*Для експериментального визначення теплотехнічного стану ізотермічних вагонів в умовах функціонування запропоновано процедуру роздільного визначення показників тепло-масообміну. Її особливість полягає в тому, що для експериментального визначення показників кондуктивної передачі теплоти та герметичності використані умови, методи та засоби теплотехнічних випробувань, які застосовуються при будівництві, експлуатації і ремонті ізотермічних вагонів. Для роздільного визначення істинного коефіцієнта теплопередачі і площі еквівалентного отвору фільтрації Fek використані експериментальні умови теплового процесу нагрівання повітря у вантажному приміщенні кузова вагона і вимірювання об'єму витрати повітря крізь нещільності при створенні в кузові постійного стандартного надлишкового тиску 49 Па.*

*На підставі значень істинного коефіцієнта теплопередачі і площі еквівалентного отвору фільтрації Fek з урахуванням теплофізичних властивостей вантажу та використанням засобів MSExcel побудовані графічні залежності зміни температури вантажу в ізотермічному вагоні на умови транспортування.*

*Результати дослідження пропонується використовувати для роздільного визначення показників тепло-масообміну та оцінки теплозахисних якостей огородження кузова ізотермічних вагонів в умовах функціонування. На підставі значення істинного коефіцієнта теплопередачі та площі еквівалентного отвору фільтрації можна визначати зміни температури вантажу на умови транспортування з урахуванням перепаду температур атмосферного повітря*

*Ключові слова: ізотермічний вагон, теплоізоляція, теплотехнічні випробування, тепло-масообмін, коефіцієнт теплопередачі, площа еквівалентного отвору, математична модель*

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# EXPERIMENTAL DETERMINATION OF INDICATORS OF THERMAL STATE OF REFRIGERATOR CARS UNDER OPERATING CONDITIONS

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## 1. Introduction

Rail freight transportation is carried out by various types of rolling stock. Perishable goods and goods requiring protection against weathering and sudden temperature changes are transported in refrigerated rolling stock. The fleet of refrigerated rolling stock is currently structured according to volumes, nomenclature and conditions of cargo transportation and contains:

– 87.1 % – insulated boxcars converted from refrigerated rolling stock;

– 7.7 % – TN-4-201 thermos cars built by the Dessau plant, Germany;

– 5.2 % – refrigerated 5-car sets.

The volumes of cargo transportation in refrigerated rolling stock over the last 5 years are:

– 91 % – insulated boxcars converted from refrigerated rolling stock;

– 2.8 % – thermos cars;

– 6.2 % – refrigerated 5-car sets [1].

Insulated boxcars, which are able to provide the necessary protection and storage conditions during transportation, are advantageous for carrying large volumes of cargo.

For the manufacture and delivery of this type of cars to the railway, their development, testing, production and research are carried out, aimed at further improvement of thermal properties of the body sheathing and methods for assessing their thermal properties.

The implementation of new approaches to increasing the efficiency of insulated boxcars by improving methods of experimental determination of thermal parameters of the body in operating conditions testifies to the relevance of the chosen research direction [2].

## 2. Literature review and problem statement

In [3], the results of analysis of heat exchange processes occurring in refrigerated rolling stock (RRS) under operating conditions are presented, and also methods of thermal tests of cars are considered. It is proposed to estimate the thermal properties of individual body sheathing structures on the basis of determining heat transfer coefficients in local zones, which allows identifying defects in the body insulation, during construction and repair of cars. But control of thermal properties of the RRS body by an average heat transfer coefficient gives relative values of car body tightness. All this suggests that as the car life increases, the error of evaluating the thermal properties will increase. This is the main disadvantage [3] of the work.

The work [4] uses data on air temperature inside and outside the car body to determine the thermal properties. The method involves accumulation of test results with subsequent differentiation. Differentiation occurs after the temperature of the outer and inner surfaces of the car body is equal. The disadvantage of [4] is great complexity of the data acquisition process. But this is almost impossible to implement in the conditions of a car repair enterprise. The necessary data are obtained in the stationary mode of operation of the insulation layer, so the test time is very long.

In [5], a method for determining thermal properties in building structures is developed. The method consists of two steps of surface temperature measurement inside and outside. Measurements are taken within 24 hours. The thermal resistance of insulation is determined from the comparison of the first and second measurement stages. The main drawback of this method [5] is the need to scale the surface to be tested.

The paper [6] proposes to determine the reduced heat transfer coefficient of RC. Determination of the coefficient consists in heating the air inside the car body to a predetermined temperature. Air temperature inside and outside the car is recorded. Heating occurs before steady state is established, after which the power source is reduced to almost zero. Temperatures are measured during cooling. This method [6] aims to reduce the test time. But there are difficulties in determining local heat transfer coefficients of the car body.

In [7], tightness coefficient is attributed to the thermal characteristics of the car body, along with the heat transfer coefficient. The method of tightness assessment is based on stabilization of infiltrated air coming under the influence of partial pressure difference inside and outside the body. The tightness coefficient shows how much infiltrated air falls per 1 $m^3$ of the test room per unit time at a temperature difference of 1 °C. The disadvantage of this method is that it takes into account relative humidity of air. So, the tightness coefficient of one car when tested in summer and winter will be different. This introduces a small error in the determination of the combined heat transfer coefficient.

