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STUDY OF THE CHARACTERISTICS ABOUT INSULATION DAMAGE BASED ON THE ACCELERATED LIFE TESTS

BADANIE CHARAKTERYSTYK USZKODZEŃ IZOLACJI W OPARCIU O TESTY PRZYSPIESZONEGO STARZENIA

In this study the Maximum Likelihood Estimator is taken to identify the characteristics of insulation failure about the class-H motors by considering the accelerated life testing data under censored situation from Nelson. Based on the Weibull survival modeling the failure is expressed as the series connection of three modes, namely the turn, phase, and ground, respectively, the so-called competing failure. The main concern in present investigation is about the variation of shape parameters, β with the temperature. The Gompertz-type relation of $\beta_i(T)$ is suggested with the reference temperature, T_{r_i} for the i-th failure mode. It is found that the T_{r_i}'s not only distinguish the characteristics of cumulative damage process about the insulation, but also involve the estimation of mean-time-to-failure (MTTF). Physically T_{r_i} denotes the turning point of varied β_i as the i-th failure mode becomes moderate in a sense of less capability about the accumulation of insulation damage at higher temperature where corresponds the thermal degradation process. The numerical results indicate that the insulation technique used is acceptable as the operation temperature kept in the use condition 363K. According to the predicted lifetime as the temperature rises up to 440K, which still within the allowed range in application, the turn structure needs to be rearranged primarily, then the phase next. The ground mode has only influence on the failure at much higher temperature.

Keywords: *accelerated life testing, competing failure mode, insulation degradation, Gompertz-type relation of shape parameter.*

W prezentowanej pracy zastosowano estymator największej wiarygodności do określenia charakterystyk uszkodzenia izolacji silników klasy H z wykorzystaniem danych z badań przyspieszonego starzenia w sytuacji cenzurowanej wg. Nelsona. Na podstawie Weibullowskiego modelu prawdopodobieństwa przetrwania, uszkodzenie określono jako szereg trzech przyczyn dotyczących, odpowiednio, zwoju, fazy i ziemi, czyli jako tzw. uszkodzenie konkurujące. Głównym zagadnieniem przedstawionych badań jest zmienność parametrów kształtu β wraz z temperaturą. Zaproponowano zależność Gompertza $\beta_i(T)$, z temperaturą odniesienia T_{r_i}, dla n-tego trybu awaryjnego. Stwierdzono, że temperatury T_{r_i} nie tylko wyróżniają charakterystykicałościowego procesu uszkodzenia izolacji, ale również służą ocenie średniego czasu do awarii (MTTF). W kategoriach fizycznych T_{r_i} oznacza punkt zwrotny o zróżnicowanym β_i gdy n-ta przyczyna uszkodzenia staje się umiarkowana w sensie mniejszej zdolności akumulacji uszkodzeń izolacji w wyższej temperaturze, odpowiadającej procesowi termicznej degradacji. Wyniki liczbowe wskazują, że stosowana technologia izolacji jest akceptowalna, ponieważ temperatura pracy wynosi 363K. Zgodnie z prognozowanym czasem pracy, wraz ze wzrostem temperatury do 440K, co nadal mieści się w dozwolonym zakresie temperatur użytkowania, zachodzi konieczność zmiany najpierw struktury zwoju a w dalszej kolejności struktury fazy. Przyczyny dotyczące gruntu mają wpływ na uszkodzenie jedynie przy wyższych temperaturach.

Słowa kluczowe: *badania przyspieszonego starzenia, konkurujące przyczyny uszkodzeń, degradacja izolacji, funkcja Gompertza dla parametru kształtu.*

Abbreviations

ALT - accelerated life test,
CFMA - competing failure mode analysis,
fpdd - failure probability density distribution,
MLE - maximum likelihood estimation,
MTTF - mean-time-to-failure,

Symbols

β_i, θ_i - shape and scale parameter of each failure mode,
τ - observed lifetime,
X_i - random failure lifetime of the failure mode,
m - number of failure modes,
L - likelihood function,
r - number of failures among test samples,
n - total sample size,
δ_{ij} - decision factor of the likelihood function,
p - number of test levels,
$f_{S,i}$ - failure probability density distribution for the i-th mode failure,
r^* - rate constant of the reaction,
A^* - characteristic parameter for the chemical process,
E_a activation energy of the reaction,
K - Boltzmann constant,
T - temperature in Kelvin,
L_T - estimation of the lifetime,
T_{r_i} - reference temperature.

