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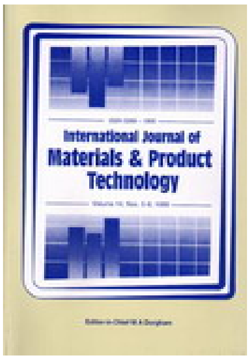

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Residual life prediction of thermal insulation material for cold chain logistics transportation vehicle

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Abstract: Aiming at the problems of low prediction accuracy and long prediction time cost in traditional methods, a residual life prediction method of thermal insulation material for cold chain logistics transportation vehicle is proposed. The distribution position of thermal insulation material in the car body is analysed. According to the distribution position of thermal insulation materials, the life prediction parameters of thermal insulation material are calculated. According to the determined parameters, the key degree of thermal insulation material is calculated by gradient descent method. So as to construct the residual life prediction model of cold chain logistics transport vehicle compartment thermal insulation material, the key parameters of thermal insulation material is taken as the input, and the residual life prediction results of compartment thermal insulation material as the output. Experimental results show that the prediction accuracy of the proposed method is about 97% when 100 times, and the shortest time cost is about 0.5 s.

Keywords: compartment thermal insulation material; life prediction; gradient descent method; residual life prediction model.

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1 Introduction

With the continuous improvement of people's living standards, more and more kinds of items are purchased online. Some products purchased from a long distance, especially cold chain food, need higher requirements in their transportation (Liu and Wang, 2019). Therefore, there are more and more cold chain logistics transportation vehicles, and the compartment of the vehicle is the key to preserve the cold chain transportation goods. The temperature and humidity of the carriage affect the quality of goods transported in the cold chain, which has high requirements for the environment in the vehicle. Among them, the heat insulation material of the car body is one of its essential transportation materials. The material occupies most of the position of the cold chain carriage and plays a role in adjusting the temperature and humidity of the goods. Therefore, the requirements for thermal insulation materials are also increasing (Micari et al., 2021). With the continuous increase of transportation time and the long service life of vehicles, the service life of thermal insulation materials in the car body has attracted much attention. The remaining service life of thermal insulation material refers to the end time when it cannot play any role under current conditions (Hammami et al., 2019). In order to ensure the transportation effectiveness of cold chain goods, the service life of thermal insulation materials is extremely important. Therefore, relevant researchers have also studied the remaining service life of thermal insulation materials, and achieved some results.

Wang et al. (2021) proposed a material residual life prediction method based on double exponential particle filter model. Firstly, the characteristic structure of the thermal insulation material is analysed, the stress relaxation failure mechanism of the thermal insulation material is determined, and a double exponential stress degradation model is constructed to determine the stress of the material. On this basis, the obtained result data are fused with the help of the least square method, and then the historical sample data of the material are tracked through Bayes to determine the state transfer function, analyse the load retention rate of the material, and complete the prediction of the remaining life of the material. This method effectively analyses the structure of materials, but this method considers less influencing factors of materials and has the problem of low prediction accuracy. Xie (2019) proposed a method for predicting the storage life of polyimide cage materials, which is applied to the prediction of thermal insulation materials. Firstly, the characteristics of polyimide material are analysed, and the characteristic quantities affecting the service life of the material are obtained. On this basis, these data are used as the prediction parameters to complete the data prediction and realise the remaining life prediction. The material parameters obtained by this method are accurate, but the quantity is large, and the prediction takes a long time, which has some limitations.

As the life prediction parameters of insulation materials were not analysed and calculated in depth in the design process of the above method, the prediction accuracy was low and the prediction time cost was long. In order to improve the shortcomings of the above methods, this paper proposes a residual life prediction method of thermal insulation material for cold chain logistics transportation vehicle, which has the characteristics of high prediction accuracy and short prediction time cost. The technical route of this paper is as follows:

Firstly, the distribution position of cold chain logistics transport vehicle compartment insulation materials in the compartment is analysed, including: insulation layer on both sides of the vehicle compartment, insulation layer at the air duct at the top of the compartment, insulation layer at the air duct of the compartment, insulation material of compartment frame, and insulation layer at the lower part of the compartment.

