ISSN 2307–3489 (Print), ISSN 2307–6666 (Online)

Наука та прогрес транспорту. Вісник Дніпропетровського
національного університету залізничного транспорту, 2013, № 6 (48)

UDC 628.84:519.6

I. YU. KHOMENKO[1*]

[1*]Dep. «Cars and Carriages' Economy», Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, Lazaryan St., 2, Dnipropetrovsk, Ukraine, 49010, tel. +38 (097) 677 84 70, e-mail irina.in_ua@yahoo.com

MATHEMATICAL MODELING OF UNSTEADY HEAT EXCHANGE IN A PASSENGER CAR

Purpose. Existing mathematical models of unsteady heat exchange in a passenger car do not satisfy the need of the different constructive decisions of the life support system efficiency estimation. They also don't allow comparing new and old life support system constructions influence on the inner environment conditions. Moreover quite frequently unsteady heat exchange processes were studied at the initial car motion stage. Due to the new competitive engineering decisions of the life support system the need of a new mathematical instrument that would satisfy the mentioned features and their influence on the unsteady heat exchange processes during the whole time of the road appeared. The purpose of this work is creation of the mathematical model of unsteady heat exchange in a passenger car that can satisfy the above-listed requirements. **Methodology.** For the assigned task realization system of differential equations that characterizes unsteady heat exchange processes in a passenger car was composed; for the system of equations solution elementary balance method was used. **Findings.** Computational algorithm was developed and computer program for modeling transitional heat processes in the car was designed. It allows comparing different life support system constructions influence on the inner environment conditions and unsteady heat exchange processes can be studied at every car motion stage. **Originality.** Mathematical model of unsteady heat exchange in a passenger car was improved. That is why it can be used for the heat engineering studying of the inner car state under various conditions and for the operation of the different life support systems of passenger cars comparison. Mathematical modeling of unsteady heat exchange in a passenger car was made by the elementary balance method. **Practical value.** Created mathematical model gives the possibility to simulate temperature changes in passenger car on unsteady thermal conditions with enough accuracy and to introduce and remove additional elements to the designed model. Thus different constructive decisions of the life support system can be estimated by the mathematical experiment.

Keywords: mathematical modeling; passenger car; unsteady thermal processes; life support system

Introduction

Nowadays mathematical modeling approach is widely used for different constructive decisions efficiency estimation. This way of modeling allows reconstructing real-life equipment operation and influence of different factors on it. In addition mathematical models can be applied to make a comparison of variant constructive decisions among themselves [11]. Thereby creation of a mathematical model of unsteady heat exchange processes in a passenger car on transitional operation modes of the life support system is a significant scientific problem. That is why the creation of such model is a purpose of this article.

In the papers [4, 5, 6] mathematical modeling of unsteady heat exchange processes in a passenger car was considered. Integral mathematical model of transient processes was created. Generalized model of unsteady heat mode, that was given in [4] is based on the assumption that the temperature of inside walls of the compartment of railway carriage and the temperature of the inside air are equal. This hypothesis decreases considerably the accuracy of the modeling, especially on the initial phase of unsteady process, when value and sometimes direction of a heat flows increases dramatically. On this phase the difference between wall and air temperature is significant and characterizes the nature of the heat exchange processes.

Numerical approaches of the unsteady heat exchange problems solving are wildly used [2, 14]. Contemporary methods of heat and mass exchange processes calculation are based on differential equations of moving, continuity, heat conductivity and diffusion, which were derived for the small volumes of material [13]. Differential equation of heat conductivity has variety of solutions. Specifics of every concrete process are adjusted for single value requirements, which consist of geometric, physical and time boundary conditions.

Purpose

The purpose of this work is creation of the mathematical model of unsteady heat exchange in a passenger car that can be used for the different constructive decisions of the life support system efficiency estimation on every stage of the road.

Methodology

For the assigned task realization system of differential equations that characterizes unsteady heat exchange processes in a passenger car was composed; for the system of equations solution elementary balance method was used.

Mathematical modeling

At a physical point of view a passenger car equipped with an air conditioning system is an open self-regulating thermodynamic system. Controlled variables in this system are: temperature t, humidity φ and the inner air structure. To handle them atmospheric air is used. It is forced through the car and through the air conditioner [4].

Interior, systems and equipment of the car influence the heat exchange processes behavior. In the heat exchange processes convective, radiative and conductive heat transfer are combined [12]. Great number of used materials that have different heat capacity; ramified surface of the inner car interior and intensive passenger saloon ventilation promote to do this.