1. Introduction

Accelerated life tests (ALT) are usually carried out by stressing specimens at overstress conditions to explore the defects and estimate the mean-time-to-failure (MTTF) at normal use. The basic assumption in conducting ALT is that the tests should be followed the same failure mechanism as the product failed at normal condition. The failure mechanism is related to the degradation of the material due to the stress from certain physical phenomena. Due to the complexity of the product geometry, failure may occur at different locations, each with its own particular features, e.g. the notch shape which is in common to induce the fatigue failure of structure etc. These are the so-called the failure modes. There is a specific probability for failure at each different position. The lifetime estimation becomes obviously optimistic if only the most frequently occurred failure mode considered. The competing failure mode analysis (CFMA) takes all potential failure modes into account at the same time. The other mission of CFMA is to predict the proportion of each mode in the apparent failure which is observed under the same mechanism without the location details. Such information helps in the product development. In early study, Nelson [11] took the concept of competing risk in the analysis of ALT. Sometimes to simplify the tests, the failure is periodically checked as the system function qualified with the particular mode or not, i.e. the recorded time may not be the exact time as the system failed at those modes considered. To shorten the total time of ALT the process is in usual terminated with a certain amount of survivals, the so-called censored situation [13]. In this case the estimation becomes much more sophisticated. It should be not only conformed in some degree with the data but also explained well with physical sense. Therefore, a deep understanding of the material degradation with stress has to be addressed. In the present study the motor failure due to the deterioration of insulation, which is caused by the thermogravimetic phenomenon of insulation materials, is investigated about the censored data as multiple failure modes involved. At higher temperature the mass loss rate becomes larger, thus it leads to weaken the insulation more seriously and results in a shorter lifetime of the product. The Maximum Likelihood Estimation (MLE) [5] is a typical approach adopted for the prediction in such case.

The Weibull distribution is widely used in the reliability expression due to its flexibility in describing different behavior of the hazard rate. Klein and Basu [8] investigated the ALT data with the Weibull distribution as several failure modes considered. Miller and Nelson [10] applied the MLE in the analysis of a set of step-stress ALT data as the lifetime decreased exponentially with the temperature. Later Bai et al [1] studied how to arrange a failure-censored ALT sampling plan with equal recorded test time at different thermal environment.

All of these studies worked on that the scale parameter, , varies based on Arrhenius assumption [4] and the shape parameter β remains fixed in the analysis. The Arrhenius assumption describes the deterioration of oxidation which introduces acid groups into the insulation to increase the conductivity and power factor of the insulation. However the shape parameter characterizes the process of the insulation damage due to the material degradation as well as the increasing stress from continuous changing of the local geometry i.e. β should be considered varying with the temperature also. It is also known that these parameters are related to a number of load cycles and other factors in fatigue [7]. From experience as the thermal environment kept at lower temperature the damage process continues in a submerged manner. At higher temperature, another type of deterioration, thermal decomposition [2], becomes an important factor.The polymer chains break into shorter units occurs in all polymers including cellulose at elevated temperatures even in the absence of oxygen. In terms of reliability the insulation vanishes more or less suddenly, i.e. the corresponding shape parameter should be much larger than one. On the contrary, as the temperature at higher level the material degradation is more serious, the reliability decays in a some degree of constant failure rate situation. Such point of view has already been mentioned by Nelson [12]. Seo and Kim [14] designed an accelerated life test sampling plan in the consideration of the Weibull distribution with both shape and scale parameter taken in the power-law forms of temperature. On the other hand, [3] made an estimation followed Bayesian framework for the ALT data about all possible failure modes by constant failure assumption, each hazard rate with different proportion to the temperature.