Then, according to the different positions of the thermal insulation material distribution, the life prediction parameters of the thermal insulation material of the car body of the cold chain logistics transportation vehicle are calculated, including thermal conductivity, heat conduction parameters and heat convection parameters.

Finally, the entropy method is used to calculate the weight of the prediction parameters and determine the key degree of the prediction parameters, so as to construct the residual life prediction model of the compartment insulation material of cold chain logistics transportation vehicles. The key parameters of the insulation material are taken as the model input, and the output result of the model is the residual life prediction result of the compartment insulation material.

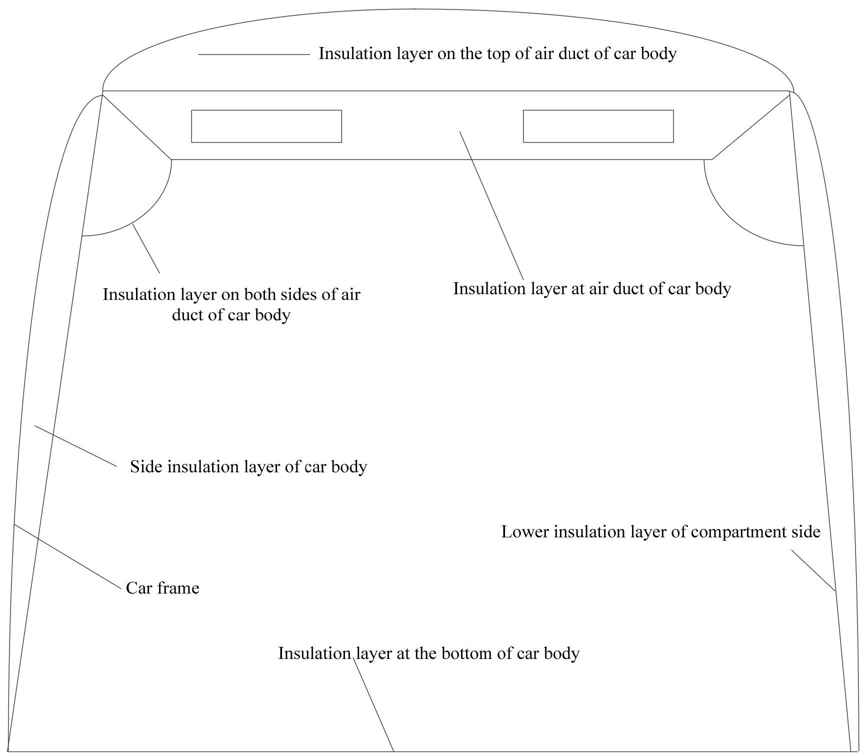
2 Design of residual life prediction method of thermal insulation material for cold chain logistics transportation vehicle

2.1 Distribution of thermal insulation materials

In the cold chain logistics transportation, the thermal insulation performance of the carriage has high requirements for the transportation of goods, especially cold and fresh food. Therefore, in order to study the remaining life of compartment insulation materials, it is necessary to analyse the specific layout of compartment insulation materials of cold chain logistics transportation vehicles in the compartment, because compartment insulation materials are mainly located in each insulation layer of the compartment (Xiong et al., 2019). Therefore, firstly, the main positions of compartment thermal insulation materials are analysed in order to analyse the performance parameters of materials. Due to the particularity of cold chain logistics transport vehicle carriage structure and its thermal insulation performance characteristics, the thermal insulation materials in the thermal insulation layer and live refrigeration layer at different positions are superimposed by multiple layers (Wan et al., 2020). The insulation materials used in each layer are also different. Therefore, in this study, the layout of compartment insulation materials is carried out through different insulation layers. The local basic setting of compartment insulation materials is shown in Figure 1.

