Study on the Rapid Assessment Method of Thin-Walled Cable Service Life Based on Arrhenius Equation

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Abstract: *Cable is a crucial material in high-speed EMUs. Predicting and evaluating cable service life is essential to ensure safe vehicle operation and reduce operation and maintenance costs. This paper utilizes the Arrehenius equation method to predict and evaluate the service life of wires and cables for high-speed EMUs. The life assessment model parameters were obtained through accelerated thermal aging experiments. The corresponding life assessment model of the experimental cable was then obtained, verifying the feasibility of the method.*

Keywords: *high-speed EMU, cable, Arrehenius equation, cable life evaluation*

1. Introduction

High-speed EMU have become the most important means of transportation for travel, and China is now the world's leading manufacturer of high-speed rail [1]. High-speed EMU are more and more demanding in terms of safety, reliability and comfort. The electric cable is one of the most important materials in high-speed EMU, covering the traction, braking, control and lighting fields of the whole rolling stock, and the operation status of the cable directly affects the operation status of the whole vehicle and the operation safety of the vehicle [2]. Therefore, the correct assessment of the service life of electrical cables is of great significance to ensure the operational safety of high-speed EMU and reduce the cost of vehicle operation and maintenance. In order to solve the problem of predicting and evaluating the service life of the electric cable in high-speed EMU, this paper proposes a rapid assessment method for determining the service life of thin-walled cables based on the Arrhenius equation. The method aims to provide accurate predictions of the service life of electrical cables, which can serve as important reference technical data for the design, operation, and maintenance of high-speed EMU. Additionally, the method can provide reliable technical support for the rational development of high-speed train set repair procedures.

2. Modeling Service Life Prediction and Evaluation

Over time, the atoms or molecules of the material will react due to physical or chemical reasons. When the reaction results accumulate to a certain level, the properties of the material will be degraded, and when the degradation accumulates to a certain level, the material will fail, and the failure of the material means the material's life is going to the end [3,4]. Therefore, materials with faster reaction rates have shorter lifespans.

During the research on acid-catalyzed sucrose hydrolysis conversion reactions, Arrhenius summarized the relationship between the working temperature, activation energy, and the rate of degradation of the material's properties [5]. The relationship of transformation can be described as

$$\frac{\partial M}{\partial t} = A_0 \cdot e^{-\Delta E/kT} \tag{1}$$

Among them:

M is the amount of degradation of a certain eigenvalue of the material;

$\frac{\partial M}{\partial t}$ is the degradation rate at temperature T;

k is the Boltzmann constant;

A0 is a constant;

t is the reaction time;

T is the thermodynamic temperature;

△E Deactivation energy, which is constant for the same type of material in the same failure mode.

The degradation of material properties results in a change in energy, which can be described through an integral. Therefore, the total energy loss of the material from its initial state to the point of failure can be expressed as

$$M_f - M_o = \int_{t_o}^{t_f} A_0 \cdot e^{-\Delta E/kT} dt \tag{2}$$

where temperature T is the temperature constant; t is the degradation time.

Applying the integral transformation to Equation (2) results in

$$M_f - M_o = A_0 \cdot e^{-\Delta E/kT} \left[t_f - t_o \right] \tag{3}$$

Assume t as a time variable that can be expressed as

$$t = t_f - t_o \tag{4}$$

The transformations according to equations (3) and (4) result that

$$t = \frac{M_f - M_o}{A_0} e^{\Delta E/kT} \tag{5}$$

A logarithmic treatment of equation (5) result that

$$\ln t = \ln\left(\frac{M_f - M_o}{A_0} \right) + \frac{\Delta E}{kT} \tag{6}$$

assume that

$$a = \ln\left(\frac{M_f - M_o}{A_0} \right) \qquad b = \frac{\Delta E}{k} \tag{7}$$

Equation (6) can be described as

$$\ln t = a + \frac{b}{T} \tag{8}$$

The equation assumes that t represents the thermal aging life of the cable insulation, while T represents the thermal aging temperature of the cable insulation. The constant 'a' is related to the specified failure properties, and 'b' is related to the activation energy.