Assumptions

The following assumptions are made to simplify the mathematical model:

Temperature field of the air in the main, central zone of the open compartment, with the help of the free and forced convection stays close to steady in spite of the fact that the air heat conductivity is very low. That is why during the modeling of the heat exchange between the air and the walls heat model with isothermal core, which is circled with a heat-insulated cover, can be used. Cover heat capacity can be neglected while its specific conductivity coincides with the heat-transfer coefficient. Such heat model of isothermal core which is circled with a heat-insulated cover is often used in the heat exchange theory [7].

Heat and mass exchange processes are considered as if they occur independently from each other.

Heat flow from the solar radiation will be counted as if it is applied directly to the inner volume of the open compartment (notably it is modeled as a three-dimensional heat source) [14].

Flow G_x of a cold air from the air conditioner or from the cold accumulator, which comes to the passenger saloon with the temperature t_x, relative humidity φ_x and specific enthalpy i_x, agitates instantly inside the car and can absorb the heat of the heated inner walls and heat and moisture emissions from the passengers. Notably, heat flow, which is taken by the air conditioner, is considered as volume heat outflow.

Model formulation

Heat flow, which is absorbed by the cooled air during its way through the passenger saloon, evaluates the air temperature change and consists of the next components:

$$mc_p\frac{dt}{d\tau}=Q_{wall}+Q_{solrad}+Q_{in}+Q_{evap}+Q_{outair}-Q_{cond}\,, \quad (1)$$

where m – air mass in the car, c_p – air heat capacity;

The heat flow that is given by the all inner elements and the car walls:

$$Q_{wall}=\sum\alpha F_{wall}\left(t_{wall}\left(\tau\right)-t_{air}\left(\tau\right)\right),$$

where α – heat-transfer coefficient, F_{wall} – surface area of the wall or inner interior element, t_{wall} – temperature of the wall or inner interior element, τ – time, t_{air} – air temperature of the passenger saloon; Q_{solrad} – heat flow from the solar radiation; Q_{in} – heat flow that comes from passengers and inner equipment. It is constant and its value depends on passengers' number and on the installed equipment; Q_{evap} – heat flow that comes to the air directly from the passengers moisture evaporation; Q_{cond} – heat flow that withdraws by the air conditioner; Q_{outair} – heat flow that comes from the outdoor air that is inputted to the passenger saloon and that is determined as its enthalpy change:

$$Q_{outair}=G_{out}\rho\left(i_{out}-i_{in}\right),$$

where G_{out} – amount of the outdoor air that is inputted to the passenger saloon, ρ – air density, i_{out} and i_{in} – outdoor and indoor air heat content.

Thus heat balance combined equation for the air in the passenger saloon of the car on unsteady mode comes from the general substance equation and can be calculated by the following correlation:

$$mc_p \frac{dt}{d\tau} = \sum \alpha F_{wall} \left(t_{wall}(\tau) - t_{air}(\tau) \right) + Q_{solrad} +$$

$$+ Q_{in} + Q_{evap} + G_{out} \rho \left(i_{out} - i_{in} \right) - Q_{cond} . \quad (2)$$

On the other hand heat conduction in the elements of the car construction is determined by the thermal conductivity processes typical for solid bodies and in general case is described by the equation:

$$c_k \rho_k \frac{\partial t_k}{\partial \tau} = div \left(\lambda_k \; gradt_k \right), \quad (3)$$

where $k = 1, 2, 3$ – indices of corresponding construction elements; c – heat capacity; ρ – specific density; λ – thermal conductivity.

Boundary conditions

Boundary conditions that determine heat exchange between elements surface and the inner and outdoor air have the appearance:

$$\left(\lambda_{wall} \frac{\partial t_{wall}}{\partial n} \right)_F + \alpha \; (t_{air} - t_{wall}) = 0 , \quad (4)$$

where α – heat-transfer coefficient.

Thus heat balance equations (2), (3) and equation (4) describe the researched thermal processes. In order to solve the composed system of the differential equations the elementary balance method was chosen [1, 3, 8, 10]. This method also can be met in literature as the direct finite element method, global balance or power balance method [8] and is a special case of the residual method.

Heat penetration per second to the element is characterized by the heat exchange conditions on its boundaries or by the conditions on the boundaries between constructional elements i and j:

$$\left(\lambda \frac{\partial t}{\partial n} \right)_{i,F} = - \left(\lambda \frac{\partial t}{\partial n} \right)_{j,F} ,$$

where $t_{ij} = t_{ji}$ (condition for continuity of the temperature);

index F shows that values refer to the surface of the contact Fij between the elements i and j. Temperature approximation difference on the border is based on the idea that temperature changes linear on the segment δ_{ij} along the normal between centre of mass of i-element and surface of contact:

$$\frac{\partial t}{\partial n} = \frac{t_i - t_{ij}}{\delta_{ij}} . \quad (5)$$

From (5) we get equation for the temperature on the boundary of two neighboring elements:

$$T_{ij} = \frac{\frac{\lambda_{ji}}{\delta_{ji}} t_j + \frac{\lambda_{ij}}{\delta_{ij}} t_i}{\frac{\lambda_{ji}}{\delta_{ji}} + \frac{\lambda_{ij}}{\delta_{ij}}} ,$$

and equation for the heat flow from i-element to j-element

$$q_{ji} = \frac{1}{\frac{\delta_{ji}}{\lambda_{ji}} + \frac{\delta_{ij}}{\lambda_{ij}}} \left(t_j - t_i \right) .$$