The paper [8] defines the direction of cars perfection by improving the test procedure. The necessity to improve the test procedure by reducing the cost and time of implementation is noted. However, this paper does not detail the implementation of such a direction for testing the thermal properties of cars.

The work [9] presents promising directions of designing car body elements. They include the need to adapt them to transporting specialized cargoes that require a special temperature regime. However, experimental verification of providing the appropriate regime has been paid insufficient attention.

In [10], an estimation of thermal requirements for body sheathing and insulation materials used in car building is given. Test methods to determine the heat and mass transfer parameters of the car body are considered, and the need to pay special attention to determining the car body tightness in order to significantly improve the thermal properties of RC during major repairs is noted. Based on experimental data processing, a proportional relationship between the air flow through leaks and the reduced heat transfer coefficient of the car body is established, this relationship acquires individual characteristics for each car over the years. It is suggested to use the tightness factor as an indicator of tightness. This indicator is qualitative and suiTable only for comparing similar structures and does not contain quantitative characteristics.

Experimental studies are given in [11]. On the basis of the analysis of the methods of experimental control of thermal properties of the car body, proposals for their rational use in RRS operation are presented. Particular attention is paid to the search for new criteria for assessing the quality of the car body sheathing in terms of air infiltration. It is stressed that in the conditions of repair companies it is difficult to obtain the most informative heat and mass transfer indicators according to the results of thermal tests.

On the basis of this information, it can be summarized that there are currently a large number of methods for determining the thermal characteristics of RC based on the heat balance equation and they differ only in the way of obtaining primary information.

Part of the research can be solved by the implementation of new approaches to the experimental determination of heat and mass transfer indexes of the car body. The true heat transfer coefficient $\overline{K}$ and effective opening $F_{ek}$ are the most informative heat transfer indicators, which are independent of service life and test conditions.

## 3. The aim and objectives of the study

The aim of the study is to develop a procedure for the experimental determination of the parameters of the thermal state of insulated boxcars and increase their operation efficiency.

To achieve this aim, the following objectives must be accomplished:

– to perform analysis of operational performance, transportation volumes and conditions of cargos requiring protection from weathering and sharp temperature differences;

– to develop a procedure for separate determination of heat and mass transfer indices of the car body sheathing, true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$, based on the results of thermal tests;

– to carry out experimental studies to determine the true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$.

## 4. Theoretical analysis of operation features of insulated cars

In today's market economy, there are a large number of senders and consumers with small volumes of transportation. Conditions of carriage of a large part of cargoes do not require maintenance of temperature regime and only need protection against weathering and sharp temperature changes. The use of 5-car refrigerated sets for cargo transportation is inefficient since it is necessary to wait for the required amount of cargo transported with cooling, heating, ventilation or thermos. According to experts and scientists, preference is given to single refrigerator cars, which meet modern requirements of storage conditions for most of the goods carried by rail. Such refrigerator cars include insulated boxcars (IB). The modern IB fleet consists of thermos cars, insulated cars converted from refrigerator cars. There is also the development, testing and production of modern IB, research continues with further improvement of the insulating sheathing of the body and methods of experimental evaluation of their thermal properties.

Thanks to the existing theoretical and experimental developments, it is possible to comprehensively study the processes of heat and mass transfer through the body sheathing during cargo transportation, as well as thermal tests. This allows obtaining enough general information on the thermal state of RC and the level of the main operational factors influencing the thermal properties of the body sheathing [12].

However, known developments do not consider the possibility of separately determining heat transfer parameters by conduction and air exchange through the filtration openings of the car body sheathing. As the use of solely computational approaches is much more complicated and differences between computational and actual values obtained experimentally during tests are quite large. For separate determination of heat and mass transfer parameters, it is necessary to have data of thermal tests and to develop a procedure for calculating their values.

Separate determination of conductive heat transfer and tightness parameters makes it possible to investigate more closely the influence of operational factors on the thermal characteristics of the car body sheathing. There are two groups of the main factors that can be distinguished: permanent, regardless of service life, and non-permanent, related to the car life from construction or major repairs.

The first group includes average insulation temperature, train speed, intensity of solar radiation. In this case, some deterioration of thermal properties during the operation period is only due to intensification of heat transfer on the outer surfaces of the body. A more significant decrease in these properties is seen under the influence of factors of the second group: wetting, aging and insulation subsidence, as well as deterioration of body density due to the increase in operation period.

In the study, this is achieved by improving the methods of experimental determination of parameters of the thermal state of RC and the proposed thermal calculations with separate determination of heat and mass transfer parameters.

The standards governing the performance of railway RRS during cargo transportation establish that one of the key indicators characterizing the overall thermal properties of the RC body is the total heat transfer coefficient – $K_{pr}$. Railways have a car maintenance and repair system based on the application of the combined criterion when sending cars for scheduled repairs, which consists of the criterion of calendar duration (years) and the criterion of actual volume of work (thousand km).

