circulatory motion that is often called thermogravitational convection (TGC).

A traffic oil route on the Railways of Russia depends on "the situation" and, inserting mean values, it is necessary to consider that changes are possible. At the end of the last century, the average time of transportation of liquid cargo in the European part of Russia, including the Urals, was 7.5 days with an average range of 1,500 km [3]. This corresponds to the average track speed of the rolling stock of about 11-12 km/h. To date, this indicator has not changed significantly.

If we assume that a self-loading train moves at a speed of 60 km/h, then 18% of the total travel time falls on the actual movement of cars, and 82% on their Parking. At the same time, the TGC of liquid oil cargo inside the boiler of the tank car will be dominant, and forced convection will be an important but secondary process. We will limit ourselves to the consideration of TGC.
Figure 5. Distribution of speeds of circulation movement of fuel oil M100 at thermogravitational convection inside the boiler of the tank car: a) in the first 45 minutes after filling the tank; b) Distribution of the speed of circulation of fuel oil M40 with a distance from the boiler wall along the horizontal diameter in the first 45 minutes after filling; c) 360 minutes after filling the tank.
In Figure 4a and Figure 4c schematically show the lines of fluid currents, generalizing the results of experiments on the study of TGC in a horizontal cylinder, used in mathematical modeling of the process [4, 5]. The arrows indicate the direction of movement of the fluid, and the density of the current lines shows the areas with the highest speed of movement.

In Figure 4a shows the pattern that occurs when the cylinder is heated symmetrically, Figure 4b shows the pattern that occurs when the cylinder is cooled asymmetrically, and Figure 4c shows the expected movement of hot petroleum products in the boiler of a tank car during symmetric cooling (constructed by analogy with Figure 4a).

In all the works devoted to TGC, it is noted that the most intense flows occur in the thin wall layer of the liquid. Because of this, TGC is described using the laminar boundary layer model [6].

In the calculations based on this model, the basic equations of hydrodynamics and convective thermal conductivity were considered in a cylindrical coordinate system and solved by the finite element method using software package the ANSYS 18.2.

The results of the calculations are shown in Figure 5.

When performing calculations, it was assumed that:
- fuel oil M100 had a filling temperature of plus 70 °C, ambient temperature minus 20 °C, symmetrical cooling with an external heat transfer coefficient \( \alpha = 15 \text{ W/m}^2\circ\text{C} \);
- filling of petroleum products into the boiler of the tank car lasted 40 minutes;
- the point of 45 minutes was taken as the beginning of the calculation, it was assumed that the temperature distribution and velocity field in the circulating oil product were equalized before that.

After 45 minutes, the velocity distribution at TGC was considered steady. The pictures shown in Figure 5a and Figure 5b show that the thickness of the laminar flow descending along the boiler wall is 0.30 m, and the highest flow velocity of 0.27 m/s is observed at a distance of 0.13 m from the boiler wall. At a distance exceeding 0.3 m, countercurrents are formed rising up, closing the circulation vortices schematically depicted in Figure 4c. The Regions B, also shown in Figure 4c, called "fixed cores" were not separated, but merged in the center of the boiler. In them, the liquid remains stationary at TGC.

At the very beginning, the TGC process is observed throughout the entire cross-section of the boiler, and then gradually shifts upwards. The distribution of velocities at TGC of liquid 360 minutes after filling into the tank is shown in Figure 5c.

At high speeds of circulation movement, as indicated by the curve in Figure 5b, TGC of hot petroleum product is the main mechanism that provokes its rapid cooling.

If TGC is suppressed, the liquid petroleum product will be cooled as a quasi-solid body by molecular thermal conductivity, and the temperature distribution in it will correspond to the picture shown in Figure 3.

TGC suppression can be practically carried out by transferring the hot oil product in the boiler of the tank car to a stratified state.

In this state, the Archimedean force prevents the lowering of less dense masses of liquid at the walls of the boiler, and the lifting of more dense masses in its center also becomes impossible.

The stratified state of liquid VPP can be created by increasing its initial temperature at the stage of filling into the boiler of the tank car, but with the mandatory preservation of the conditions for safe operation of rubber sealing elements on the boiler drain device. The last point is fundamentally important, and we will note it especially.

### 3. Design features

Currently, most tank cars have lower drain devices. These devices, with some differences in design, have a common property - in them the drain device shown in Figure 6 is placed strictly under the filling hatch. The device is opened and closed manually by the operator, using a rod and a collar, which is placed in the upper filling hatch. The drain device is attached to the flanges when bolted to the boiler of the tank car. In this case, a sealing sleeve made of oil-resistant and gasoline-resistant
rubber is placed between the flanges of the boiler and the drain device, in Figure 6b it is marked with position 1.

![Figure 6](image_url)

Figure 6. The drain device of the tank: a) General view; b) Diagram of the device presented in axonometric.

