----- APPLIED MECHANICS -----

DETERMINING THE FEATURES OF LOADING THE BEARING STRUCTURE OF A MULTIFUNCTIONAL CAR UNDER OPERATING MODES

This paper substantiates the modernization and commissioning of a railroad car for high-temperature, bulk/loose cargoes in order to improve the efficiency of railroad transportation. A feature of the car is the presence of an open-type boiler, which is made of heat-resistant material. To prevent splashing of transported cargo, it is possible to use a removable cover, which is attached to the top of the boiler.

The boiler of the car was calculated for strength under the main operating modes. The vertical load on the boiler was taken into consideration while accounting for the transportation of bulk cargo, as well as longitudinal, and the effect of temperature load. The strength was calculated by the method of finite elements. It is taken into consideration that the boiler is made of composite heat-resistant material. The calculation results showed that with the considered load modes, the strength of the boiler is ensured.

The dynamic load of the boiler was mathematically modeled at car shunting. The calculation was performed in a flat coordinate system. Solving the mathematical model of the car dynamic load has established that the maximum acceleration that acts on the boiler is 36.5 m/s^2.

The dynamic load of the boiler was simulated. The dislocation fields and numerical values of accelerations that act on it were determined. The maximum acceleration, in this case, is concentrated in the bottom of the boiler; it is 37.4 m/s^2.

To verify the dynamic load model, the F-criterion was used for calculation. It has been established that the hypothesis about the adequacy of the model is confirmed.

The study reported here could contribute to improving the efficiency of railroad transport operation and advancing the design of multifunctional car structures

Keywords: transport mechanics, railroad car, load-bearing structure, composite material, structure load

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1. Introduction

Ensuring the sustainable development of the state economy is possible if the efficiency of the transport industry is maintained. For a long time, the most priority component of the transport industry is rail transport. At the same time, the increase in the competitive environment in the transport market leads to the commissioning of high-efficiency rolling stock. This necessitates additional capital investments. Therefore, it is possible to modernize the existing fleet of vehicles for the transportation of the applied nomenclature of goods.

A rational solution in this case is the commissioning of multifunctional structures of cars intended for the transportation of a wide range of goods. At the same time, it is necessary to study the possibility of transporting high-temperature cargoes from industrial enterprises. Transportation of such cargoes is carried out by specialized rolling stock. Given the lack of it, cars that are not intended for these purposes can be used. This causes their damage, the need for unscheduled repairs, and, accordingly, maintenance costs. In addition, such a circumstance threatens the safety of transportation of goods by rail. Therefore, it becomes necessary to conduct research into the design, as well as the modernization of existing vehicle structures to ensure their versatility. This will contribute to improving the efficiency of operation of railroad transport and the transport industry in general.

2. Literature review and problem statement

Work [1] highlights the features of the automated car to improve the efficiency of rail transportation. The car is

intended for work under the conditions of internal terminals, ports, and industrial railroad enterprises. The results of experimental tests of the design of the car are given. However, the structure of that car does not allow the transportation of bulk cargo by rail.

The design of the Zans-type car for the transportation of bulk cargoes is considered in work [2]. The prospects for the operation of this car have been determined. The results of calculations for the strength of its supporting structure are given.

The analysis of static strength of the bearing structure of the Zans series car is reported in [3]. To that end, the authors built a refined finite-element model of the load-bearing structure of the car and determined the fields of dislocation of maximum stresses in it.

It is important to note that a given type of car is not intended for the transportation of high-temperature cargoes, which limits the possibility of its operation.

Optimization of the load-bearing structure of the freight car is carried out in [4]. A gondola car was chosen as a prototype. The results of calculations for strength confirmed the feasibility of structural improvements of the gondola car.

Work [5] considers the features of modernization of the freight car of Sgnss-type based on dynamic tests. The results of numerical and experimental modeling of load on the car are presented. It must be said that in the cited works the authors did not conduct mathematical modeling of the dynamics of bearing structures to determine the specified dynamic loads. That could contribute to the occurrence of errors in the calculation of strength.