A mature technology should be robustness against the operation condition within an acceptable range during its service.In other word it needs be reliable and predictable. Generally to the electrical insulation material, the dielectric strength is degraded with rising temperature. The density of material is losing and becomes non-uniform,this causes the specimens not only have shorten life but also the failures become more unpredictable.Based on the thermogrvimetric analysis, it requires that the characteristic of cumulative damage of insulation changes little as the operation condition around the normal temperature, thus the motor quality can be assured. Meanwhile at much higher temperature environment, say beyond an assumed reference point, the characteristic of damage process is basically changed with less capability of accumulation and then the insulation failure tends to be in a constant hazard rate situation. This means that the failures are induced mainly by some unpredictable fluctuations of circumstance, e.g. the moisture, etc. It is worth to denote that such change differs from the estimation about lifetime, which is related primarily to the scale parameter by Arrhenius assumption, decreasing with increasing the temperature. Therefore the shape parameter should slip down from its saturation value to one, as the constant failure rate situation, when the thermal environment at much higher temperature. Gompertz-type variation [17] can be chosen as one of the candidate to show such tendency. It is

$$y(x) = z \times \exp\left[-b \times \exp\left[-cx\right]\right] \tag{1}$$

where z is the upper asymptote and c is the change rate. $(\ln \frac{1}{b})/(-c)$ denotes the inflection point of Eq. (1).The effects of varying z, b and c for y are depicted in Fig. 1.

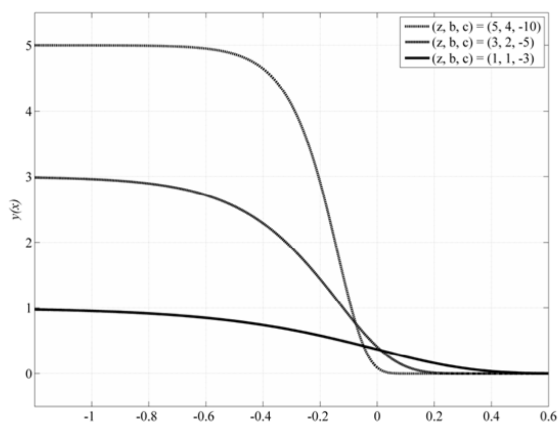

Fig. 1. Typical Gompertz variation curves

2. Model assumptions and likelihood function for competing failure analysis

Consider in the presence of m failure causes, the observed lifetime τ of a set of tests is the minimum among $X_1, X_2, \ldots, X_m$; X_i the random failure lifetime of mode i, i.e.

$$\tau = \min\left(X_1, X_2, \ldots, X_m\right) \tag{2}$$

Let the failure modes be independent to each other, thus a series connection of these modes represents the apparent failure in the tests. Now we have the reliability $R_{cf}(t)$ as

$$\begin{aligned} R_{cf}(t) &= P(\tau > t) = P\left(X_1 > t, X_2 > t, \ldots, X_m > t\right) \\ &= \prod_{i=1}^{m} P\left(X_i > t\right) = \prod_{i=1}^{m} R(t) \end{aligned} \tag{3}$$

with probability density function $f_{cf}(t)$ as

$$f_{cf}(t) = -\frac{dR(t)}{dt} = -\sum_{i=1}^{m}\left[\frac{dR_i(t)}{dt}\left(\prod_{\substack{j=1 \\ j\neq i}}^{m} R_j(t)\right)\right]. \tag{4}$$

Suppose that the Weibull survival model for the i-th failure mode in the ALT data exists as the scale and shape parameter both varied with the thermal environment condition. The corresponding reliability decays with the time t as

$$R_i(t) = \exp\left[-\left(\frac{t}{\theta_i(T)}\right)^{\beta_i(T)}\right], \tag{5}$$

where $\theta_i(T)$ and $\beta_i(T)$ are the scale and shape parameter, respectively, of the Weibull expression, T the temperature. The probability density function $f_i(t)$ becomes

$$f_i(t) = \frac{\beta_i(T)}{\theta_i(T)}\left(\frac{t}{\theta_i(T)}\right)^{\beta_i(T)-1} \exp\left[-\left(\frac{t}{\theta_i(T)}\right)^{\beta_i(T)}\right]. \tag{6}$$