During calculations we determine coefficients of thermal conductivity at average temperatures on the segments δ_{ij} between the centre of mass of the elements and the surface of contact. This can demand several iterations.

In the case when we discuss heat exchange between the constructional element and the inner air of the passenger saloon, general equations for boundary temperatures and heat flows are true

$$t_{ij} = \frac{r_{ij} t_j + r_{ji} t_i}{r_{ij} + r_{ji}} ,$$

$$q_{ji} = \frac{1}{r_{ij} + r_{ji}} \left(t_j - t_i \right), \quad (6)$$

where r_{ij} and r_{ji} – coefficients of thermal resistance between neighboring elements. They are calculated as:

$$r_{ij} = \begin{cases} \alpha^{-1}, when\ i\text{-}element\ is\ inner \\ open\ compartment\ volume \\ \frac{\delta_{ij}}{\lambda_{ij}}, when\ i\text{-}element\ is\ constructonal\ element \end{cases}$$

Whereas (6), heat balance equation (3) becomes:

$$m_i c_i \frac{dt_i}{d\tau} = \sum_{j=1}^{N_{nb,i}} b_{ji}\left(t_j - t_i\right),$$

where coefficients b_{ij} is $F_{ij} / \left(r_{ij} + r_{ji}\right)$, and among number of neighbors $N_{nb,i}$ can be constructional elements and the open compartment inner volume.

Equation (2) for the inner volume of the car in this case will be:

$$mc_p \frac{dt}{d\tau} = \sum_{j=1}^{N_{nb,i}} b_{ji}\left(t_j - t_i\right) + Q_{solrad} + Q_{in} +$$

$$+ Q_{evap} + G_{out}\rho\left(i_{out} - i_{in}\right) - Q_{cond},$$

Knowing boundaries elementary areas value of the time step-interval Δτ should be chosen from the condition of quasiequilibrium process К=ΔP/P<1, where ΔP – parameter value change (in our case of the temperature) between neighboring areas; P – parameter value in a calculation element.