The strength of the bearing structure of the car, taking into consideration its modernization, is estimated in [6]. The main indicators of strength, as well as fatigue strength of the bearing structure of the car are calculated. The requirements for its re-equipment are defined.

The justification for the modernization of freight cars is considered in [7]. In this case, modernization is proposed to be carried out during periodic types of repair of cars. The purpose of such modernization is to improve the operating conditions of the cars. At the same time, the modernization does not contribute to ensuring the multifunctionality of the car.

In work [8], the authors proposed a methodology for extending the service life of cars in order to further re-equip them for the transportation of the specified range of cargoes. The results of the calculations confirmed the feasibility of the proposed measures. However, the authors did not consider the possibility of designing or upgrading cars with multifunctional properties.

The justification for extending the service life of a covered car that has exhausted its regulatory life is carried out in paper [8]. It is indicated that the service life of the covered car may be extended. In addition, that structure of the car can be modernized to fulfill the tasks of cargo transportation [9]. It is important to say that the authors have not proposed possible options for the modernization of the covered car.

Study [10] reports an analysis of practical experience in the construction and operation of launch vehicles with multi-layer composite casing and cellular filler. The approach to optimizing the design of the main streamer of the carrier rocket by weight is substantiated. However, it is also of scientific interest to use those materials in relation to the railroad industry.

The analytical dependences on the justified purpose of tolerance fields for the physical and mechanical characteristics of polymer composite material are established in [11]. It is found that when used for the manufacture of a product of reinforcing material with a passport field of tolerance, the value of the volumetric content of fibers is always in its interval. However, the data from the cited study are focused on the rocket and space industry and were not considered for railroad transport.

Our review of literary sources [1–11] reveals that it is expedient to conduct research into the possibility of designing a multifunctional structure of the car for the transportation of a wide range of cargoes. This will help construct competitive high-efficiency rolling stock and contribute to improving the efficiency of rail transportation.

3. The aim and objectives of the study

The purpose of this study is to determine the dynamics and strength of the load-bearing structure of the multifunctional car under basic operating modes. This will help reduce the empty mileage of cars and improve the efficiency of railroad transport.

To accomplish the aim, the following tasks have been set:
– to determine the strength of the boiler of the car for the transportation of high-temperature, bulk/loose cargoes under operating modes;
– to determine the dynamic load of the boiler of the car for the transportation of high-temperature, bulk/loose cargoes;
– to verify the models of dynamic load of the boiler of the car for the transportation of high-temperature, bulk/loose cargoes.

4. The study materials and methods

To ensure the multifunctionality of cars in order to expand the range of cargoes transported in them, modernization of existing structures is proposed. A feature of the modernization is the use on cars, the bearing structure of which is represented by a frame, of an open-type boiler, which is made of heat-resistant material (Fig. 1). It is possible to install such a boiler on the frames of a tank car or platform car. It is also possible to carry out modernization on tank cars by cutting the boiler and covering it with heat-resistant material.
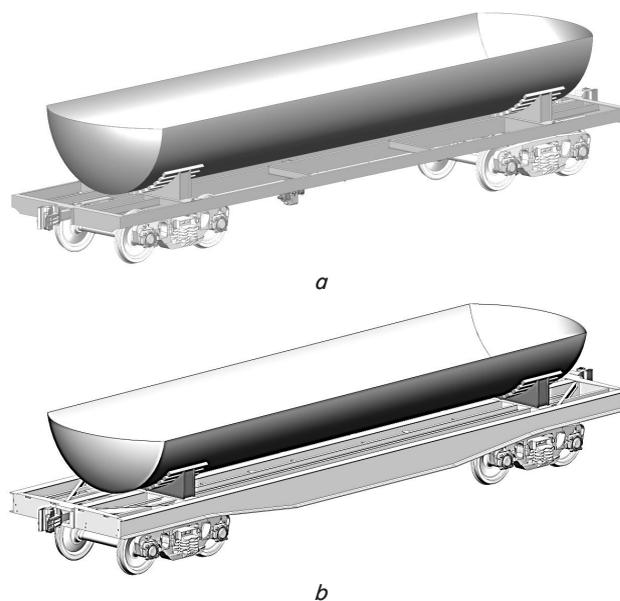

a

b

Fig. 1. Multifunctional car: *a* — built on the base of a tank car; *b* — built on the base of a platform car