Let the r-th among n causes lead to n specimens failed, and each failure comes only from a single cause. The corresponding likelihood function L is defined as

$$L = \prod_{j=1}^{r}\prod_{i=1}^{m}\left(f_i^{\delta_{ij}}\left(t_j\right) \times R_i^{1-\delta_{ij}}\left(t_j\right)\right) \times \prod_{j=r+1}^{n} R_{cf}\left(t_j\right), \tag{7}$$

where δ_{ij} is the decision factor, i.e. δ_{ij}=1 as the specimen failed in test time point t_j with the i-th failure mode; otherwise δ_{ij}=0. For censored testing the effect of j-th survival on the likelihood function is accounted in the term $\prod_{j=r+1}^{n} R_{cf}\left(t_j\right)$. For a p-constant temperature levels ALT, the likelihood function becomes

$$L = \prod_{k=1}^{p}\prod_{j=1}^{r}\prod_{i=1}^{m}\left(f_{ik}^{\delta_{ijk}}\left(t_{jk}\right) \times R_{ik}^{1-\delta_{ijk}}\left(t_{jk}\right)\right) \times \prod_{k=1}^{p}\prod_{j=r+1}^{n} R_{cf}\left(t_{jk}\right). \tag{8}$$

The probability density function for the i-th mode failure is expressed as

$$f_{S,i}(t) = \frac{dR_i(t)}{dt} \times \prod_{\substack{j=1 \\ j\neq i}}^{m} R_j(t) = f_i(t) \times \prod_{\substack{j=1 \\ j\neq i}}^{m} R_j(t). \tag{9}$$

The integral value of $f_{S,i}(t)$ is theproportion of i-th mode failure on the total. It points out which modes should be paid attention and improved in the product developing.

3. Temperature dependence of the Weibull parameters

A rough examining about the data shown in Table 1 reveals three facts, as the temperature kept at lower level,

(1) the average failure time $\bar{X}_g$ about the ground mode, is overall the largest one,

(2) for all modes $\bar{X}_i$ decreases as the temperature increasing, and

(3) the failure times are much more concentrated, respectively, for each mode.

The third point requires that the smaller shape parameter is the higher temperature is.

3.1. Arrhenius relationship for the scale parameter

Arrhenius relation presents the chemical reaction rate among the material components under a specific thermal environment. It is expressed as

$$r^* = A^* \times \exp\left[-\frac{E_a}{KT}\right],$$

where r is the rate constant of reaction, A^* the characteristic parameter about the chemical process, K the Boltzmann constant, E_α the activation energy of the reaction and T the temperature in Kelvin scale. Since higher reaction rate yields less lifetime of the insulation, a straightforward assumption can be made as $r \cdot L_T \sim$ constant, while L_T is the estimation of lifetime. Therefore we have

$$L_T = \exp\left[A + \frac{B}{T}\right]. \tag{10}$$

For the Weibull description of reliability the expected lifetime varies primarily with the scale parameter (a proportional factor related to a gamma function of both parameters), thus for the i-th mode scale parameter θ_i can be assumed in the form as

$$\theta_i(T) = exp\left[A_i + \frac{B_i}{T}\right], \tag{11}$$

where A_i and B_i are decided by maximizing the likelihood estimator shown in the previous section.

3.2. Gompertz relationship for the shape parameter

The ASTM standard D3850 [15] provides the measurement of thermal stability about the content of volatile components of the insulation material involved. As the specimen operated under a harsh thermal environment, the effect of material decomposition [9] [16] will lead to the loss of insulation property early. The sustainability is much lower as the mass loss rate is small because of less normal material existed. Thus, any disturbance can destroy the insulation. To modeling of the thermal decomposition process, the Gompertz model and its modified forms have beensuccessfully applied[6] [18]. According to the observed fact mentioned in the beginning of this section, in this study, the shape parameter varying with temperature is suggested in the form

$$\beta_i(T) = 1 + z_i \times \exp\left[-\exp\left[-c_i\left(\frac{1}{T} - \frac{1}{T_{r_i}}\right)\right]\right], \tag{12}$$

T_{ri} is the reference temperature which plays the role of b, see Eq. 1 in the combination $b = \exp\left(\frac{c_i}{T_{r_i}}\right)$. When the testing temperature beyond the reference much higher the failure occurrence is considered rather unpredicted, thus the corresponding β reduces to one. Since at such circumstance a significant change of the characteristic of insulation decay has taken place, the process of damage accumulation becomes mild; the failure tends to be a constant failure rate condition.