With the existing maintenance and repair system, the operation of IB can be described by a random process $x(\tau)$, which characterizes its condition $S_i$ at an arbitrary time $\tau$ and takes the following values shown in Fig. 1.

$$x(\tau)\begin{cases} S_0\text{– when the IB is operable at time } \tau; \\ S_1\text{– when maintenance is performed at time } \tau; \\ S_2\text{– when diagnostic maintenance is performed at time } \tau; \\ S_3\text{– when routine repair is performed at time } \tau; \\ S_4\text{– when roundhouse servicing is performed at time } \tau; \\ S_5\text{– when major repair is performed at time } \tau; \\ S_6\text{– when major repair with life extension is performed at time } \tau. \end{cases}$$

Fig. 1. Existing IB maintenance system

Possible transitions of the processes $x(\tau)$ in IB operation are shown in Fig. 2.

Analysis of IB operation, taking into account the current structure of maintenance and repair with the type and nature of restoration work showed that in the process of operation, thermal tests to determine the total heat transfer coefficient of the body sheathing are performed only during major repairs, determining the body tightness during roundhouse servicing and major repairs and values of these indicators are not reflected in the car datasheet.

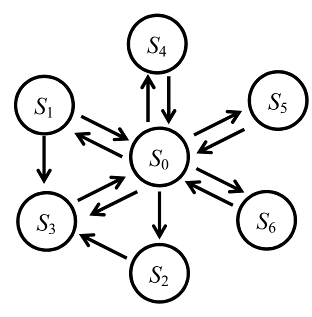


Fig. 2. Transition diagram of the process x(τ) during IB operation

$S_0$ condition of IB is ensured by proper organization of operation and maintenance [13].

IB transition from $S_0 - S_2 - S_3 - S_0$ condition is ensured by diagnostic maintenance and routine repair.

Technical diagnosis determines the actual need for a particular maintenance operation. In case of fault detection, the transition from $S_2$ condition to $S_3$ condition is carried out to perform current uncoupling repair.

IB transition from $S_0 - S_4 - S_0$, $S_0 - S_5 - S_0$, $S_0 - S_6 - S_0$ condition is provided by carrying out repair works at repair enterprises. The progress of the process $x(\tau)$ depends on the amount of work actually completed after construction or major repair. The process $x(\tau)$ in this case proceeds from $S_0 - S_5 - S_0$, $S_0 - S_6 - S_0$ condition, taking into account that all structural elements of IB are completely restored during major repairs.

## 5. Theoretical processes of heat and mass transfer through the insulated car body sheathing

Development of a design scheme for the study of heat and mass transfer through the car body sheathing is based on the physical nature of the process. The mathematical model determines the thermal parameters in the real thermal process during thermal tests.

The design scheme and physical essence of the mathematical model of the thermal state of IB under freight transportation conditions based on $\bar{K}$ and $F_{ek}$ indices are also considered.

The study examines the classic design of IB, where using the hierarchy and decomposition (block) methods, the thermal characteristics of the body sheathing are determined by the heat and mass transfer indicators of groups of solid insulation, thermal bridges and seals. Formulation of the problem of analyzing thermal properties of the body sheathing structure is based on a generalized heat transfer equation for stationary heat transfer conditions in the form of thermal balance

$$Q = K \cdot S\left(\theta_e - \theta_i\right), \tag{1}$$

where $Q$ is the heat flow through the car body sheathing, W; $K$ is the total heat transfer coefficient, W/m$^2$K; $S$ is the average body surface area, m$^2$; $\Theta_e$ is the ambient temperature, K; $\Theta_i$ is the temperature inside the car, K.

The body of the insulated car is a rather complex spatial system. Numerous metal elements of a rather complex geometric shape in the body sheathing make it almost impossible to accurately calculate the heat transfer coefficient of the body. Heat transfer through the car body sheathing is accompanied by processes of unorganized natural air exchange due to leaks. These processes cause additional heat gain (heat loss) and impair the body's thermal properties.

Therefore, it is possible to state only about the methods that give the most approximate calculated and true average thermal characteristics of the car body.

In this regard, it seems advisable to use control methods that would allow estimating the thermal performance of the car body through tests and thermal calculations. The most informative indices of thermal properties of RC are the true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$. It is proposed to determine their values in the real thermal process by the results of thermal tests to determine the reduced heat transfer coefficient by the method of internal heating with setting to the equilibrium thermal regime and tightness factor, by measuring the volume of air coming through leaks when constant overpressure is created in the car body.

When determining the true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$, the data obtained during the thermal process experiment were used. The experiment consists in heating the air in the cargo space of the car and measuring the volume of air flow through leaks when constant standard overpressure of 49 Pa is created in the body. On the basis of regulatory documents of thermal tests, a mathematical model and procedure were developed for separate determination of heat and mass transfer indices such as true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$ of the insulated car body sheathing [14].

The scheme of interaction of individual elements of the thermal system with each other and with the environment is shown in Fig. 3.