To prevent splashing of transported cargo, it is proposed to use a removable lid, which is attached to the top of the boiler (Fig. 2).
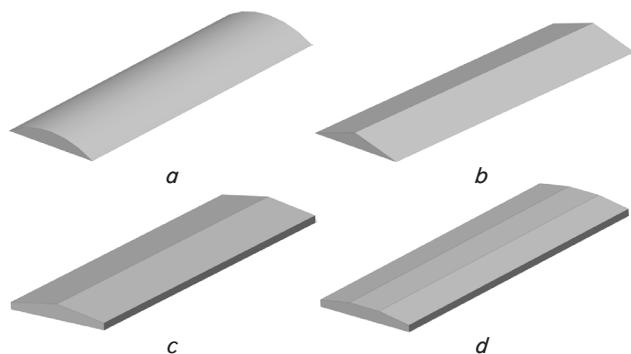

Fig. 2. Possible options for removable lids:
a — option one; *b* — option two; *c* — option three;
d — option four

If necessary, removable lids can be equipped with devices for maintenance and storage.

In the proposed car, it is possible to carry out transportation of not only bulk/loose cargoes but also dumped.

To design a spatial model of the multifunctional car structure, the SolidWorks software package (France) was used. In order to determine the strength of the boiler, a finite-element method was applied [12–15]. The calculation was carried out in the SolidWorks Simulation software (France). In this case, the criterion of maximum stresses was employed.

It was taken into consideration that the boiler is made of composite, which has linear elastic orthotropic properties. The basic strength characteristics of the material are given in Table 1.

Table 1

Basic strength characteristics of the material

Parameter	Value
Modulus of elasticity, MPa	$2.42 \cdot 10^5$
Poisson's ratio	0.394
Shear modulus, MPa	318.9
Strength limit in the direction of fibers, MPa	1100−1300
Strength limit in the transverse direction of the fibers, MPa	650

The composite can withstand the value of strength at a temperature of 700 °C. The number of layers of material was taken equal to 2. The calculation of the strength of the boiler was carried out for the thin-walled shell. The model was fixed in the areas of where the boiler leaned on the wooden supports of the grooves. Fixing the model was tough. That is, the possible friction forces between wooden bars and the boiler were not taken into consideration. In this case, a linear thermal calculation was performed.

When building the finite-element model, spatial ten-node isoparametric tetrahedrons [16–19] were used, the number of which was calculated by the graph analytic method [20–23]. The method is based on the graphical (geometric) representation of permissible solutions and the objective function of the problem. The essence of the method in solving a given problem is to build the dependence of maximum equivalent stresses on the number of finite elements.

When this dependence begins to be described by a horizontal line, it is an optimum of the number of finite elements.

The number of elements of the grid was 40,478, nodes – 20,573. The maximum size of the grid element was 80 mm, the minimum was 16 mm.

To determine the loads that act on the boiler during the action of longitudinal force on the car, mathematical modeling was carried out. This involved the mathematical model given in [24]. However, within the framework of the current study, it was finalized by adapting to determine the load of the proposed car structure. The case of car shunting impact was taken into consideration, considering the effect of a load of 3.5 MN on the rear stop of the auto-coupling. It was taken into consideration that the car is loaded to full load capacity with conditional cargo. The movement of the cargo during the impact of the car was not taken into account. The impact was considered absolutely rigid. During the simulation, the friction forces that arise between the wooden bars and the boiler were taken into consideration. When performing calculations, it was taken into consideration that the car rests on bogies of the model 18-100 with the corresponding stiffness characteristics of spring kits. When determining inertial coefficients, the rated parameters of the components of the bearing structure of the car were taken into consideration.