4. Case study

Consider a set of data by Nelson [10], see Table 1, which collected from a thermal-accelerated life tests of Class-H motor insulation. The material of Class-H motor insulation consists of silicone elastomeric and the combination of others such as mica, glass fiber, asbestos etc. Insulation failed according to three failure modes, namely turn, phase and ground, each occurring at different parts of the system. The life of the motor is the first occurrence of these failures. In atypical test of motor insulation the turn insulation is the winding coils, the phase is a sheet of insulation laid between the phases and the ground insulation is the slot cell. In thermal-accelerated life test, specimens go into an oven which is then raised to test temperature.

Table 1. Class-H motor insulation data under competing failure mode (hours) [11]

463K				513K			
M \ S	Turn	Phase	Ground	M \ S	Turn	Phase	Ground
1	7228	10511	10511+	1	1175	1175+	1175
2	7228	11855	11855+	2	1881+	1881+	1175
3	7228	11855	11855+	3	1521	1881+	1881+
4	8448	11855	11855+	4	1569	1761	1761+
5	9167	12191+	12191+	5	1617	1881+	1881+
6	9167	12191+	12191+	6	1665	1881+	1881+
7	9167	12191+	12191+	7	1665	1881+	1881+
8	9167	12191+	12191+	8	1713	1881+	1881+
9	10511	12191+	12191+	9	1761	1881+	1881+
10	10511	12191+	12191+	10	1953	1953+	1953+
493K				533K			
M \ S	Turn	Phase	Ground	M \ S	Turn	Phase	Ground
1	1764	2436	2436	1	1632+	1632+	600
2	2436	2436	2490	2	1632+	1632+	744
3	2436	2436	2436	3	1632+	1632+	744
4	2436	2772+	2772	4	1632+	1632+	744
5	2436	2436+	2436	5	1632+	1632+	912
6	2436	4116+	4116+	6	1128	1128+	1128
7	3108	4116+	4116+	7	1512	1512+	1320
8	3108	4116+	4116+	8	1464	1632+	1632+
9	3108	3108	3108+	9	1608	1608+	1608
10	3108	4116+	4116+	10	1896	1896	1896

M: mode, S: sequence

There is no voltage applied to the insulation in the oven. After a specified time at temperature, the specimens are removed from the oven and cooled to room temperature then a specified voltage is applied to the insulation, which failure (breaks down) or survives. Survivors go back into the oven for the next cycle at temperature. A median life over 20,000 hours is expected with temperature below 453K.In the table it presents the recorded failure times for each mode (turn, phase and ground, respectively) under different thermal environment, as the temperature held at 463K, 493K, 513K and 533K, respectively.

During the testing the motors were kept going on run till the rest failure modes appeared after the first shown. The failure is assumed as the voltage drops below the threshold defined for the particular mode. The recorded time in Table 1 is the midway between periodical inspections for the failure. It is quite different in real application; the first appearance of the defined failure may not cause the end of motor life at once but lead to less efficiency. For details, the motors appeared as in the sequence 1, 2 and 3 in the table at temperature 463K, of which the insulation decays did not reach the thresholds of the defined failure modes till at 7228 hours all of these three motors were disqualified on the turn mode and then the motor 1 failed at 10511 hours, motor 2 and 3 at 11855 hours all on the mode phase afterward quitted the tests with mode ground still qualified by marked plus to denote the censoring time. The other tests in Table 1 were also carried out in the same manner.

The LE, Eq. (8), is maximizing with the parameters shown in the relation of *θ's* and *β's*, see Eq. (11) and (12), as the data in Table 1 taken. The identified parameters for each failure mode are given in Table.2. In this study, the shape parameter β is assumed either with Gompertz-type variation or fixed. The results in Table 2 for β fixed assumption present the characteristics of insulation damage of the mode turn and phase are quite similar to each other but the mode ground with less cumulative tendency due to its small value of β. This also can be found for β followed Gompertz-type variation assumption, see Fig. 2a. Comparing these two assumptions the shape parameter of both are similar to each other for the mode ground and phase, respectively. But the corresponding for turn is quite different with larger in the Gompertz-type variation case. Such difference leads to the life estimation with remarkable change, see Table 3. The identified numerical value of reference temperature for each mode nears to the inflection point of the corresponding Gompertz curve, this reflects that the characteristics of damage process about the insulation change as mentioned in the introduction. The variations of scale parameter with the temperature for these modes are given in Fig. 2b.