Rubber retains its performance characteristics at temperatures not exceeding plus 120 °C. In case of loss of these characteristics, it is possible to spill VPP over a large area, which will cause an environmental catastrophe fraught with multimillion-dollar costs for the elimination of consequences. Therefore, there are regulatory documents prohibiting the filling of VPP at temperatures exceeding plus 100 °C.

The following very simple engineering solution is proposed. An extension pipe with a length of 0.10...0.15 m is welded to the boiler of the tank car, to the free end of which a flange is welded, which has a bolted connection with the flange on the drain device [7]. When pouring hot VPP, the first masses of the product spread over the bottom of the boiler and are cooled due to thermal contact with it. The extension pipe with an internal volume of 2...3 liters is filled with already cooled fuel oil. This fuel oil, which has a low thermal conductivity (Table 1) and will create thermal insulation of the rubber sealing cuff, from the hot oil product inside the boiler of the tank car. This event is most easily carried out on a tank car of frameless construction, which is becoming increasingly common in car building.

The following results of calculations of temperature fields of liquid VPP was believed that in the upper half of the boiler of the tank, the temperature of the oil is in the range from + 150 to + 250 °C, and at the bottom of the boiler supported at a level close to plus 80 °C. Under these conditions, the density of fuel oil and oils in the upper half of the boiler of the tank car is almost 10...14 % lower than in the lower part, which blocks TGC. Then the oil cargo will maintain a sufficiently high temperature and fluidity even after 10 days of transportation at air temperatures of minus 20 °C.

There are several ways to change the conditions of oil cargo loading with simultaneous transfer to a stratified state. The first of the possible ones, which is easy to implement, without large investments, can be implemented using a tank with a steam heating casing (Figure 2) of the model 15-1566 type, the main parameters of the boiler of which are given in Table 2. The second option can be implemented on a General-purpose oil tank without a steam-heating casing, on the upper part of which a layer of thermal insulation is applied. The lower half of the boiler remains open.
In the tank car, considered according to the first option, a chamber with a thickness of 4.5 cm is formed between the walls of the boiler and the casing, which has a volume of about 3.8 m$^3$. At present, when the VPP is drained, steam is supplied to the chamber, which provides heating of the boiler walls and a relatively thin layer of solidified petroleum product that has thermal contact with them. The layer melts, dramatically reducing its viscosity. The entire mass of VPP, which has a low temperature and high viscosity, slides along this layer and merges into a receiving pit located below ground level. Then the tank car leaves the drain area, and the task of heating and sending the merged oil product to the storage facilities falls on the ground services. The fuel oil economy of the enterprise receiving oil products must have expensive and energy-consuming equipment (heated fuel oil pipelines, pumps, etc.).

The problem of heating oil products during discharge and distribution to ground storage facilities and the associated resource costs remained.

In addition, the chamber creates structurally not provided thermal insulation of the lower half of the tank boiler. It is filled with air having low thermal conductivity, and creates a significant thermal resistance to the flow of heat from the transported hot VPP to the surrounding space. Then the hot liquid petroleum product in the upper part of the boiler of the tank car cools faster than in its lower part.

It can be assumed that the change in the density of the oil product by $\Delta \rho$, which occurs with a change in its temperature by $\Delta t$, in the first approximation satisfies the linear law:

$$\frac{\Delta \rho}{\rho_0} = \beta \cdot \Delta t.$$  \hspace{1cm} (1)

Therefore, the predominant cooling of the VPP in the upper part of the boiler is accompanied by the transition of its entire mass to a hydrodynamically unstable state, which excites TGC. Convection causes intensive heat transfer from the hot oil product to the steel walls of the boiler, which do not have thermal insulation on the upper half of the boiler, above the steam heating casing. With a high thermal conductivity of steel $\lambda = 42 \text{ W/m}\degree\text{C}$, the heat stored in the oil cargo is transferred to the surrounding space and is irretrievably lost. This explains the curve that characterizes the rapid cooling of fuel oil, shown in Figure 1.

According to the proposed variant of transportation of VPP, the boiler is filled at temperatures in the temperature range from plus 250 $\degree$C to 150 $\degree$C. Simultaneously with the filling, which lasts about 40 minutes, and it is possible that some time after it, but even before sending the tank car, the oil product, in the lower half of the boiler of the tank car, is forcibly cooled by filling the chamber with cold technical water with an approximate temperature of plus 10 $\degree$C. The water in the chamber is heated and boils, and the steam is discharged into the environment through the nozzle of the chamber. Heating and boiling of water in the chamber is provided by absorbing heat from the poured VPP, which cools, increasing its density. The upper half of the boiler of the tank car continues to be filled with oil products, with a high temperature. This half of the boiler is not forced to cool; moreover, it can also have thermal insulation.

Putting in the equation (1) $\Delta t = 50 \degree$C and given the data in Table 1, it is easy to get that $\Delta \rho/\rho_0 = 0.1395$, i.e. the difference in the density of VPP in the lower and upper halves of the tank car is almost 14%. Therefore, it can be assumed that in this case, the effects associated with TGC disappear.