Equation (8) presents an approximately linearized mathematical model that relates the service life of cable insulation material to its operating temperature. This model conforms to the transformed relationship between the service life of the chemically reactive material and temperature. The logarithm of the service life of cable insulation is a linear function of the inverse of the temperature. Therefore, the task of predicting and assessing the lifespan of cable services is reduced to determining the coefficients a and b for the service life assessment model.

3. Thermal Aging Test and Data Analysis

The aging of an electric cable refers to the deterioration of its insulating materials, resulting in the failure of its insulation function. During the aging process of electric cables, the breakdown rate of the insulating material decreases as its molecular chain degrades. The rate of breakdown of electric cable insulation materials is a key technical indicator for evaluating the aging of cables and is the most important factor affecting the service life of wire and cable [6,7]. Therefore, this paper employs the method of accelerated thermal aging experiments on wire and cable insulating materials.

The cable specifications for the experiment are as follows: working voltage of 300V, wire gauge of 1.0mm2, and a maximum operating temperature of 90°C.

Experimental cable specifications: operating voltage 300V, standard EN50306, wire diameter 1.0mm2, maximum operating temperature 90°C.

Table 1: Results of the 220°C test (initial sampling interval of 1 day)

Sampling Date	Test Duration(h)	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#
8/13	24	√	√	√	√	√	√	√	√	√	√	√
8/14	48	√	√	√	√	√	√	√	√	√	√	√
8/15	72	√	√	√	√	√	√	√	√	√	√	√
8/16	96	√	√	√	√	√	√	√	√	√	√	√
8/17	120	√	√	√	√	√	√	√	√	√	√	√
8/18	144	√	√	√	×	√	√	√	√	√	√	√
8/19	168	××	××	××	××	××	××	××	××	××	××	××

Table 2: Results of the 200°C test (initial sampling interval of 2 day)

Sampling Date	Test Duration(h)	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#
8/14	48	√	√	√	√	√	√	√	√	√	√	√
8/16	96	√	√	√	√	√	√	√	√	√	√	√
8/18	144	√	√	√	√	√	√	√	√	√	√	√
8/20	192	√	√	√	√	√	√	√	√	√	√	√
8/22	240	√	√	√	√	√	√	√	√	√	√	√
8/24	288	√	√	√	√	√	√	√	√	√	√	√
8/26	336	√	√	√	√	√	√	√	√	√	√	√
8/28	384	√	√	√	√	√	√	√	√	√	√	√
8/30	432	√	√	√	√	√	√	√	√	√	√	√
9/1	480	√	×	×	√	√	√	√	√	×	√	√
9/3	528	××	××	××	××	××	××	××	××	××	××	××

Table 3: Results of the 180°C test (initial sampling interval of 4 day)

Sampling Date	Test Duration(h)	1#	2#	3#	4#	5#	6#	7#	8#	9#	10#	11#
8/16	96	√	√	√	√	√	√	√	√	√	√	√
8/20	192	√	√	√	√	√	√	√	√	√	√	√
8/24	288	√	√	√	√	√	√	√	√	√	√	√
8/28	384	√	√	√	√	√	√	√	√	√	√	√
9/1	480	√	√	√	√	√	√	√	√	√	√	√
9/5	576	√	√	√	√	√	√	√	√	√	√	√
9/9	672	√	√	√	√	√	√	√	√	√	√	√
9/13	768	√	√	√	√	√	√	√	√	√	√	√
9/17	864	√	√	√	√	√	√	√	√	√	√	√
9/21	960	√	√	√	√	√	√	√	√	√	√	√
9/25	1056	√	√	√	√	√	√	√	√	√	√	√
9/29	1152	√	√	√	√	√	√	√	√	√	√	√
10/3	1248	√	√	√	√	√	√	√	√	√	√	√
10/7	1344	√	√	√	√	√	√	√	√	√	√	√
10/11	1440	×	√	√	×	√	√	×	√	×	√	√
10/15	1536	××	××	××	××	××	××	××	××	××	××	××