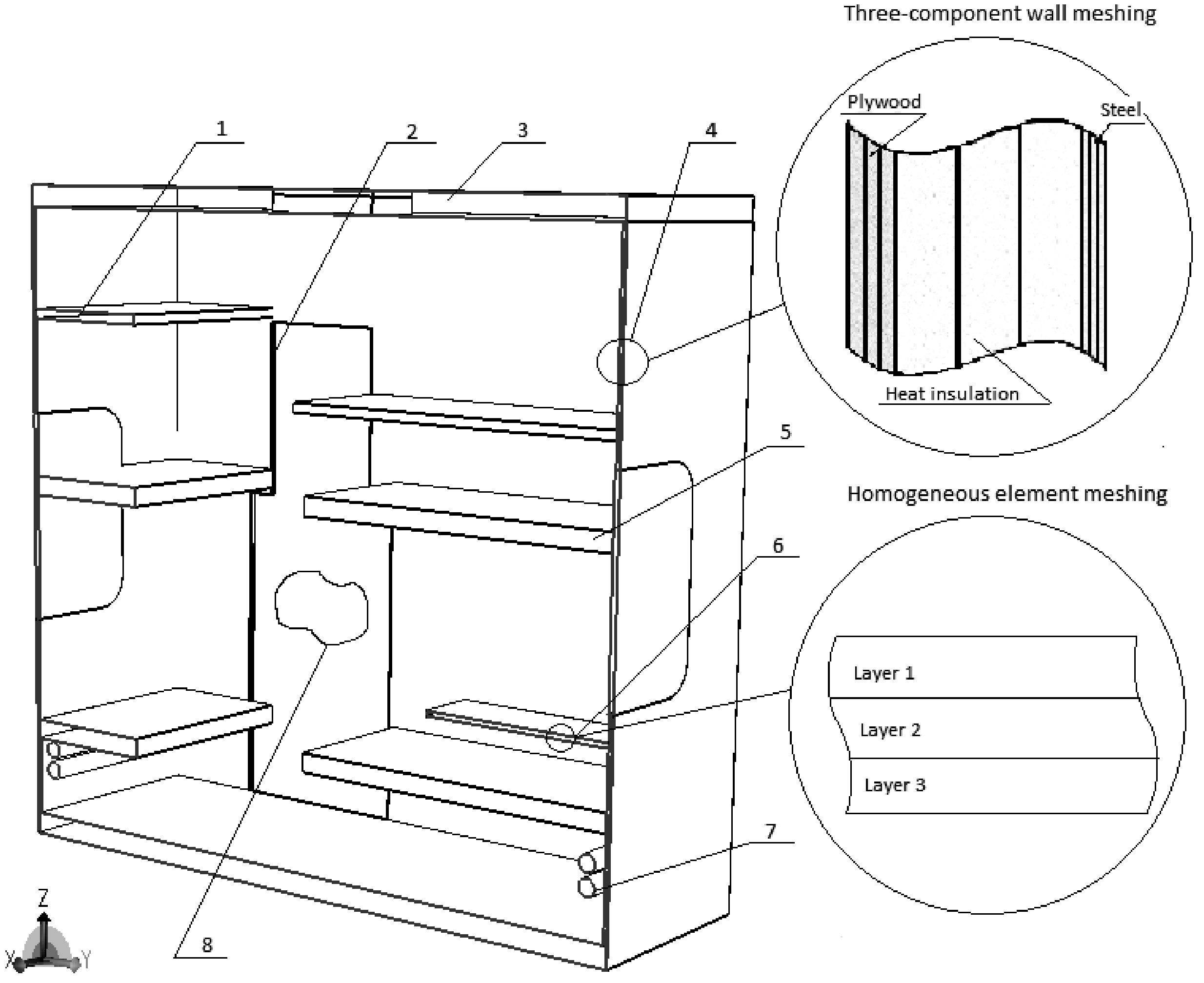

Fig. 1. Three-dimensional model of the open compartment of the second-class sleeping carriage:
1 – luggage rack ($c = 0.435 \, kJ/kg \cdot K$); 2 – inner partition ($c = 2.5 \, kJ/kg \cdot K$); 3 – ceiling ($c_1 = 0.435 \, kJ/kg \cdot K$, $c_2 = 0.879 \, kJ/kg \cdot K$, $c_3 = 2.512 \, kJ/kg \cdot K$); 4 – external walls ($c_1 = 0.435 \, kJ/kg \cdot K$, $c_2 = 0.879 \, kJ/kg \cdot K$, $c_3 = 2.512 \, kJ/kg \cdot K$); 5 – sleeping berth ($c = 1.256 \, kJ/kg \cdot K$); 6 – table ($c = 2.512 \, kJ/kg \cdot K$); 7 – tubes of the heating system ($c = 0.435 \, kJ/kg \cdot K$); 8 – inner air ($c = 1.005 \, kJ/kg \cdot K$)

In order to solve the composed system of the differential equations the three-dimensional model of the passenger car compartment was designed. (Fig.1). Main calculation elements - «bricks» of discrete representation of investigated systems, which we need for elementary balance method usage, are constructional elements, elements of concentrated volume and bracing members. Bracing members do not have volume and serve for specifying hydrodynamic and thermal resistance and other boundary conditions.

Thus car model is presented as a set of finite elements (elementary volumes), which are the parts of the most big elements of the car construction: out walls, interior and inner partitions and also of the element that describes the inner volume of the open compartment as a system with lumped parameters. As boundary conditions 1) inflow of a cold air from the air conditioner (with a help of a bracing member); 2) heat flow from the environment as a result of convective and the solar radiation heat transfer; 3) heat flow that comes from passengers and inner equipment are specified. In fact we are modeling just one open compartment and hypothesize that thermal situation in the other compartments is the same. That is the right and the left wall heat gain make 0.

The out walls of the passenger car are modeled as three-layered, as you can see on the Fig. 1. Exterior layer – it is metal sheathing, than goes heat insulation on the basalt base and the third inner layer is a plywood. Every layer by-turn is divided into three calculation elements. Inner partitions were modeling homogeneous. They also were divided into three elements. Components of the interior are specified in a simplified form in the shape of rectangular element set, which have definite thickness, mass and heat exchange surface.

Calculation and verification

For the system of differential equations solving computer program was created. The results of the modeling are presented on the Fig. 2. In addition you can see temperature curve in the compartment that was obtained corresponding to the integral model that was created according to the equations in the paper [4]; and the sanitary and hygienic tests results [9]. Fig. 2 shows that results of the modeling are very close to the test results.