In Figure 1, the thermal insulation material of the cold chain logistics transport vehicle compartment mainly includes: the thermal insulation layer on both sides of the vehicle compartment, the thermal insulation layer at the air duct at the top of the compartment, the thermal insulation layer at the air duct of the compartment, the thermal insulation material of the compartment frame, and the thermal insulation layer at the lower part of the compartment. The bottom floor of the car body is provided with an insulating layer.

Figure 1 Setting of heat insulation material for cold chain logistics transport vehicle



To sum up, the distribution position of thermal insulation materials in the car body of cold chain logistics transportation vehicles is analysed.

2.2 Extraction of remaining life prediction parameters

2.2.1 Thermal conductivity

According to the different positions of the thermal insulation materials, the life prediction parameters of the thermal insulation materials of the cold chain logistics transport vehicle compartment are calculated, including thermal conductivity, heat conduction parameters and heat convection parameters, so as to lay a solid foundation for the subsequent prediction of the remaining life of the thermal insulation materials of the cold chain logistics transport vehicle compartment.

In the thermal insulation material of the car body of cold chain logistics transportation vehicles, the thermal conductivity of the thermal insulation material of each insulation layer of the car body can measure the specific temperature value of the thermal insulation material in the insulation layer. Therefore, the thermal conductivity (Cai et al., 2020) of the thermal insulation material of the thermal insulation layer of the cold chain transportation logistics vehicle is set to lay a foundation for the subsequent life prediction. The thermal conductivity of thermal insulation material for thermal insulation layer of cold chain transportation logistics vehicle is shown in Table 1.

Table 1 Thermal conductivity of thermal insulation material for thermal insulation layer of cold chain transportation logistics vehicle (W/(m·k))

Position of compartment insulation material	*Compartment side*	*Upper part of car body*	*Air duct*	*At the top of the air duct*
Equivalent thermal conductivity	0.0792	0.1065	0.1023	0.04231
Location of insulation material	Compartment floor	Both sides of the air duct of the compartment	Car frame	
Equivalent thermal conductivity	0.1634	0.1232	45	

The service life of the thermal insulation material for the car body of cold chain logistics transportation vehicles is directly related to its continuous heat transfer and heat conduction. Therefore, it is necessary to further calculate the thermal conductivity of the material at different positions, and calculate the remaining life of the thermal insulation material on this basis (Cai et al., 2021).

In the application, the temperature of the car body is controlled through heat transfer. In this process, the temperature variation range of the thermal insulation material is set according to the transported articles. In the normal transportation environment, the heat conduction of thermal insulation materials is regarded as a steady state. When the thermal insulation material reaches a steady state, the calculation formula of cross-sectional heat conductivity (Yadollahi et al., 2020; Liao et al., 2020) of a certain length of thermal insulation material is:

$$A = \frac{2\pi EL\left(B_x - B_y\right)}{Ln\left(\frac{r_y}{r_x}\right)} \tag{1}$$

In formula, *A* represents the heat flux in the steady state of the insulation, *E* represents the sectional thermal conductivity of the insulation, B_x, B_y represents the radius of the insulation at different positions, and r_x, r_y represents the specific temperature of the material when transporting the equilibrium state.

At this time, the calculation formula of thermal resistance value of side section of thermal insulation material is:

$$z = \frac{Ln\left(\frac{r_y}{r_x}\right)}{2\pi EL} \tag{2}$$

At this time, the calculation formula of thermal resistance value of side section of thermal insulation material is:

$$z_{all} = \frac{1}{2\pi EL}\left|\frac{Ln\left(\frac{a_0}{a_1}\right)}{k_1} + \frac{Ln\left(\frac{a_1}{a_2}\right)}{k_2} + \frac{Ln\left(\frac{a_2}{a_3}\right)}{k_3}\right| \tag{3}$$

Among them, k represents the thermal conductivity of the insulation and a at the top of the box.