Table 2. The fitted parameters for the ALT data in Table 1, θ expressed in Eq. (11)

Mode		β with Gompertz-type-relation in Eq. (12)	β fixed
Turn	β (z, g, T_r)	(6.69, 5789, 516)	4.23
	θ (A, B)	(−5.16, 6644)	(−3.83, 5942)
Phase	β (z, g, T_r)	(3.31, 5983, 839)	4.12
	θ (A, B)	(−4.25, 6381)	(−4.25, 6381)
Ground	β (z, g, T_r)	(1.54, 69112, 614)	2.54
	θ (A, B)	(−12.63, 10753)	(−12.84, 10665)

The plots show that all have similar trend. The important information of scale parameter relates to the lifetime estimation. From CFMA the mode with the lowest scale parameter dominates the apparent failure, i.e. the actual lifetime is somewhat below that of dominant mode. At lower temperature, say below 450K, the failure due to the ground

Table 3. The comparison of the MTTF in hours for each failure mode and the apparent failure at maximum allowed temperature (453K) and use condition (363K)

Mode	β fixed		β with Gompertz-relation Eq. (12) for T_r			Nelson (1990)	
	453K	363K	453K	400K	363K	453K	363K
Turn	9.82E3	2.54E5	1.25E4	1.94E4	4.79E5	1.23E4	1.00E6
Phase	1.70E4	5.58E5	1.71E4	2.58E4	5.55E5	1.70E4	5.41E5
Ground	3.95E4	9.99E6	5.92E4	8.83E4	9.70E6	3.51E4	4.81E6
Apparent failure (failure in series connection)	9.52E3*	2.51E5	1.19E4*	1.85E4*	4.43E5	1.16e4*	5.22E5

***** *denotes not qualified with respect to the specification***

mode can be ignored because its scale parameter is much larger than the other two; however as temperature higher than 550K the effect of ground mode failure becomes significant. The MTTF at maximum allowed temperature (453K) and use condition (365K) for these failure modes and the corresponding apparent failure are shown in Table 3. The predictions based on -fixed assumption are quite different with the other two especially about the MTTF of the apparent failure which is dominated by the mode turn primarily and then the mode phase secondly while the mode ground has little influence.