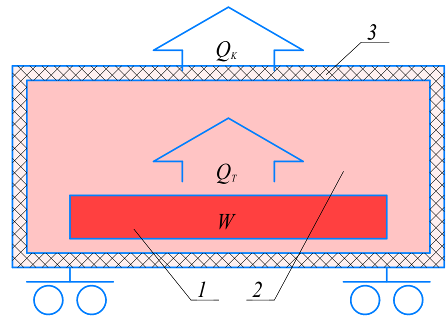


Fig. 3. Scheme of interaction of individual elements of the car thermal system during tests: 1 — electric furnace; 2 — cargo space of the car; 3 — body sheathing; W — power consumption, W·h; $Q_T$ — coolant flow, W; $Q_K$ — heat flow through the body sheathing into the environment, W

Based on the scheme of interaction of individual elements of the thermal system during tests "cargo space – heat source – coolant – body sheathing – environment", a mathematical model and procedure for separate determination of heat and mass transfer indicators were developed. The mathematical model includes a system of balance equations, characteristics of the thermal system, system of constraints, and heat-mass transfer indicators.

The system of balance equations contains:

a) equation of thermal balance of the system

$$\begin{cases} W_{ne} = K_{pr} \cdot S\left(\theta_e - \theta_i\right), \\ pv = \left(m - m_f\right) R\left(\theta_e - \theta_i\right), \\ W_{ne} = Q - Q_f, \end{cases} \tag{2}$$

where $W_{ne}$ is the power of heating devices, W; $p$ is the absolute air pressure, Pa; $v$ is the volume of cargo space, m$^3$; $m$ is the mass of air in the cargo space of the RC body at the beginning of heating, kg; $m_f$ is the mass of air losses through the filtration openings during heating, kg; $Q_f$ is the heat flow of air filtration, W;

b) equation of heat flow through the body sheathing due to conductive heat transfer

$$\begin{cases} Q = \bar{K} \cdot S\left(\theta_e - \theta_i\right), \\ \bar{K} = \dfrac{1}{F} \sum\limits_{i=1}^{n} K_i \cdot S_i, \\ K_i = \dfrac{1}{R_a} + \dfrac{1}{R_\lambda}, \end{cases} \tag{3}$$

where $R_a$ is convection thermal resistance, m$^2$K/W; $R_\lambda$ is conduction thermal resistance, m$^2$K/W;

c) equation of heat flow from air filtration through the body leaks

$$\begin{cases} Q_f = L_f \cdot \rho_e \left(h_e - h_i\right), \\ L_f = F_{ek} \cdot \omega, \\ \omega = \sqrt{2\left(h_e - h_i\right)}, \end{cases} \tag{4}$$

where $L_f$ is the volume air flow through filtration openings, m$^3$/s; $\rho_e$ is the air density, kg/m$^3$; $h_e$ is the enthalpy of air inside the body, J/kg; $h_i$ is the enthalpy of air outside the body, J/kg; $\omega$ is the velocity of air flow through filtration holes, m/s;

d) equation of air flow through filtration openings during body tightness tests when constant standard overpressure is created in the body

$$\begin{cases} L_{ct} = \omega_{ct} \cdot F_{ek}, \\ \omega_{ct} = \sqrt{\dfrac{2\Delta p}{\rho}}, \\ F_{ek} = \dfrac{L_{ct}}{\omega_{ct}}, \end{cases} \tag{5}$$

where $L_{ct}$ is the volume air flow through filtration openings, at overpressure $\Delta p$, m$^3$/s; $\omega_{ct}$ is the velocity of air flow through filtration openings, at overpressure $\Delta p$, m/s; $F_{ek}$ is the effective opening in the body sheathing, m$^2$; $\Delta p$ is the standard overpressure in the cargo space of the body, Pa; $\rho$ is the air density, kg/m$^3$.

Heat-mass and design parameters change only within the possible and technically feasible states of energy carriers and structures, as well as within technically possible initial and operational states of materials in system elements. These constraints are shown as the inequalities of the parameter set [15]

$$\theta_e^{*} \le \theta_e \le \theta_e^{**}, \quad \bar{K}^{*} \le \bar{K} \le \bar{K}^{**}, \quad F_{ek}^{*} \le F_{ek} \le F_{ek}^{**}.$$

One and two stars in the index show the minimum and maximum parameter values, respectively.

The true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$ are taken as heat and mass transfer indicators of the thermal system.

For separate determination of heat and mass transfer indices such as true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$, the procedure is developed (Fig. 4).

Also, the formulation of the problem of studying the rational use of IB according to the thermal properties of the body sheathing is supplemented by a generalized mathematical model of the "environment – car body – cargo" system (E – CB – C). By the accepted analogy of division of the thermal system into separate elements, the highest level is the overall solution for the thermal system (E – CB – C). The next levels are body sheathing and cargo, for which a sufficient number of specific solutions have been accumulated at present.

The structure of the thermal system (E – CB – C) is shown in Fig. 5.