The enclosure structure of the cold chain logistics transport vehicle also contains some thermal insulation materials. According to the calculated pure thermal conductivity problem (Georgescu et al., 2019), the thermal conductivity of this part is calculated by differential equation to obtain:

$$pc\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\gamma\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\gamma\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\mu\frac{\partial T}{\partial z}\right)+S \tag{4}$$

In the formula, pc represents the density value of the insulation, the specific heat capacity of the γ insulation, T represents the temperature of the insulation, x, y, z represents the thermal conductivity of the insulation, S represents the material heat source, μ represents the thermal insulation temperature variable of the spatial material at different locations, and t represents the time variable.

In the determination of thermal conductivity parameters of thermal insulation materials for cold chain logistics transport vehicles, firstly, the thermal conductivity of thermal insulation materials for thermal insulation layers of cold chain logistics transport vehicles is set. According to the set thermal conductivity, the thermal conductivity of thermal insulation materials with different sections is determined, and the total thermal conductivity of materials is determined through differential equations, complete the determination of thermal conductivity parameters of thermal insulation materials for cold chain logistics transportation vehicles.

2.2.2 Conduction parameters

The thermal insulation material of the car body of cold chain logistics transportation vehicle is not only affected by the thermal conductivity parameters, but also transmits part of the temperature heat while conducting heat. Therefore, the heat transfer parameters of the compartment insulation material are also the key parameters affecting its remaining life. The heat transfer mechanism of the heat insulation material of the car body is a movement of heat transfer mode, and there are many types of this movement in the heat transfer mode. It mainly includes: heat conduction, heat convection and heat radiation, which is difficult to appear in the vehicle compartment. Therefore, in the determination of this parameter, this paper mainly calculates the heat transfer of heat conduction and heat convection.

1 Determination of heat conduction of heat insulation material of car body

It is a complex circulation mode in the heat conduction of compartment thermal insulation material. The heat insulation material of the car body needs the mutual contact between objects during heat conduction. During its transportation, there is direct contact between the article and the compartment (Perre et al., 2019), set this condition as:

$$\sigma=\frac{\tau Q\Delta U}{\varepsilon} \tag{5}$$

In formula, σ represents the uniform flow of the plane when the object is in contact with the material, τ represents the temperature difference generated after contacting the object, Q represents the conductivity, U represents the thickness of the compartment insulation, and ε represents the area of the object contact.

2 Determination of thermal convection of heat insulation material for car body

During the transportation of cold chain transport vehicles, the convection phenomenon between the goods in the compartment and the insulation layer, that is, the insulation material, occurs due to the different positions of each insulation material. The temperature change of other positions is caused by the change of the temperature of the thermal insulation material, and a certain exchange between two is enough to form the thermal convection of the thermal insulation material. At this time, the heat transfer between the bottom of the thermal insulation material in the compartment and the wall of the compartment can be expressed as:

$$\vartheta = Q\beta\Delta U \tag{6}$$

In the formula, ϑ represents the mean surface of heat convection through the object surface, β represents the temperature change value on both sides of the transported objects in the compartment, and ΔU represents the heat exchange coefficient.

After determining the heat conduction and heat convection parameters of the car body insulation material of the cold chain transport vehicles, it is also necessary to determine the transient state of the temperature field during the car body insulation material heat conduction, which is obtained through the differential equation (Zhao et al., 2019) under the right angle coordinate system:

$$gc\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(V_x\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(V_y\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(V_z\frac{\partial T}{\partial z}\right) \tag{7}$$

In the formula, gc represents the density of the thermal insulation material, $\frac{\partial}{\partial x}$ represents the specific heat of the material, and V represents the conduction heat coefficient of different coordinate points.

In the determination of heat conduction parameters of cold chain logistics transport vehicle compartment insulation materials, the heat conduction of compartment insulation materials and the heat convection parameters of compartment insulation materials are calculated, and the transient state of temperature field during heat conduction of compartment insulation materials is determined through the differential equation in rectangular coordinate system, so as to complete the determination of heat conduction parameters of compartment insulation materials of cold chain logistics transport vehicles.

