A Statistical Treatment of Accelerated Life Test Data for Copper-Water Heat Pipes

By

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Summary: A statistical method is proposed to treat accelerated life test data conducted at several elevated temperatures for a sufficient number of commercially available Cu-water heat pipes to predict the operation life. The temperature distribution measurements periodically carried out yield both data sets concerning the temperature drop and the gas column length as measures of non-condensible gas accumulation. The gas analysis with a mass spectrometer is also carried out to obtain the gas quantity data. A method of unified regression analysis to take account of the acceleration factor resulted from a number of elevated test temperatures is proposed to establish a method to predict the long-term performance degradation from life test data. The mutual correlations among three kinds of data sets are also discussed.

1. INTRODUCTION

The recent development of high speed and large capacity communication systems using a large number of high power LSI's which locally generate large amount of heat has demanded highly efficient cooling methods. The application of heat pipes has been expected to play a crucial role for such a purpose. The utilization of commercially available Cu-water heat pipes is proposed in the light of previous test results. However, it does not seem to be quite clear whether, or how, they are reliable for very long operation time, say 20 years, though it has been frequently described that copper is compatible with water as working fluid [*1, 2, 3*]. It was steel-water heat pipes that most of the efforts in life tests in the medium temperature range have been concentrated on [*1, 2, 4, 5*]. On the other hand, the reliability consideration should be based on the statistical treatment of sufficient amount of life test data with the aid of a rigorous mathematical model, because existing life test data exhibit large scattering. Only one report is found to comply with the line [*6*].

In this study, a sufficient number of commercially available Cu-water heat pipes have been put to an accelerated life test at several elevated temperatures so that a statistical treatment can be of significance. During the test they have been thermally activated, and variations of the temperature distribution along pipes with time have been periodically monitored. In addition, three pipes, at a time, have been offered to a gas analysis with a mass spectrometer to examine the non-condensible gas generation. These two kinds of measurements have produced the following three data

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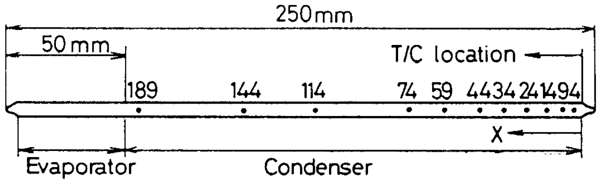
sets; the temperature drop data, the gas quantity data and the gas column length data. The last is independently induced from the results of both measurements. All the data are utilized to make a regression analysis to establish a method of statistical prediction of long-term performance degradation. The analysis includes a new attempt to correlate the data obtained at different test temperatures in terms of the single reduced time defined on the basis of the Arrhenius model. Mutual relations among three kinds of the data are discussed to check the validity of the method.

2. ACCELERATED LIFE TEST

The schematic illustration of a test heat pipe is given in Fig. 1. These are commercially available axially grooved Cu-water heat pipes. They are horizontally mounted on heater blocks whose temperatures are controlled so that the temperature at the entrance to the condenser denoted by T_{test} may be kept at one of the followings, 313 K, 333 K, 353 K, 393 K and 433 K, in the thermally activated state during the life test. They have no adiabatic sections and the whole condenser sections are exposed to the temperature controlled atmosphere at 300 K as a heat sink to which heat is rejected by natural convection. The temperature distributions along pipes are periodically monitored in the vertical position to avoid the puddle effect of the working fluid, whose reference temperature measured at the entrance to the condenser section, T_{meas}, is, in turn, set at about 297 K, 333 K and 363 K, respectively. The temperature drop in the condenser section, ΔT, and the length of the non-condensible gas column, x_0, as seen in Fig. 2, are taken as measures of non-condensible gas quantity. Here, ΔT is defined by $T_{ad}-T_{ci}$, where T_{ad} is the mean temperature in the constant temperature portion of the active condenser section, and T_{ci} is that of the inactive section. x_0 measured from the effective pipe end is given as the location whose temperature is equal to $(T_{ad}+T_{ci})/2$ as shown in Fig. 2. Three heat pipes, at a time, out of the subset members characterized by a test temperature, T_{test}, are regularly offered to a gas analysis. Each pipe is drilled to sample water vapor and non-condensible gas, and then is scrapped. Therefore, each gas quantity data is independent of each other.



Material Phosphorous deoxidized Cu
Pipe OD 6.35mm
60 Axial grooves
Working fluid Water

Fig. 1. Schematic of a test heat pipe. Locations of copper-constantan thermocouples are also given.

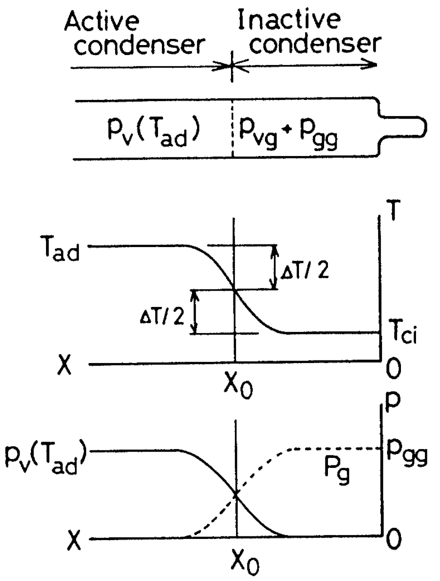


Fig. 2. Illustration of an equilibrium state in condenser section with non-condensible gas in inactive condenser section.