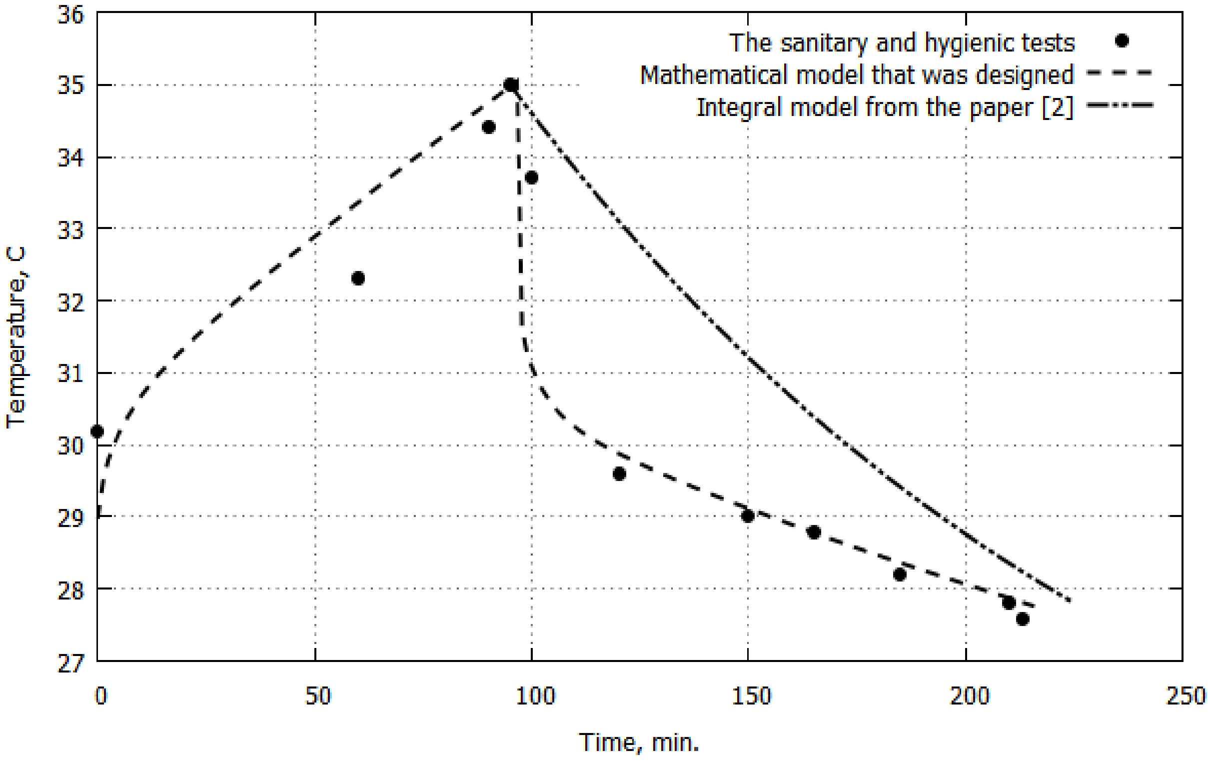

Fig. 2. Temperature diagrams in the passenger car

© I. YU. Khomenko, 2013

Thus mathematical model that have been designed can be considered to be accurate enough and can be used for further theoretical research.

Findings

Computational algorithm was developed and computer program for modeling transitional heat processes in the car was designed. It allows comparing different life support system constructions influence on the inner environment conditions and unsteady heat exchange processes can be studied at every car motion stage.

Originality and practical value

Mathematical model of unsteady heat exchange in a passenger car was created taking into account the features that are determined by the present requirements. That is why it can be used for the heat engineering studying of the inner car state under various conditions and for the operation of the different life support systems of passenger cars comparison. Mathematical modeling of unsteady heat exchange in a passenger car was made by the elementary balance method. Created mathematical model gives the possibility to simulate temperature changes in passenger car on unsteady thermal conditions with enough accuracy and to introduce and remove additional elements to the designed model. Thus different constructive decisions of the life support system can be estimated by the mathematical experiment.

Conclusions

In the article the mathematical model of unsteady heat exchange processes in a passenger car was designed. Existing mathematical models and their disadvantages were analyzed. Assumptions were made and contemporary methods of heat exchange processes calculations were used. The system of differential equations that characterizes unsteady heat exchange processes in a passenger car was composed and computational algorithm was developed. Computer program for modeling transitional heat processes in the car was designed and tested. It can be used for the further theoretical studies (for instance the car heat mode comparison) and for making changes of construction of the car life support system.