Table 4: Results of the 160°C test (initial sampling interval of 7 day)

Sampling Date	**Test Duration(h)**	**1#**	**2#**	**3#**	**4#**	**5#**	**6#**	**7#**	**8#**	**9#**	**10#**	**11#**
8/9	**168**	√	√	√	√	√	√	√	√	√	√	√
8/16	**336**	√	√	√	√	√	√	√	√	√	√	√
8/23	**504**	√	√	√	√	√	√	√	√	√	√	√
8/30	**672**	√	√	√	√	√	√	√	√	√	√	√
9/6	**840**	√	√	√	√	√	√	√	√	√	√	√
9/13	**1008**	√	√	√	√	√	√	√	√	√	√	√
9/20	**1176**	√	√	√	√	√	√	√	√	√	√	√
9/27	**1344**	√	√	√	√	√	√	√	√	√	√	√
10/4	**1512**	√	√	√	√	√	√	√	√	√	√	√
10/11	**1680**	√	√	√	√	√	√	√	√	√	√	√
10/18	**1848**	√	√	√	√	√	√	√	√	√	√	√
10/25	**2016**	√	√	√	√	√	√	√	√	√	√	√
11/1	**2184**	√	√	√	√	√	√	√	√	√	√	√
11/8	**2352**	√	√	√	√	√	√	√	√	√	√	√
11/15	**2520**	√	√	√	√	√	√	√	√	√	√	√
11/22	**2688**	√	√	√	√	√	√	√	√	√	√	√
11/29	**2856**	√	√	√	√	√	√	√	√	√	√	√
12/6	**3024**	√	√	√	√	√	√	√	√	√	√	√
12/13	**3192**	√	√	√	√	√	√	×	√	√	√	√
12/20	**3360**	×	√	×	×	√	√	××	√	×	√	√
12/27	**3528**	××	×	××	××	××	×	××	××	××	××	××

The test temperature was chosen in accordance with EN50305 and GB/T 2951-2008 [8]. The experimental thin-walled cable's maximum operating temperature is 90°C. Therefore, the experiment's lowest temperature point is set at 110°C. The experiment will be conducted at four temperature points: 110°C, 130°C, 150°C, and 170°C, as shown in Table 1-4.

The experimental data results above were processed and analyzed, and the heat-resistant characteristics of the cable were plotted on a graph, as shown in Figure 1.

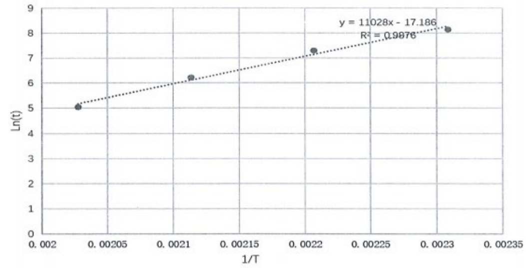

Figure 1: Heat resistance graph

Solvable parameters

$$a = -17.186$$

$$b = 11028$$

Obtaining life assessment models for experimental cables

$$\ln t = 11028\frac{1}{T} - 17.186 \tag{9}$$

Based on the maximum cable operating temperature of 125°C

$$T = 273.15 + 125 = 398.15 \tag{10}$$

Including T in the life assessment model equation

$$t \approx 36757\ h \tag{11}$$

Based on the data, it can be estimated that the experimental cable has a remaining service life of approximately 36,757 hours, equivalent to around 4.20 years.

4. Conclusion

The paper conducted an assessment of the service life of electrical cables in moving trains. The model's characteristic parameters were obtained through experiments, and the experimental cable's service life model was established, which verified the feasibility of the research method adopted in this paper.

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