The system of differential equations was solved according to the Runge-Kutta method under the initial conditions equal to zero [25, 26]. To verify the mathematical model, variational calculations of the dynamic load of the boiler of the car were performed. As a variation parameter, the force of the car's impact in the auto-coupling was taken into consideration. The initial parameter of the model is the acceleration of the load-bearing structure of the car. To determine the optimal number of experiments, the Student criterion [27–29] was applied, and verification was carried out according to the F-criterion [30–33].

5. Results of analyzing the load on the boiler of the car for the transportation of high-temperature bulk/loose cargoes

5. 1. Determining the strength of the boiler of the car for the transportation of high-temperature bulk/loose cargoes

To determine the strength of the boiler at vertical load, taking into consideration the transportation of bulk cargo in it (load scheme I), we performed calculation. The estimated scheme of the boiler is shown in Fig. 3. When compiling it, it was taken into consideration that the boiler was exposed to a vertical static load P_v^{st}, taking into consideration the use of the full load capacity of the boiler, as well as the pressure of the bulk cargo P_{bc}. The calculation was made in statics, so it does not take into consideration the action of the dynamic load.

The pressure of the bulk cargo is calculated from the formula given in [34]:

$$P_{bc} = \rho \cdot g \cdot h, \tag{1}$$

where ρ is the density of bulk cargo, kg/m³; h is the height of the distribution of cargo relative to the boiler, m.

The results of our calculation are shown in Fig. 4.

The maximum stresses were registered in the zones of interaction between the cylindrical part of the boiler and the bottoms; they amounted to 184.4 MPa, that is, they do not exceed the permissible ones.

To determine the longitudinal load of the boiler (load scheme II), an estimation scheme was drawn up, shown in Fig. 5. The calculation was performed in quasi-statics.
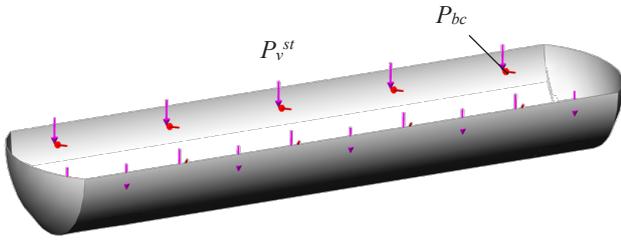

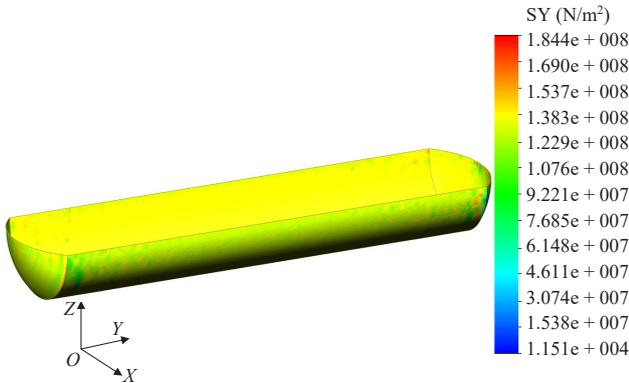Fig. 3. Estimation scheme of the boiler (load scheme I)

Fig. 6. Stressed state of the boiler (load scheme II)

Fig. 4. Stressed state of the boiler (load scheme I)

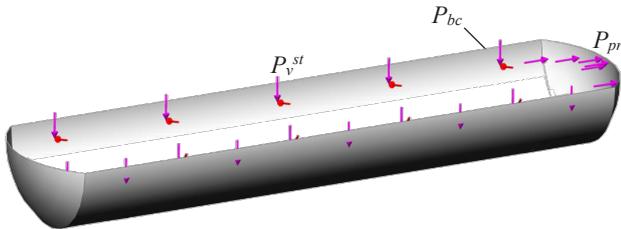Fig. 7. Scheme of applying the temperature load to the boiler (load scheme III)