When solving various problems related to RC operation, there are first of all questions related to changes in cargo temperature in the cargo space of the car due to the amount of heat entering the car in summer and the amount of heat lost in winter.

The criteria for efficiency of this system are:

– heat transfer surface area of the car body, $H$, m$^2$;
– true heat transfer coefficient of the body sheathing, $\bar{K}$, W/m$^2$K;
– effective opening, $F_{ek}$, m$^2$;
– cargo thermal equivalent, $W_{te}$, J/K;
– ambient temperature, $\theta_i$, K;
– cargo temperature, $\theta_e$, K.

Initial data

$$\{S,\ \theta_i,\ h_i\}$$

Test parameters

$$\{\theta_e,\ \theta_i,\ W_{ne},\ K_{pr},\ \rho,\ L_{ct}\}$$

Solution of heat and mass transfer parameters determination

$$\begin{Bmatrix} F_{ek} = \dfrac{L_{ct}}{\omega_{ct}}, \\ \omega_{ct} = \sqrt{\dfrac{2\Delta P}{\rho_e}} \\ Q_f = F_{ek} \cdot \omega_{ct} \cdot \rho_e \left(h_e - h_i\right) \\ Q = W_{ne} + Q_f \\ \bar{K} = \dfrac{Q}{S\left(\theta_e - \theta_i\right)} \end{Bmatrix}$$

Results of separate determination of heat and mass transfer parameters

$$\begin{Bmatrix} \text{True heat transfer coefficient}, \bar{K} \\ \text{Effectiveopening}, F_{ek} \end{Bmatrix}$$

Fig. 4. Procedure of separate determination of the heat and mass transfer index during RC thermal tests

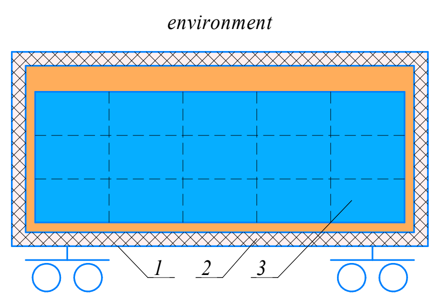


Fig. 5. Structure of the thermal system "environment – cargo space of the car – cargo": 1 – body sheathing; 2 – insulation; 3 – cargo

As the basic mathematical description of the system structure we use the equation of thermal balance

$$Q_{tot} = Q_1 + Q_2 + Q_3, \tag{6}$$

where $Q_{tot}$ is the total amount of heat, W; $Q_1$ is the amount of heat transmitted by conduction through the body sheathing due to the difference in air temperatures outside and inside the cargo space, W; $Q_2$ is the amount of heat entering the cargo space of the car due to air exchange through cargo space leaks, W; $Q_3$ is the amount of heat absorbed by the outer surface of the sheathing from the action of solar radiation, W.

We make a system of balance equations of the system elements

$$\begin{cases} Q_1 = \bar{K} \cdot S \cdot (\theta_i - \theta_e), \\ Q_2 = F_{ek} \cdot \rho \cdot C(\theta_i - \theta_e) \cdot \sqrt{2C \cdot (\theta_i - \theta_e)}, \\ Q_3 = \bar{K} \cdot S \cdot \Delta\theta_{ek}, \end{cases} \quad (7)$$

where $\bar{K}$ – true heat transfer coefficient, W/m²·K; $S$ – surface area of the car body sheathing, m²; $\theta_з$ – ambient temperature, K; $\theta_в$ – air temperature inside the cargo space, K; $F_{ek}$ – effective opening, m²; $\rho$ – air density, kg/m³; $C$ – air heat capacity, J/kg·K; $\Delta\theta_{ek}$ – conditional equivalent increase in ambient temperature due to solar radiation, deg [18].

The total amount of heat entering the cargo space of the car depends on the following parameters

$$Q = f\left(\bar{K}, S, F_{ek}, C, \rho, \Delta\theta_{ek}, \theta_i, \theta_e\right), \quad (8)$$

where $C$ is air heat capacity, J/kg·K; $\rho$ is air density, kg/m³; $\Delta\theta_{ek}$ is the conditional equivalent increase in ambient temperature due to solar radiation, deg.

Changes in cargo temperature in the cargo space of the car, with changes in atmospheric air temperature are determined by the relationship [15]

$$Q_{tot} = W_{te} \cdot \Delta t \cdot \tau^{-1}, \quad (9)$$

where $W_{te}$ is cargo thermal equivalent, J/kg; $\Delta t$ is cargo temperature change, K; $\tau$ is the duration of heat action, s.

The constraints shown as the inequalities of the parameter set

$$\theta_e^{\min} \le \theta_e \le \theta_e^{\max},$$

$$W_{te}^{\min} \le W_{te} \le W_{te}^{\max},$$

$$\Delta t^{\min} \le \Delta t \le \Delta t^{\max}.$$

In the case of cargo transportation in winter, the amount of heat lost from the car is determined by the effect of the processes of heat transfer through the body sheathing due to the difference in air temperatures inside the cargo space of the car and the outside air and air exchange through the body leaks. To determine the total heat loss from the car in winter, we use the equation to determine the amount of heat that enters the cargo space in summer, taking into account changes in heat flow direction. Using the above formulas and MS Excel software, graphical dependencies are developed (Fig. 6).