2.3 Construction of residual life prediction model of thermal insulation materials

The entropy method is used to calculate the weight of the prediction parameters to determine the key degree of the life prediction parameters of the cold chain logistics transport vehicle compartment insulation materials, so as to construct the residual life prediction model of the cold chain logistics transport vehicle compartment insulation materials. The key parameters of the insulation materials are taken as the model input, and the output result of the model is the residual life prediction result of the compartment insulation materials.

Set the life prediction parameter sequence (Li et al., 2021) of thermal insulation material for cold chain logistics transport vehicle as:

$$A(i) = p(a \times b + c) \tag{8}$$

In the formula, $A(i)$ represents the life prediction parameter sequence of compartment insulation, a, b, c represents the multivariate data in the sequence of life insulation parameters in compartment, and p represents the bias value of the life prediction parameters of compartment insulation.

Since the life prediction parameters of compartment insulation materials will change with the transportation environment, and the parameter prediction parameter sequence will change due to slight temperature changes, it is necessary to correct the sequence. The gradient descent method is used to correct the unchanged parameter sequence, and the following results are obtained:

$$A(i)' = -\sum_{i \in I} A(t)(a \times b + c) \tag{9}$$

where $A(t)$ represents the parameter sequence correction factor.

According to the parameter sequence corrected above, the weight value of the life prediction parameter of heat insulation material of the compartment of cold chain logistics transport vehicle is calculated, and the weight value of the prediction parameter is determined by the entropy method, so as to obtain:

$$R = \sum_{i=1}^{j} A(i)' f(a\gamma + \rho c) \tag{10}$$

In formula, R represents the weight value of the life prediction parameters of the compartment insulation material, f represents the weight factor and γ represents the proportional coefficient.

According to the weight value of the determined life prediction parameters of vehicle compartment insulation materials, the residual life prediction model of vehicle compartment insulation materials is constructed.

Assuming the influence of gas pressure and water vapour on the effective thermal conductivity of the compartment insulation material, it is considered that the residual life of the compartment material is affected by the material. At this time, the thermal conductivity parameters of the insulation material can be expressed as:

$$\rho\left(h_g, X_g\right) = \rho_v + p_g\left(h_g\right) + p_w\left(X_g\right) \tag{11}$$

In the formula, $\rho(h_g, X_g)$ represents the initial thermal conductivity of the thermal insulation material, and ρ_v represents the corresponding pressure value of the thermal conductivity under the gas influence conditions. At this time, the maximum thermal conductivity of the thermal insulation material is:

$$\rho_g\left(h_g\right)=\frac{\frac{h_g}{h}}{1+\frac{\frac{1}{2}}{h_g(t)}} \tag{12}$$

In formula, h_g represents the relationship between thermal insulation and air in the compartment space.

Based on the above analysis, the remaining life of the heat insulation material of the car body is expressed as the remaining average life, and the average value of the working time of the heat insulation material before complete failure is set as:

$$\overline{f_{avg}}=\frac{1}{n}\sum_{p=1}^{n}q_i \tag{13}$$

Since the consumption and thermal conductivity of heat insulation materials in different positions cannot be completely consistent, the remaining working time of heat insulation materials in different positions shall be considered, and the average remaining life shall be expressed as:

$$\overline{w_t}=\frac{1}{n}\sum_{p=1}^{n}l_i \tag{14}$$

In the formula, $\overline{w_t}$ represents the remaining working hours of the heat insulation material.

In order to further accurately determine the service life of the compartment insulation material, the arithmetic mean value is calculated to obtain:

$$\overline{e_p}=\frac{1}{n}\sum_{i=1}^{n}v_i \tag{15}$$

In formula, $\overline{e_p}$ represents the average life of insulation and v_i represents the remaining average life of insulation.