Fig. 5. Estimation scheme of the boiler (load scheme II)

The value of the maximum pressure from the hydraulic shock is determined by the ratio of the force of inertia of the cargo to the area of the vertical projection of the bottom [34]:

$$P_{pr} = N \cdot \frac{m_b}{m_{gw}} \cdot \frac{1}{F}, \qquad (2)$$

where N is the force of impact against the auto-coupling, MN; m_b is the weight of cargo in the boiler, kg; m_{gw} is the gross weight of the car, kg; F – the area of the internal cross-section of the boiler, m².

The results of our calculation are shown in Fig. 6. The maximum stresses, in this case, occur in the middle part of the bottom and are 307.4 MPa, that is, they do not exceed the permissible ones.

At the next stage of the study, we determined the possibility of transporting a high-temperature bulk cargo in the boiler (load scheme III). The estimation scheme of the boiler is identical to the one shown in Fig. 5. In this case, the pressure of the bulk cargo was replaced by the pressure of loose cargo. Also, the temperature load P_t was applied to the inner surface of the boiler, which is equal to 700 °C (Fig. 7).
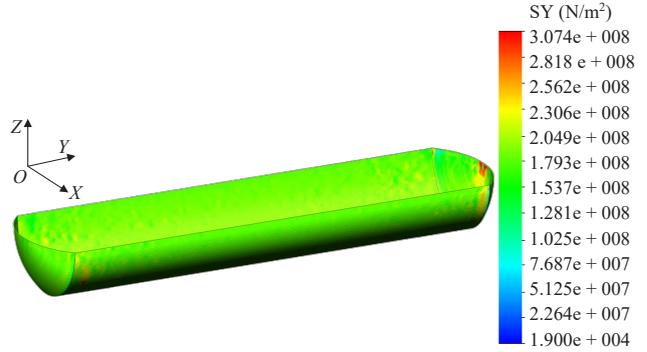
To determine the longitudinal dynamic load on the boiler, it is necessary to carry out mathematical modeling.

5. 2. Determining the dynamic load on the boiler of the car for the transportation of high-temperature bulk/loose cargoes

The estimation scheme for determining the longitudinal load on the car is shown in Fig. 8. The system of differential equations of car movement is as follows:

$$\begin{cases} M_{gw} \cdot \ddot{x} + (M_C \cdot h) \cdot \ddot{\varphi} = P_l - 2P_{fr}, \\ I_C \cdot \ddot{\varphi} + (M_C \cdot h) \cdot \ddot{x} - g \cdot \varphi \cdot (M_C \cdot h) = \\ = l \cdot P_{FR} (\mathrm{sign}\dot{\Delta}_1 - \mathrm{sign}\dot{\Delta}_2) + l (k_1 \cdot \Delta_1 - k_2 \cdot \Delta_2), \\ M_C \cdot \ddot{z} = k_1 \cdot \Delta_1 + k_2 \cdot \Delta_2 - P_{FR} (\mathrm{sign}\dot{\Delta}_1 - \mathrm{sign}\dot{\Delta}_2), \end{cases} \qquad (3)$$