The values of $\bar{K}$ and $F_{ek}$ obtained experimentally for the 11-1807-04 car were used in the construction of these graphs. The thermal equivalent is obtained in accordance with the nomenclature of cargo, which is allowed to be transported by the abovementioned vehicle.

The minimum and maximum values of the thermal equivalent of cargo are determined depending on its thermophysical properties. The difference in ambient temperatures corresponded to the range from minus 40 °C to plus 40 °C. Using the above formulas and MSExcel tools, it is possible to construct graphical dependences of changes in the temperature of any cargo under transportation conditions in refrigerator cars.

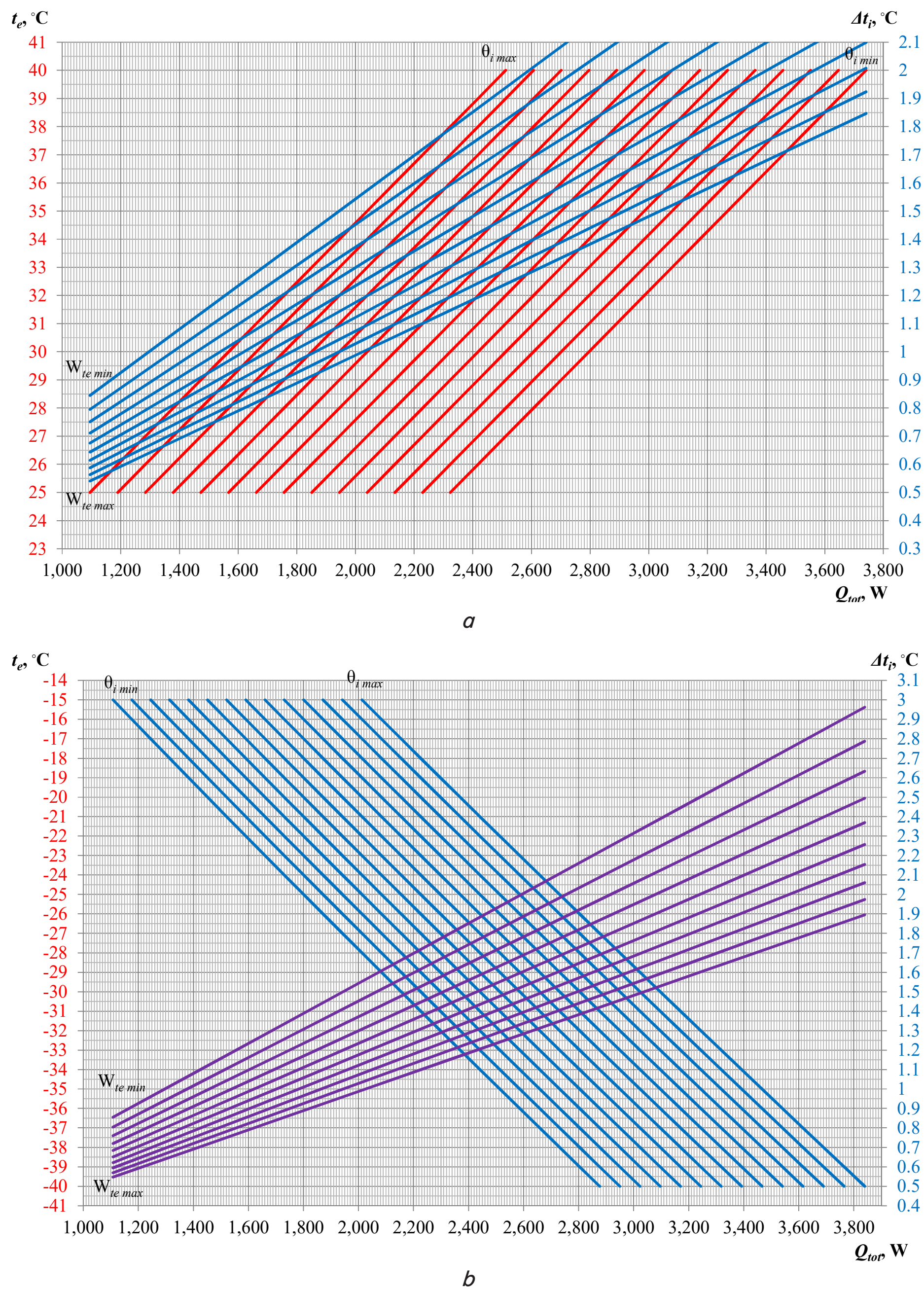


Fig. 6. Binary dependences of cargo temperature changes during transportation in IB: *a* – in summer; *b* – in winter

## 6. Experimental evaluation of compliance of the developed mathematical model and theoretical studies

The experiment was conducted on a full-scale prototype of 11-1807-04 4-axle insulated boxcar (Fig. 7), which is intended for the transportation of perishable and non-perishable goods that are thermally prepared for loading. For heat protection of walls, roof and floor, heat-shielding material polyurethane foam is used, which is protected from damage by metal facing sheets. Basic specifications of the car are given in Table 1.