Finally, according to the prediction of the above remaining average life, the final prediction model of the remaining life of the thermal insulation material of the car body of the cold chain logistics transportation vehicle is constructed, and the following results are obtained:

$$\varphi_{e^{-1}}=\delta^{-1}\left(e^{-1}\right) \tag{16}$$

The life prediction key parameters of cold chain transport vehicle compartment insulation materials are input into the model, and the final output value is the residual life value of cold chain logistics transport vehicle compartment insulation materials.

To sum up, analyse the distribution position of cold chain logistics transport vehicle compartment insulation materials in the compartment, calculate the life prediction parameters according to the different positions of insulation materials, calculate the weight of prediction parameters by entropy method, and determine the key degree of prediction parameters, so as to build the remaining life prediction model of cold chain logistics transport vehicle compartment insulation materials, in order to achieve the goal of accurately predicting the remaining life of thermal insulation materials for the car body of cold chain logistics transportation vehicles.

3 Experimental analysis

3.1 Experimental scheme design

In order to verify the effectiveness of residual life prediction of thermal insulation materials for cold chain logistics transportation vehicles, experimental analysis was carried out. The overall experimental scheme is as follows:

1 Experimental environment: The computer system is Windows 10, the operating system is Apache Tom cat5.028, the database is SQL server2000, the development tool is C++, and the processor is Intel (R)Core(TM) i7-4710HQ CPU @ 2.50 GHz. The memory size is 8 GB, and the simulation software is MATLAB 7.2.

2 Experimental data: In the experiment, the carriage of a certain type of cold chain logistics transportation vehicle is taken as the research object, and the length, width and height of the carriage is about 10 m * 4.5 m * 1.5 m. Taking the distribution of thermal insulation materials in the carriage as the research object, the specific life prediction parameters of thermal insulation materials in the carriage are calculated, and the remaining life prediction of the experimental vehicle is studied. The sample of cold chain logistics transport vehicles is shown in Figure 2.

Figure 2 Sample of cold chain logistics transport vehicles (see online version for colours)

3 Experimental index: According to the setting of the above experimental environment, the accuracy of remaining life prediction and the time cost of prediction are set as the experimental indicators of the study. Among them, the higher the prediction accuracy, the higher the prediction method effect, and the shorter the prediction time cost, the higher the prediction efficiency. In order to highlight the effectiveness of this method, the experiment is carried out in the way of comparison, and the method of this paper, Wang et al. (2021) method and Xie (2019) method are compared to verify the effectiveness of the method.

3.2 Analysis of experimental results

3.2.1 Accuracy analysis of residual life prediction of thermal insulation materials for cold chain logistics transportation vehicles with different methods

The accuracy of residual life prediction of thermal insulation materials for cold chain logistics transportation vehicles is the most key index to measure the effectiveness of the design method. Therefore, in order to ensure the effectiveness of the experiment, the data extraction and prediction method of this paper, Wang et al. (2021) method and Xie (2019) method are carried out for many times, and the results can ensure the effectiveness of the experiment. The specific experimental results are shown in Table 2.

Table 2 Residual life prediction accuracy analysis of thermal insulation materials for cold chain logistics transportation vehicles with different methods (%)

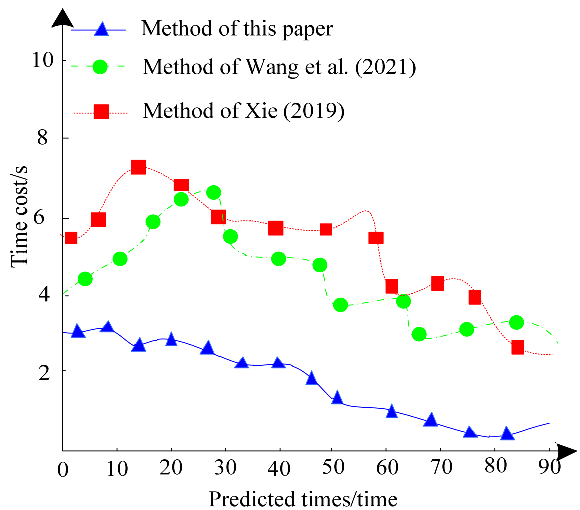
Number of predictions/times	*Wang et al. (2021) method*	*Xie (2019) method*	*Method of this paper*
10	85	82	89
20	84	81	90
30	85	83	91
40	86	82	92
50	85	86	93
60	82	87	94
70	84	86	95
80	86	85	95
90	87	86	96
100	85	83	97