LIST OF REFERENCE LINKS

1. Антонов, В. И. Численный метод тепловых балансов решения задач теплопроводности для областей сложной формы [Электронный ресурс] // Дифференциальные уравнения и процессы упр. – 2002. – № 1. – С. 71–78. – Режим доступа: http://www.neva.ru/journal/pdf/2002/vol1/j086.pdf. – Загл. с экрана.
2. Білобородова, І. М. Оцінка основних теплотехнічних параметрів системи охолодження дискового гальма локомотива / І. М. Білобородова, Ю. І. Осенін, І. І. Соснов // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2009. – Вип. 28. – С. 7–11.
3. Голінко, І. М. Моделювання температурного режиму теплообмінника / І. М. Голінко, А. І. Кубрак, А. С. Кравченко // Восточно-Европ. журн. передовых технологий. – 2010. – № 2/7. – С. 24–27.
4. Емельянов, А. Л. Обобщенная математическая модель нестационарного теплового режима пассажирского вагона с СКВ [Электронный ресурс] / А. Л. Емельянов, С. Е. Буравой, Е. С. Платунов // Холодильная техника и кондиционирование. – 2007. – № 1. – С. 34–42. – Режим доступа: http://refrigeration.open-mechanics.com/articles/71.pdf. – Загл. с экрана.
5. Емельянов, А. Л. Системы индивидуального регулирования температуры воздуха в купе пассажирского вагона [Электронный ресурс] / А. Л. Емельянов, С. Е. Буравой, Е. С. Платунов // Холодильная техника и кондиционирование. – 2008. – № 1. – С. 15–22. – Режим доступа: http://refrigeration.open-mechanics.com/articles/72.pdf. – Загл. с экрана.
6. Емельянов, А. Л. Тепловая инерционность воздуха в помещениях с системами кондиционирования [Электронный ресурс] / А. Л. Емельянов, С. Е. Буравой, Е. С. Платунов // Холодильная техника и кондиционирование. – 2007. – № 1. – С. 27–33. – Режим доступа: http://refrigeration.open-mechanics.com/articles/70.pdf. – Загл. с экрана.
7. Исаченко, В. П. Теплопередача : учеб. для втузов / В. П. Исаченко, В. А. Осипова, А. С. Сукомел. – Изд. 3-е. – М. : «Энергия», 1975. – 488 с.
8. Нестационарные тепловые процессы в энергетических установках летательных аппаратов / Н. Д. Коваленко, А. А. Шмукин, М. И. Гужва, В. В. Махин. – К. : Наукова думка, 1988. – 224 с.
9. Протокол санітарно-гігієнічних випробувань вагона № 035-12936. Дніпропетровський національний університет залізничного транс-

порту імені академіка В. Лазаряна. Випробувальна лабораторія вагонів. – Д. : ДНУЗТ, 2011. − 8 с.

10. Фуркало, С. А. Автоматизация расчета теплового прогрева многослойной стенки / С. А. Фуркало, Ю. В. Огир // Космическая техника. Ракетное вооружение : науч. техн. зб. – Д., 2012. – Вип. 1. – С. 197–205.
11. Ягода, П. А. Решение задач оптимизации конструкций с применением современных программных комплексов // Вісн. Дніпропетр. нац. ун-ту залізн. трансп. ім. акад. В. Лазаряна. – Д., 2005. – Вип. 17. – С.174–177.
12. Guedri, K. Modelization of combined radiative and conductive heat transfer in three-dimensional complex enclosures / K. Guedri, M. N. Borjini, H. Farhat // Intern. J. of Numerical Methods for Heat & Fluid Flow. – 2005. – Vol. 15, iss. 3. – P. 257–276.
13. Lienhard, John H. V. A Heat Transfer Textbook: Fourth Edition / John H. Lienhard V., John H. Lienhard IV. – 4th edition. – Cambridge : Phlogiston Press, 2011. – 768 p.
14. Wilson, E. L. Finite element analysis of linear and nonlinear heat transfer / E. L Wilson, K. J. Bathe, F. E. Peterson. – Nuclear Engineering and Design. – 1974. – № 1. – P. 110–124.

І. Ю. ХОМЕНКО[1*]

[1*]Каф. «Вагони та вагонне господарство», Дніпропетровський національний університет залізничного транспорту імені академіка В. Лазаряна, вул. Лазаряна, 2, Дніпропетровськ, Україна, 49010, тел. +38 (097) 677 84 70, ел. пошта irina.in_ua@yahoo.com

МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ НЕСТАЦІОНАРНИХ ТЕПЛОВИХ ПРОЦЕСІВ У ПАСАЖИРСЬКОМУ ВАГОНІ

Мета. Існуючі математичні моделі нестаціонарних теплових процесів у пасажирському вагоні не придатні для повної оцінки ефективності нових технічних рішень системи життєзабезпечення пасажирських вагонів та для їх порівняння з уже існуючими конструкціями. Крім того, нестаціонарні теплові процеси найчастіше досліджувалися на початковому етапі руху вагона. У зв’язку з появою нових конкурентоспроможних технічних рішень системи життєзабезпечення виникла потреба й у створенні нового математичного інструменту, який давав би змогу врахувати ці особливості та їх вплив на перебіг нестаціонарних теплових процесів протягом усього часу рейсу. Метою даної роботи є створення математичної моделі нестаціонарних теплових процесів, що задовольняла б вищеперераховані вимоги. **Методика.** Для реалізації поставленої задачі було складено систему диференціальних рівнянь, що описують нестаціонарні теплові процеси у вагоні; для розв’язання складеної системи рівнянь використовувався метод елементарних балансів. **Результати.** Розроблено розрахунковий алгоритм та створено комп’ютерну програму для моделювання перехідних теплових процесів у пасажирському вагоні, що дозволяє враховувати різні конструктивні рішення системи життєзабезпечення пасажирських вагонів та здійснювати моделювання нестаціонарних теплових процесів на будь-якому етапі рейсу. **Наукова новизна.** Удосконалено математичну модель теплових процесів у вагоні в динаміці, що дозволяє досліджувати теплотехнічний стан у салоні за різних умов та порівнювати роботу різних систем життєзабезпечення пасажирських вагонів. Проведено математичне моделювання нестаціонарних теплових режимів у пасажирському вагоні з використанням методу елементарних балансів. **Практична значимість.** Складена розрахункова модель дає змогу моделювати зміни температури у вагоні на нестаціонарних теплових режимах, досить легко вводити та виводити до розрахункової схеми додаткові елементи. Це дозволяє проводити оцінку різних схем та конструктивних рішень системи життєзабезпечення вагона шляхом математичного експерименту.

Ключові слова: математичне моделювання; пасажирський вагон; нестаціонарні теплові процеси; система життєзабезпечення

И. Ю. ХОМЕНКО[1*]

[1*]Каф. «Вагоны и вагонное хозяйство», Днепропетровский национальный университет железнодорожного транспорта имени академика В. Лазаряна, ул. Лазаряна, 2, 49010, Днепропетровск, Украина, тел. +38 (097) 677 84 70, эл. почта irina.in_ua@yahoo.com

МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ НЕСТАЦИОНАРНЫХ ТЕПЛОВЫХ ПРОЦЕССОВ В ПАССАЖИРСКОМ ВАГОНЕ

Цель. Существующие математические модели нестационарных тепловых процессов в пассажирском вагоне не подходят для полной оценки эффективности новых технических решений системы жизнеобеспечения пассажирских вагонов и для их сравнения с уже существующими конструкциями. Кроме того, нестационарные тепловые процессы чаще всего исследовались на начальном этапе движения вагона. В связи с появлением новых конкурентоспособных технических решений системы жизнеобеспечения, возникла потребность и в создании нового математического инструмента, который давал бы возможность учесть эти особенности и их влияние на протекание нестационарных тепловых процессов на протяжении всего времени в пути. Целью данной работы является создание математической модели нестационарных тепловых процессов, которая бы удовлетворяла вышеперечисленные требования. **Методика.** Для реализации поставленной задачи была составлена система дифференциальных уравнений, которые описывают нестационарные тепловые процессы в вагоне; для решения сложной системы уравнений использовался метод элементарных балансов. **Результаты.** Разработан расчетный алгоритм и создана компьютерная программа для моделирования переходных тепловых процессов в пассажирском вагоне, что позволяет учитывать различные конструктивные решения системы жизнеобеспечения пассажирских вагонов и осуществлять моделирование нестационарных тепловых процессов на любом этапе рейса. **Научная новизна**. Усовершенствована математическая модель тепловых процессов в вагоне в динамике, что позволяет исследовать теплотехническое состояние в салоне при различных условиях и сравнивать работу различных систем жизнеобеспечения пассажирских вагонов. Выполнено математическое моделирование нестационарных тепловых режимов в пассажирском вагоне с использованием метода элементарных балансов. **Практическая значимость.** Составленная расчетная модель дает возможность моделировать изменения температуры в вагоне на нестационарных тепловых режимах, довольно легко вводить и выводить в расчетную схему дополнительные элементы. Это позволяет проводить оценку разных схем и конструктивных решений системы жизнеобеспечения вагона путем математического эксперимента.