where

$$\Delta_1 = z - l \cdot \varphi, \ \Delta_2 = z + l \cdot \varphi,$$

where M_{gr} is the gross weight of the car; M_C is the mass of the bearing structure of the car; I_C is the moment of inertia of the car; P_l is the longitudinal force that acts on the rear stop of the auto-coupling; P_{fr} is the friction forces that arise between the boiler and wooden bars; $2l$ is the base of the car; P_{FR} is the dry friction forces in spring suspension; k_1, k_2 is the rigidity of springs of the suspension of bogies; x, φ, z are the coordinates corresponding to the longitudinal, angular around the transverse axis, and vertical movement of the car, respectively.
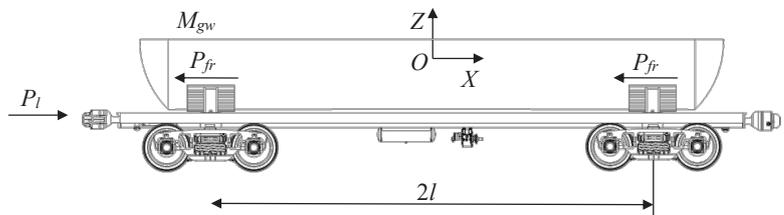

Fig. 8. Estimation scheme for determining the longitudinal load on the car

The results of our calculation established that the maximum acceleration acting on the boiler was 36.5 m/s², it acquires a negative value and occurs at the time of impact (Fig. 9).
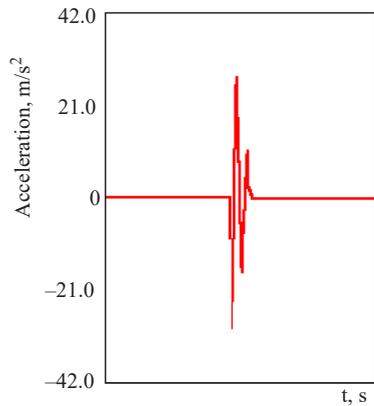

Fig. 9. Accelerations that act on the load-bearing structure of the car at its longitudinal load

The resulting acceleration value was taken into consideration when calculating strength as a component of the dynamic load acting on the boiler at its longitudinal load.

The results of our calculation are shown in Fig. 10. The maximum stresses, in this case, arise in the zones of interaction between the bottoms and the cylindrical parts of the boiler and are 314.5 MPa; therefore, they are within the permissible limits.

According to the estimation scheme shown in Fig. 3, the fields of dislocation of accelerations that act on the boiler, as well as their numerical values, were determined. The calculation was performed using the options of the SolidWorks Simulation software package. The results of our calculation are shown in Fig. 11.
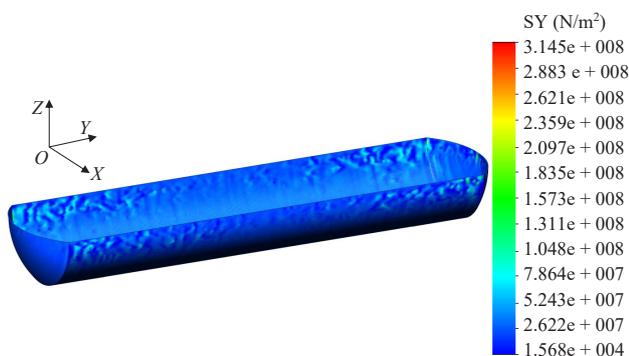

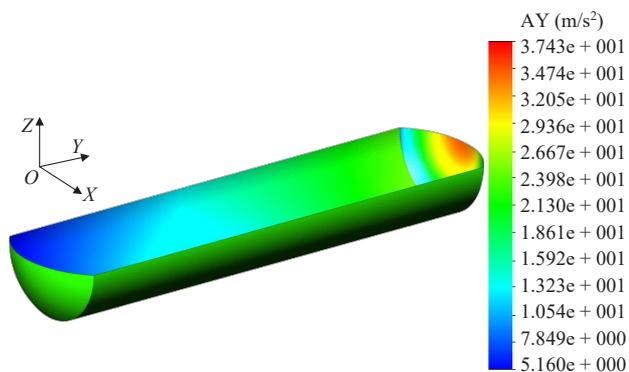Fig. 10. Stressed state of the boiler (load scheme III)

Fig. 11. Fields of dislocation of accelerations relative to the boiler

The maximum acceleration that acts on the boiler is concentrated in the bottom and is 37.4 m/s². In the cylindrical part of the boiler, the acceleration value is in the range of 28.0–12 m/s².