By analysing the experimental results in Table 2, it can be seen that the prediction research has been carried out many times by using the method of this paper, Wang et al. (2021) method and Xie (2019) method. With the continuous change of prediction times, the prediction accuracy of the three prediction methods changes to some extent. When the prediction times are 50, the prediction accuracy of the Wang et al. (2021) method is about 85%, the prediction accuracy of the Xie (2019) method is about 86%, and the prediction accuracy of the method in this paper is about 93%; When the prediction times are 80, the prediction accuracy of the Wang et al. (2021) method is about 86%, the prediction accuracy of the Xie (2019) method is about 85%, and the prediction accuracy of the method in this paper is about 95%; When the prediction times are 100, the prediction accuracy of the Wang et al. (2021) method is about 85%, the prediction accuracy of the Xie (2019) method is about 83%, and the prediction accuracy of the method in this paper is about 97%; In contrast, the prediction accuracy of this method is higher than that of the other three methods. This is because this method analyses the key parameters affecting the life of compartment insulation materials in the prediction, and studies the prediction model to improve the effectiveness of the method.

3.2.2 Time cost of remaining life prediction of thermal insulation materials for cold chain logistics transportation vehicles with different methods

On the basis of determining the accuracy of residual life prediction of thermal insulation materials for cold chain logistics transportation vehicles, in order to highlight the effectiveness of this method, the residual life prediction time of thermal insulation materials for cold chain logistics transportation vehicles based on method of this paper, Wang et al. (2021) method and Xie (2019) method are compared. The prediction results are shown in Figure 3.

Figure 3 Remaining life prediction time cost of thermal insulation materials for cold chain logistics transportation vehicles with different methods (see online version for colours)



By analysing the experimental results in Figure 3, it can be seen that there are certain differences in the time cost of predicting the remaining life of the sample vehicle compartment insulation material by using the three methods. Among them, the time cost of this method in predicting the remaining life of the sample vehicle compartment insulation material is about 0.5 s, the time cost of Wang et al. (2021) method in predicting the remaining life of the sample vehicle compartment insulation material is about 3s, and the time cost of Xie (2019) method in predicting the remaining life of the sample vehicle compartment insulation material is about 2.8 s. In contrast, the time cost predicted by this method is the shortest, which verifies the effectiveness of this method. The reason is that the method by gradient descent method to calculate the thermal conductivity, heat conduction, heat convection parameters of key, in order to build cold-chain logistics transportation vehicle body heat insulation material residual life prediction model, the heat insulation material key parameters as input and output side body insulation prediction of residual life, so it has lower forecast time overhead.

4 Conclusions

In order to solve the deficiency of residual life prediction of vehicle compartment insulation materials, a new residual life prediction method of thermal insulation material for cold chain logistics transportation vehicle is proposed in this paper. Analyse the distribution position of thermal insulation material in the car body of cold chain logistics transportation vehicle, calculate the life prediction parameters of thermal insulation material in the car body of cold chain logistics transportation vehicle according to different positions of thermal insulation material distribution, and calculate the key degree of thermal insulation material by gradient descent method according to the determined parameters. On this basis, the residual life prediction model of cold chain logistics vehicle compartment insulation material is constructed, the key parameters of the insulation material are input, and the output result of the model is the residual life prediction result of compartment insulation material. Compared with traditional methods, this method has the following advantages:

1 The prediction accuracy of the residual life of vehicle compartment insulation materials by the proposed method is high;

2 The proposed method has the lowest time cost for predicting the remaining life of vehicle compartment insulation materials.

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