Ключевые слова: математическое моделирование; пассажирский вагон; нестационарные тепловые процессы; система жизнеобеспечения

REFERENCES

1. Antonov V.I. Chislennyy metod teplovykh balansov resheniya zadach teploprovodnosti dlya oblastey slozhnoy formy [Heat balance numeral method for the thermal conduction problems solving for the areas of irregular shape]. *Differentsialnyye uravneniya i protsessy upravleniya – Differential equations and the management processes*, 2002, no. 1, pp. 71-78. Available at: http://www.neva.ru/journal/pdf/2002/vol1/j086.pdf (Accessed 18 November 2013).
2. Biloborodova I.M., Osenin Yu.I., Sosnov I.I. Otsinka osnovnykh teplotekhnichnykh parametriv systemy okholodzhennia dyskovoho halma lokomotyva [Estimation of the main heat engineering parameters of the disk brake cooling system]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2009, issue 28, pp. 7-11.
3. Holinko I.M., Kubrak A.I., Kravchenko A.S. Modeliuvannia temperaturnoho rezhymu teploobminnyka [Modeling of the heat exchanger temperature conditions]. *Vostochno-Yevropeyskiy zhurnal peredovykh tekhnologiy – Eastern-European Journal of Enterprise Technologies*, 2010, no. 2/7, pp. 24-27.
4. Yemelyanov A.L., Buravoy S.Ye., Platunov Ye.S. Obobshchennaya matematicheskaya model nestatsionarnogo teplovogo rezhima passazhirskogo vagona s SKV [Generalized mathematical model of the unsteady thermal mode of the passenger car equipped by the air conditioning system]. *Kholodilnaya tekhnika i konditsionirovaniye – Refrigeration and Conditioning*, 2007, no. 1, pp. 34-42. Available at: http://refrigeration.open-mechanics.com/articles/71.pdf (Accessed 18 November 2013).

5. Yemelyanov A.L., Buravoy S.Ye., Platunov Ye.S. Sistemy individualnogo regulirovaniya temperatury vozdukha v kupe passazhirskogo vagona [Systems of individual regulation of the air temperature in the passenger car compartment]. *Kholodilnaya tekhnika i konditsionirovaniye – Refrigeration and Conditioning*, 2008, no. 1, pp. 15-22. Available at: http://refrigeration.open-mechanics.com/articles/72.pdf (Accessed 18 November 2013).
6. Yemelyanov A.L., Buravoy S.Ye., Platunov Ye.S. Teplovaya inertsionnost vozdukha v pomeshcheniyakh s sistemami konditsionirovaniya [Thermal air inertia in the areas equipped by the air conditioning systems]. *Kholodilnaya tekhnika i konditsionirovaniye – Refrigeration and Conditioning*, 2007, no. 1, pp. 27-33. Available at: http://refrigeration.open-mechanics.com/articles/70.pdf (Accessed 18 November 2013).
7. Isachenko V.P., Osipova V.A., Sukomel A.S. *Teploperedacha* [Heattransfer]. Moscow, Energiya Publ., 1975. 488 p.
8. Kovalenko N.D., Shmukin A.A., Guzhva M.I., Makhin V.V. *Nestatsionarnyye teplovyye protsessy v energeticheskikh ustanovkakh letatelnykh apparatov* [Unsteady heat exchange processes in the power installations of the aircrafts]. Kyiv, Naukova dumka Publ., 1988. 224 p.
9. *Protokol sanitarno-hihiienichnykh vyprobuvan vahona № 035-12936.* [Report of the sanitary and hygienic tests of the passenger car 035-12936]. Dnipropetrovsk, DNURT Publ., 2011. 8 p.
10. Furkalo S.A., Ogir Ju.V. Avtomatizatsiya rascheta teplovogo progreva mnogosloynoy stenki [Automation of calculation of the thermal warm-up of laminated wall]. *Kosmicheskaya tekhnika*. *Raketnoye vooruzheniye* [Space engineering. Missile armament], 2012, no. 1, pp. 197-205.
11. Yagoda P.A. Resheniye zadach optimizatsii konstruktsiy s primeneniyem sovremennykh programmnykh kompleksov [Solving of problems of the construction optimization using modern software packages]. *Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu imeni akademika V. Lazariana* [Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan], 2005, issue 17, pp. 174-177.
12. Guedri K., Borjini M.N., Farhat H. Modelization of combined radiative and conductive heat transfer in three-dimensional complex enclosures. *International Journal of Numerical Methods for Heat & Fluid Flow*, 2005, vol. 15, issue 3, pp. 257-276.
13. Lienhard, John H. V., Lienhard John H. A Heat Transfer. Cambridge, Phlogiston Press Publ., 2011. 768 p.
14. Wilson E.L., Bathe K.J., Peterson F.E. Finite element analysis of linear and nonlinear heat transfer. *Nuclear Engineering and Design*, 1974, vol. 29, no. 1, pp. 110-124.

Prof. A. A. Bosov D. Sc. (Tech.); Prof. O. V. Sadovoy, D. Sc. (Tech.) recommended this article to be published

Received: Aug. 20, 2013.
Accepted: Nov. 07, 2013