5. 3. Verifying the models of dynamic load on the boiler of the car for transporting high-temperature bulk/loose cargoes

To determine the optimal number of experiments for the purpose of the subsequent verification of the model, the Student criterion was applied [27]:

$$n = \frac{t^2 \cdot \sigma^2}{\delta^2}, \tag{4}$$

where t is the tabular value of the Student criterion; σ is the standard deviation of a random variable; δ^2 is the absolute error of the measurement result.

Based on variational calculations, we determined the accelerations that act on the boiler with different force of impact against the car's auto-coupling. The results of our calculations are shown in Fig. 12.

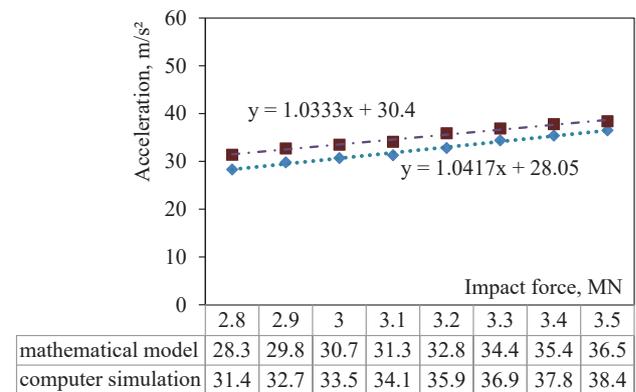|	2.8	2.9	3	3.1	3.2	3.3	3.4	3.5
mathematical model	28.3	29.8	30.7	31.3	32.8	34.4	35.4	36.5
computer simulation	31.4	32.7	33.5	34.1	35.9	36.9	37.8	38.4

Fig. 12. Results of modeling the dynamic load on the boiler

According to the data given in Fig. 12 and in (4), it was established that the number of experiments carried out was sufficient to confirm the adequacy of the result. In this case, the error of calculations was 5.45 %.

The value of the coefficient of variation for the sample obtained by mathematical modeling was 8.8 %, and computer – 7.2 %.

Using the calculations results given in Fig. 12, we verified the model of dynamic load on the boiler according to the F-criterion by comparing the two variances [35–37]. This criterion was chosen as decisive because it is one of the most used in technical calculations.

In this case,

$$F_c = \frac{S_{ad}^2}{S_r^2}, \tag{5}$$

where S_{ad} is the variance of adequacy; S_r is the reproducibility variance.

The variance of adequacy was determined:

$$S_{ad}^2 = \frac{\sum_{i=1}^{n} \left(y_i - y_i^c \right)}{(N - q)}, \tag{6}$$

where y_i^c is the calculated value of the value obtained from modeling; f_i is the number of degrees of freedom; N is the number of experiments in the planning matrix; q is the number of coefficients of the equation.

The variance of reproducibility was calculated:

$$S_r^2 = \frac{1}{N}\sum_{i=1}^{n} S_i^2, \qquad (7)$$

where S_i^2 is the variance in each line where parallel experiments were conducted.

It was established that with a variance of adequacy $S_{ad}=8.23$ and the variance of reproducibility $S_r=6.44$, the actual value of the F-criterion $F_c=1.27$, which is less than the tabular value $F_t=3.58$ at the level of significance $\alpha=0.05$. Therefore, the hypothesis of adequacy is not disputed.

6. Discussion of results of analyzing the load on the boiler of the car for the transportation of high-temperature bulk/loose cargoes

To improve the efficiency of the use of railroad transport, the modernization of existing cars is proposed. A feature of the modernization is the use on cars, the bearing structure of which is represented by a frame, of an open-type boiler, which is made of heat-resistant material (Fig. 1). It is also possible to install such a boiler on the frames of tank cars or platform cars. In the proposed car, it is possible to carry out the transportation of not only bulk/loose cargoes but also dumped owing to the features of its structural execution.