Fig. 7. Prototype of 11-1807-04 insulated boxcar manufactured by Azovobschemash plant (Ukraine)

Table 1

Basic specifications of 11-1807-04 car

| Indicator (dimension, size), units of measurement | Value |
|---|---|
| Load capacity, t | 58 |
| Body space, $m^3$ | 145 |
| Inside body length, mm | 18,360 |
| Inner body width, mm | 2,750 |
| Inner body height, mm | 2,550 |
| Roof area, $m^2$ | 68.73 |
| Clear door opening dimensions, mm | 2,294×2,850 |

The tests were conducted in a specialized room. The main task of the thermal tests was to determine the value of the reduced heat transfer coefficient $K_{pr}$ and tightness indicator $L_{ct}$. The value of the reduced heat transfer coefficient of the body sheathing $K_{pr}$ was determined by the method of heating the air in the cargo space of the car. The tightness indicator $L_{ct}$ was determined by the air flow rate under standard overpressure.

During the thermal tests, the following parameters are controlled:

– temperature inside the cargo space;

– temperature outside the cargo space of the car;

– time of cargo space heating;

– power consumption.

During the tightness test, the following parameters are controlled:

– draft and head gauge readings;

– air flow rate;

– test time.

As a result of the thermal tests, the value of the reduced heat transfer coefficient of the car body sheathing was obtained, which is $K_{pr}$=0.259 W/m$^2$K. The test data are given in Table 2.

Table 2

Results of experimental studies of 11-1807-04 insulated boxcar during thermal tests

| Measurement number | Measurement time, h | Average value ($t^e_{av}$, °C) of measurements | Average value ($t^i_{av}$, °C) of measurements | Meter readings, W |
|---|---|---|---|---|
| 1 | 23:00 | 5.55 | 51.875 | 222.30 |
| 2 | 00:00 | 5.55 | 51.842 | 224.95 |
| ... | ... | ... | ... | ... |
| 11 | 10:00 | 5.05 | 51.483 | 251.20 |
| 12 | 11:00 | 5.05 | 51.475 | 253.85 |

As a result of the tightness tests, the tightness indicator of the car body was obtained, which is determined by the air flow through the body leaks and is $L_{ct}$=51.71 m$^3$/h, at a standard overpressure of 49 Pa.

The data obtained during the tests are given in Table 3.

Table 3

Results of the car tightness test

| Measurement number | TNMP-52 draft and head gauge readings, PA | Measurement time, min | Gas meter readings, $m^3$ | | Amount of air during the test, $m^3$ | Air flow rate, $m^3$/h |
|---|---|---|---|---|---|---|
| | | | initial | final | | |
| 1 | 49 | 6 | 691.25 | 696.43 | 5.18 | 51.8 |
| 2 | 49 | 10 | 691.25 | 699.85 | 8.6 | 51.6 |
| 3 | 49 | 30 | 691.25 | 717.12 | 25.87 | 51.74 |
| Average | | | | | | 51.71 |

According to the results of the thermal tests of 11-1807-04 car, the developed procedure was used to determine the parameters of conductive heat transfer $\bar{K}$ and tightness $F_{ek}$ of the body sheathing (Fig. 3).

The standard value of the conductive heat transfer index $\bar{K}$, established in the car design and determined by the results of the test and developed procedure, coincides with the error of 5.6 %. The comparative analysis of the obtained data shows sufficient reliability of the theoretical and experimental researches.

## 7. Discussion of ways to increase the operation efficiency of insulated boxcars

Current performance indicators indicate that IB is the most numerous component of refrigerated rolling stock (RRS). The number of IB in the total RC fleet is 87.1 %. The volume of transportation in IB reaches 91 % of the total volume of freight transported by RRS.

Especially in conditions of changing nomenclature, methods and volumes of cargo transportation. These cars, unlike refrigerated ones, do not have a refrigerating and heating system that supports the temperature regime of cargo transportation on the route.

Temperature regime maintenance requires special sheathing of the cargo space of the car. Thermal insulation is crucial in this case. The thermal insulation layer has a large thermal resistance, which dramatically reduces external heat gain and allows long-term temperature and humidity conditions to be maintained in the car. Thermal insulation, sufficiently developed in thickness and volume, prevents air exchange with the environment, which also reduces heat entry into the cargo space of the car.

An important role in ensuring the efficient use of cars is played by effective evaluation of thermal performance under operating conditions. At present, it is possible to talk about thermal indicators of RC only at the initial stage of operation after release from the manufacturer. This is due to the fact that new rolling stock is subject to careful testing and research to determine the main indicators and characteristics, including load capacity, tare-load ratio, axle load, gross weight, car capacity, average heat transfer coefficient, tightness.

But after two or three years of car operation it is impossible to assert confidently enough about performance and thermal properties of the car body sheathing. This problem is even more complicated after roundhouse servicing or major repairs. This is evident from the previously given maintenance system.