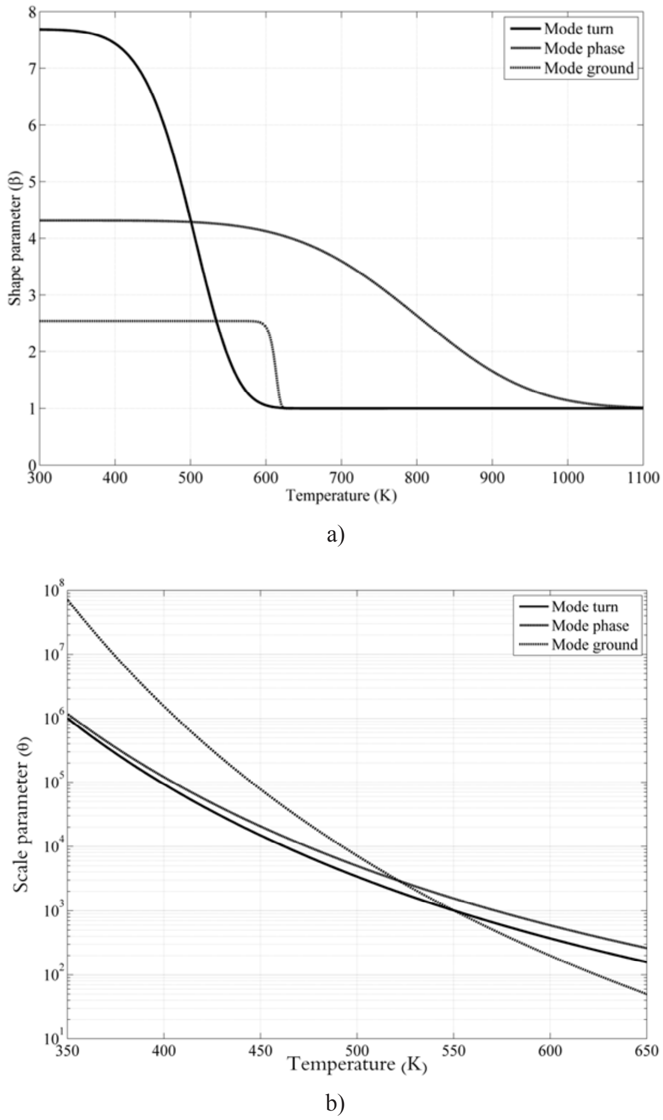

Fig. 2. The variations of (a) shape parameter and (b) scale parameter with the temperature for each failure mode

The MTTF prediction by Nelson [11] follows the reliability with a log-normal distribution under constant deviation with the data in Table 1 except those of mode turn at 533K. In the present study all information in Table 1 is taken into account. For comparison of the models Fig. 3 shows the predicted reliability variations with the data at 463K. It shows that present study with β varied with temperature fits the data even better among the models. The approach from Bunea [13] is taken in a different way, the reliability drops in a constant failure rate manner, i.e. $\beta=1$, which deviates from the data obviously, but with acceptable MTTF prediction.

The comparisons of models based on the two assumptions about β in this study are made in Fig. 4 for the temperature at 463K and 533K, respectively. Although the fitting based on β-fixed assumption is well at higher temperature but not for the lower one, such limits its application in the life estimation. This also coincides with the results shown in Table 3. At lower temperature the mode turn dominates the failure; however as the temperature getting high, the mode ground becomes meaningful. It seems that the influence of the mode phase maintains the same level about the apparent failure in the mentioned temperature range. The sum of failure probability density distributions (fpdd) of the three modes from Eq. (9) denotes the actual failure distribution. The area beneath the fpdd of some particular mode represents the percentage of that mode failure on the total. Table 4 provides such information which can be double checked with Fig. 2b about the scale parameter variation vs. temperature.

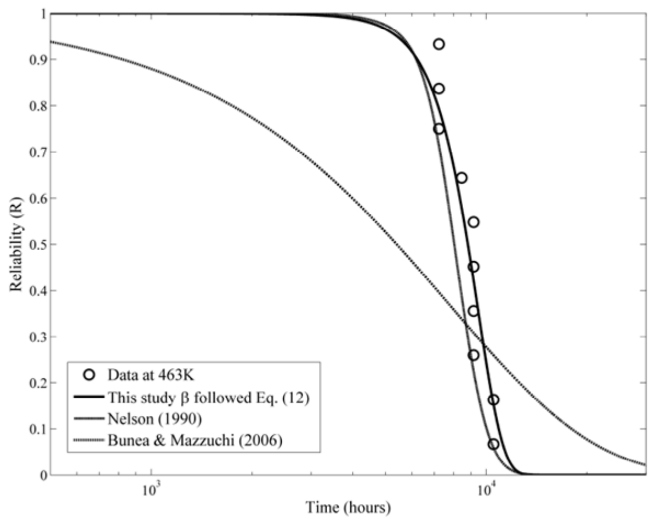

Fig. 3. The comparison of reliability fittings for data at temperature 463K

Finally the predicted reliabilities of the test motors are given in Fig. 5 for the temperature at the allowable range the lower 363K, 400K and upper 453K, respectively. It is interest that decay trend of

Table 4. The corresponding percentage of occurrence for each failure mode in the series connection at 4 test temperature and maximum allowed temperature (453K), use condition (363K)

Mode \ Temperature	363K	453K	463K	493K	513K	533K
Turn	68.7%	80.0%	79.2%	75.8%	68.8%	57.9%
Phase	31.2%	18.6%	18.6%	15.8%	13.6%	10.4%
Ground	0.1%	1.4%	2.2%	8.4%	17.6%	31.7%