In order to justify the proposed solution, we calculated the strength of the boiler. The vertical load of the boiler was taken into consideration, accounting for the transportation of bulk cargo; longitudinal, as well as the effect of temperature load.

The calculation of strength was implemented by the method of finite elements using the SolidWorks Simulation software. The results of our calculations showed that under the considered load modes, the strength of the boiler is ensured (Fig. 4, 6, 10). This is because the derived maximum equivalent stresses in its structure are lower than permissible ones.

To determine the loads that act on the boiler during the action of longitudinal force on the car, mathematical modeling was carried out. In this case, it was taken into consideration that the car is loaded to full load capacity with conditional cargo. The movement of the cargo during the impact of the car was not taken into consideration. The impact was considered absolutely rigid. During the simulation, the friction forces that arise between the wooden bars and the boiler were taken into consideration.

The results of our calculations showed that the maximum acceleration that acts on the boiler was $36.5\ \text{m/s}^2$ (Fig. 9). The resulting value of acceleration does not exceed the normative values established by the documents regulating the strength of railroad vehicles.

Computer simulation of the dynamic load on the boiler was carried out. Numerical values of accelerations were determined, as well as their distribution fields. The maximum acceleration that acts on the boiler is concentrated in the bottom and is $37.4\ \text{m/s}^2$ (Fig. 11). The limitation of the built model is that the calculation was performed in quasi-statics.

We verified the resulting models of dynamic load on the boiler according to the F-criterion.

It has been established that the hypothesis of adequacy is not rejected.

The merit of our study in comparison with works [1–3] is that we have proposed a model that makes it possible to determine the load on the car under different operating modes and types of transported cargoes. Unlike [4–7], the proposed measures for the structural execution of the car contribute to ensuring its versatility. Our structural solutions could be used to modernize freight cars, unlike those described in [8, 9].

The current study substantiates the feasibility of using composite materials in the structure of railroad vehicles, in contrast to those specified in [10, 11].

The limitation of our studies is the lack of a physical experiment.

It is important to say that the present study has theoretical properties. However, at further stages of its development, it is planned to conduct a physical experiment by the method of likeness in the laboratory.

7. Conclusions

1. We have determined the strength of the boiler of the car for transporting high-temperature bulk/loose cargoes under operating modes. The vertical load on the boiler was taken into consideration, accounting for the transportation of bulk cargo (scheme I); longitudinal (scheme II), as well as the effect of temperature load (scheme III). Under the first load scheme, the maximum stresses were registered in the zones of interaction between the cylindrical part of the boiler and bottoms: they amounted to 184.4 MPa. In scheme II, maximum stresses occur in the middle part of the bottom and are 307.4 MPa. The maximum stresses in scheme III arise in the zones of interaction between the bottoms and the cylindrical parts of the boiler; they are 314.5 MPa. So, with all the modes of loads under consideration, the maximum stresses are within the permissible limits.

2. The dynamic load on the boiler of the car for transporting high-temperature bulk/loose cargoes has been determined. The results of the mathematical modeling of dynamic load established that the maximum acceleration that acts on the boiler is $36.5\ \text{m/s}^2$.

Our results of the computer simulation of the dynamic load on the boiler showed that the maximum acceleration that acts on it is concentrated in the bottom and is $37.4\ \text{m/s}^2$. In the cylindrical part of the boiler, the acceleration value is in the range of $28.0\ \text{m/s}^2 – 12\ \text{m/s}^2$.

3. We have verified the models of dynamic load on the boiler of the car for transporting high-temperature bulk/loose cargoes. The calculation was performed according to the F-criterion. It was established that with a variance of adequacy $S_{ad}=8.23$ and the variance of reproducibility $S_r=6.44$, the actual value of the F-criterion $F_c=1.27$, which is less than the tabular value $F_t=3.58$ at the level of significance $\alpha=0.05$. Therefore, the hypothesis of adequacy has been confirmed.

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