Existing RC have technical datasheets, which mainly reflect general baseline data on the parameters of the production car and no indicators that determine the thermal properties of the body sheathing and thermal insulation. We suggest that car datasheet should contain data where thermal properties, serviceability limits, insulation reliability, production, repair and operation quality can be found at any time of operation. At the organizational level, it is advisable to include the characteristics reflecting the thermal properties of the body sheathing in the existing structure of the technical datasheet of an insulated boxcar.

For newly built cars, the following thermal characteristics can be introduced in the technical datasheet:

– reduced heat transfer coefficient ($K_{pr}$), characterizing the total heat and mass exchange of cargo and air in the cargo space of the car with the environment;

– tightness factor – volume air flow rate under the standard overpressure of 49 Pa ($V_{ct}$) in the car body.

For cars that have undergone major repairs, the following is additionally introduced in the datasheet:

– true (mainly conductive) heat transfer coefficient of the car body sheathing $\left(\bar{K}\right)$;

– effective opening ($F_{ek}$), which is a geometric indicator of tightness.

To find the values of $\bar{K}$ and $F_{ek}$, it is proposed to use the procedure developed in the study for separate determination of heat and mass transfer parameters according to the results of thermal tests by the method of heating the air in the cargo space and volume air flow rates under standard overpressure in the car body.

The above results of the experimental study confirm the compliance of the developed theoretical provisions. Comparison of the true heat transfer coefficient $\bar{K}$ obtained at the design stage and $\bar{K}$ calculated according to the results of experimental studies coincides with the error of 5.6 %. This gives grounds to claim that the thermal properties of the body designed by the developers are fully implemented by the manufacturers at the production stage.

The new car is examined by the most accurate method of equilibrium thermal regime, which reliably determines the reduced heat transfer coefficient of the body sheathing.

Even having the reduced heat transfer coefficient, it is advisable to have an independent assessment of car tightness. Car tightness is estimated by the air flow rate while maintaining the overpressure of 49 Pa inside the car.

Much more complicated is the issue of determining the thermal index of IB after undergoing major repairs. This is due to the need to check each car. Quality control of IB major repairs should provide for a minimum number of regulated tests of cars that do not interfere with technological repairs and do not significantly delay the release of repaired cars. It is considered advisable to carry out two experimental thermal researches of cars at car repair enterprises:

1) by accelerated method to determine the heat transfer coefficient of the car body;

2) by the method of creating standard overpressure in the car body to determine the tightness factor.

An important methodological step of further investigation is to determine the value of the water equivalent of the insulation sheathing of the car body ($W$). This makes it possible to create a more convenient and productive method of non-stationary modes for determining the heat transfer coefficient of the car body. $W$ values can be determined by performing special experiments, and the values of the heat transfer coefficient must be known. The most convenient and reliable method is the method of rapid heating of the air in the car, followed by natural cooling.

It is proposed to characterize the serviceability limits of the repaired car on the basis of construction and analysis of graphical dependences of changes in cargo temperature on the difference of atmospheric air temperatures in transportation conditions taking into account experimental determination of the thermal performance of the car body sheathing, ambient temperature difference and thermal equivalent of cargo.

For the construction of these graphical dependencies, the system of balance equations (7) of the thermal state of the freight car can be used.

The basic principles and methodological bases of IB certification are not generally accepted. Moreover, their implementation requires considerable efforts of research organizations and car building and car repair enterprises.

However, there is reason to believe that improving the methods of experimental determination of the parameters of the thermal state of IB and introduction of thermal certification will significantly improve the efficiency of cars in operating conditions.

## 8. Conclusions

1. Analysis of performance indicators of refrigerated rolling stock gives grounds to state that in today's conditions the volumes, nomenclature and conditions of cargo transportation change significantly. The volumes and nomenclature of cargo are growing, which requires only protection against precipitation and sharp temperature changes during transportation. For the transportation of these goods, priority is given to insulated boxcars capable of providing the necessary protection and storage conditions during transportation. According to the current state of freight transportation, the fleet of refrigerated rolling stock is now sufficiently structured and approaches are being improved to ensure the efficient functioning of refrigerator cars.

2. For separate determination of heat and mass transfer parameters, the true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$, experimental conditions of the thermal process of air heating in the cargo space of the car body and measurement of the volume of air flow through leaks under constant standard overpressure of 49 PA in the body are

used. On the basis of regulatory documents of thermal tests, a mathematical model and procedure were developed for separate determination of heat and mass transfer indices, the true heat transfer coefficient $\bar{K}$ and effective opening $F_{ek}$, of the insulated car body sheathing.

3. In the experimental verification of the developed theoretical provisions and mathematical model using thermal tests of 11180704 insulated boxcar, values of the true heat transfer coefficient $\bar{K}$, found during the car design and obtained by experimental studies, the results coincide with the error of 5.6 %. This gives reason to claim that the mathematical model and the procedure for separate determination of heat and mass transfer indices in a real thermal process are sufficiently reliable.

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