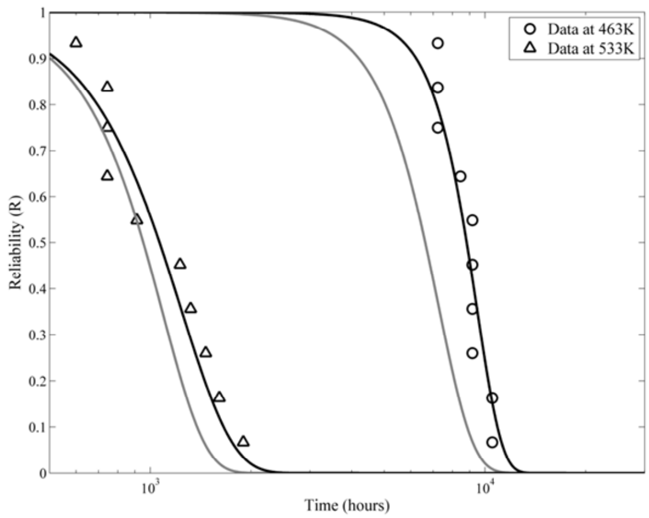

Fig. 4. The reliability fittings based on the MLE withβ-temperature depended in black and β-fixed in grey at 463K (–) and 533K (–), respectively

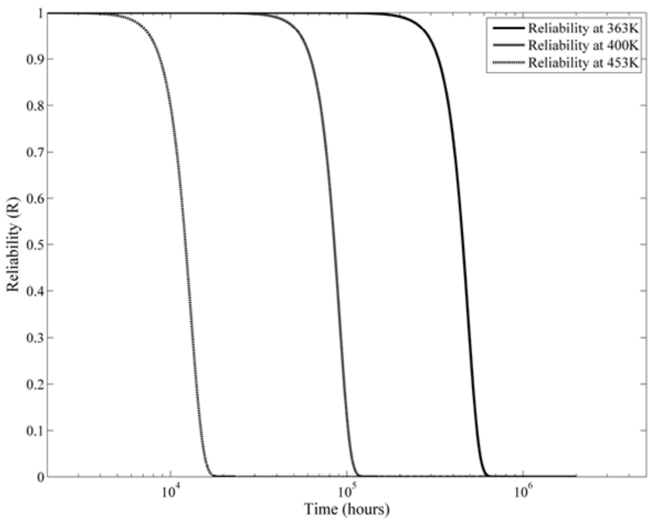

Fig. 5. The predicted variations of reliability at the allowable temperature lower 363K, 400K and upper 453K, respectively

these two curves are very similar to each other. This is because that the shape parameter, mainly decided by the mode turn, tends to its saturation value β=7.69, i.e. the characteristic of damage process about insulation changes little as the temperature within the allowable operation range. In other words the insulation technology of the test motors is suitable. The geometry about the mode turn and phase structure need to be improved for longer MTTF to meet the standard requirement as the operation temperature up to 440K and higher within the allowed range, see Table 3.

5. Conclusions

In the present study the Maximum Likelihood Estimator is taken to investigate the characteristics of the insulation failure about class-H motors with accelerated life tests data under censored situation. Three failure modes namely the turn, phase, and ground, respectively, are considered in the estimation, the so-called competing failure analysis. Several remarks can be summarized as follows:

a. About the model:
   1. Weibull representation of the reliability for each failure mode is suitable as taking the shape parameter varied with the temperature, this is necessary due to its influence on the estimation of the scale parameters which closely related to the MTTF prediction;
   2. Gompertz-type variation of the shape parameter is likely appropriated to depict the characteristics of cumulative damage process about the insulation; instead of Gompertz-type relation, other curves with both ends saturated can be considered, e.g. arctangent, logistic-like, etc. to show the variation of β with the temperature;
   3. The existence of reference temperature distinguishes the behavior of damage accumulation and correspond the thermal decomposition process.

b. About the motor in the testing:
   1. The insulation technique used is acceptable as the operation temperature kept in the use condition used 363K;
   2. As the temperature rises up to 440K, which still within the allowed range in application, the turn structure needs to be rearranged primarily , then the phase next;
   3. The mode ground has only influence on the failure at much higher temperature.
   4. Based on T_r, the maximum test temperature should below 516K because the behavior of failure is quite different to normal use condition. This is also referring to Nelson's result [11].

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