The required amount of cooling water is estimated from the heat balance equation. Let us assume that in the lower half of the boiler of the tank car, it is necessary to cool $m_1 = 30 \text{ tons}$ of fuel oil from the initial 250 $\degree$C to 100 $\degree$C when the boiling of water stops. Amount of heat removed from fuel oil:

$$Q_1 = C_1 m_1 \Delta t_1.$$  \hspace{1cm} (2)

The amount of heat absorbed by water when it is heated and boiled:

$$Q_2 = C_2 m_2 \Delta t_2 + m_2.$$  \hspace{1cm} (3)
where \( C_1 = 1.86 \text{ kJ/kg}^\circ\text{C} \) and \( C_2 = 4.2 \text{ kJ/kg}^\circ\text{C} \) specific heat capacity of oil and water, respectively, \( \Delta t_1 = 150 \, ^\circ\text{C} \) and \( \Delta t_2 = 90 \, ^\circ\text{C} \) the difference of the initial and final temperatures of oil and water, \( r = 2.258 \text{ kJ/kg} \) latent heat of vaporization of water. Equating \( Q_1 \) and \( Q_2 \), we find the necessary amount of cooling water to obtain the stratified state of the VPP:

\[
m_2 = \frac{C_1 m_1 \Delta t_1}{C_2 \Delta t_2 + r}.
\]

Substituting the numerical values of the values, we get that \( m_2 = 3,170 \, \text{kg} \), i.e. to get the desired effect, it is enough to use about 3 tons of water. When the volume of the chamber \( V = 3.8 \, \text{m}^3 \), it can be filled not to the edge, but with a small volume filled with air.

In this variant, it is assumed that the filling site at the refinery has a source of supply of hot and cold industrial water, as well as a sewage system that provides its discharge.

The presence of a steam-heating casing on the lower half of the tank boiler and a layer of heat-insulating material on its upper half, ensure safety for service personnel during filling operations.

The stratified state of the VPP in a general-purpose oil tank car without a steam-heating casing is ensured by the fact that the tank car has thermal insulation of the upper half of the boiler, while the lower half of the boiler is cooled by external air. And in this case, in the mass of the oil product, a temperature field is formed with a temperature gradient directed to the axis of the boiler from its side surface.

4. Results and discussion

The obtained results of computer calculations presented in Figure 7 show that the layers of oil product adjacent to the shell of the tank boiler are cooled most quickly with the transition to a high-viscosity state. These layers are cooled, passing into a high-viscosity state, but at the same time they form a heat-insulating shell of the tank boiler, which arises spontaneously from the transported oil product itself. The thickness of the solidified layers of VPP forming it depends on the ambient temperature and under conditions of severe winter is no more than 10 cm, their mass does not exceed 15 tons, i.e. it is not more than 20% of the weight of the contents of a 65-ton tank. The main part of the transported VPP (highlighted in red, orange and yellow) with a total weight of up to 50-55 tons, will retain its high temperature and fluidity during the entire time of transportation.

![Figure 7](image_url)

**Figure 7.** Temperature distribution in stratified fuel oil M100 (transportation at the initial temperature of the VPP \( t_0 = +150 \, ^\circ\text{C} \), air temperature \( t_a = -20 \, ^\circ\text{C} \) with the coefficient of external heat transfer \( \alpha_{\text{external}} = 15 \text{ W/m}^2 \text{ °C} \)): a) when transported in a tank with a steam-heating casing; b) when transported in a general-purpose tank with thermal insulation of the upper half.
The large thermal resistances of the air layer of the chamber under the steam-heating casing and the layer of heat-insulating material above it also contribute to a decrease in the cooling rate of the GNP (Fig. 7, a), which reduce the heat flows into the surrounding space. Unloading of the delivered GNP from the boiler of the tank car is carried out according to the method currently used. Through the inlet fitting on the steam-heating casing, steam is fed into the chamber, for heating and melting the layer of thickened petroleum product forming a heat-insulating shell, the rest of its mass has a temperature sufficient to discharge by gravity. Unloading of a general-purpose oil tank can also be carried out in a recirculating way. From Figure 7, b, it can be seen that it remains necessary to wash out not all the contents of the boiler, but a relatively thin frozen layer formed in the lower part of the boiler.

The achieved positive effects from the use of the claimed technical proposal are as follows:

- to a sharp reduction in the time and cost of thermal energy for heating up when unloading viscous oil products from the tank, obtained by reducing the cooling rate of the oil product during transportation and maintaining the fluidity of more than 80% of its total mass;
- the need for liquefaction when unloading only a layer of thickened petroleum product that is less than 20% of its mass in the tank;
- to reduce the cost of thermal energy for additional heating of oil products in ground communications that ensure its transfer to storage facilities.

5. References

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