3. MASS ANALYSIS RESULTS

The gas analysis is carried out by using a mass spectrometer (HITACHI RMS-4). The general results are summarized as follows:

i) The non-condensible gas is exclusively composed of CO_2.
ii) The CO_2 generation rate increases with the rise of T_{test}.
iii) No detectable amount of H_2 is found.
iv) Definite but very limited quantity of naturally existing gases, such as O_2 and N_2, is detected, but it is independent of both T_{test} and the test duration.

The gas quantity data presented in this report represent the quantity of 6/88 of the total gas quantity except water vapor in a heat pipe measured in the unit of $m^3 \times Pa$ at 300 K. About 90 gas quantity data covering up to 300 days of the test duration are now available (3 pipes × 5 T_{test} levels ×6 sampling times).

4. REGRESSION ANALYSIS

The gas quantity data, a part of which is shown in Fig. 3, is chosen as an example of the analysis. First, the regression analysis is individually applied to each data subset characterized by a T_{test}. It seems that every data subset indicates a fundamental relation between the gas quantity data M_{ij} and time t_{ij} as;

$$M_{ij}=F_i t_{ij}^{\beta_i} \tag{1}$$

Here i denotes the subset number, that is to say, i=0 for T_{test}=313 K, 1 for 353 K, 2 for 373 K, 3 for 393 K and 4 for 433 K, and j is the data number in the i-th subset (j=1, --, N_i). F_i and β_i are constants depending on T_{test}. The above relation suggests the

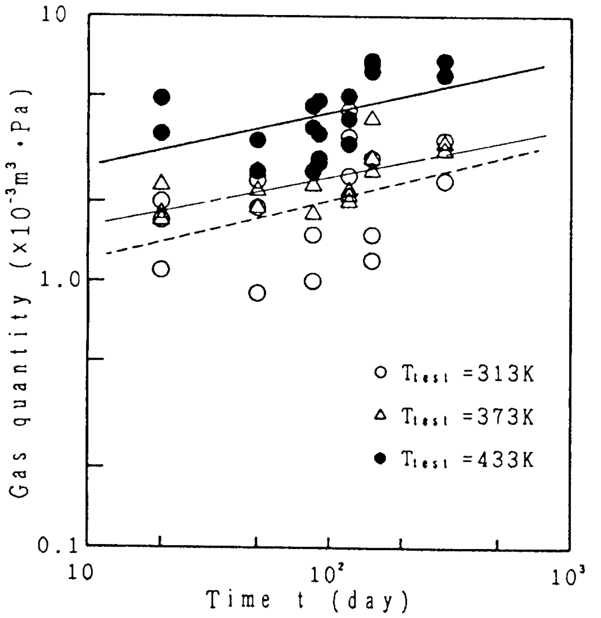


Fig. 3. Regression lines for gas quantity data for three data subsets, T_{test}=313 K, 373 K and 433 K.

following model

$$Y_{ij}=\alpha_i+\beta_i X_{ij}+\epsilon_{ij}, \tag{2}$$

$$\left.\begin{aligned} X_{ij}&=ln(t_{ij}) \\ Y_{ij}&=ln(M_{ij}) \\ \alpha_i&=ln(F_i) \end{aligned}\right\} \tag{3}$$

where α_i and β_i are to be computed and ε_{ij} is the error [7]. The best estimates b_{0i} and b_{1i} of α_i and β_i can be given by the application of the method of least squares to N_i pairs of observations (X_{ij} and Y_{ij}: j=1, 2, ---, N_i). Thus, the estimate Y of Y_{ij} is written as

$$Y_i=b_{0i}+b_{1i}X_i, \quad i=0,1,....,4 \tag{4}$$

Typical results are given by three lines for T_{test}=313 K, 373 K and 433 K in Fig. 3. The aforementioned features, that is, gradual increase of the gas quantity with time and the dependence on T_{test}, are evidently seen here. Furthermore, it shows that the slope of each line, that is, b_{1i}, is close to each other and b_{0i} reflects the effects of T_{test}.

The results of the individual regression analysis applied to other two data sets as well as to the gas quantity data lead to an attempt to treat all the data member among five data subsets (i=0, 1, --, 4) in order to seek a unified regression curve for each data set [8]. It is required for the treatment to be valid that the five individual regression lines, at least, have a common slope, b_1, as

$$Y_i = b_{0i} + b_1 X_i \tag{5}$$

If this is the case, the eq. (1) can be rewitten as;

$$\ln(M_i) = b_1 \ \ln(t_i F_i^{1/b_1}) \tag{6}$$

All the data belonging to the i-th data subset are arranged in terms of a unified function of the reduced time, $t_i F_i^{1/b_1}$. Before proceeding to the analysis, the validity of the treatment should be examined. The independence of each data is satisfied as described before. Data Y_{ij} in every subset for an X or t should be normally distributed and have equal variances. These requirements cannot be always strictly fulfilled, because the dependent variable is not M_{ij} itself but $\ln(M_{ij})$ in the formalism. However, the equality test of variances for each data subset assures that the five variances ($i=0$, 1, --, 4) may be regarded as all equal. Finally, F-test is applied to see whether the regression lines have a common slope, b_1. The result is that they may be equal in slope. It should be added here that another F-test rejects a possibility of $b_1=0$. This conclusion means that the gas quantity increases with time. These tests are also applied to ΔT-data and x_0-data and reach the same conclusions. Thus, the mutual correlations are also examined among data in the two data sets, ΔT-data and x_0 data. They indicate some fudamental features of the results as well as the validity of the unified regression analysis. The unified regression results are presented in Fig. 4 for gas quantity data, Fig. 5 for ΔT-data, and Fig. 6 for x_0-data. Other two hyperbola curves drawn in these figures are the 95% confidence limits for each true mean value for a given tF^{1/b_1}.

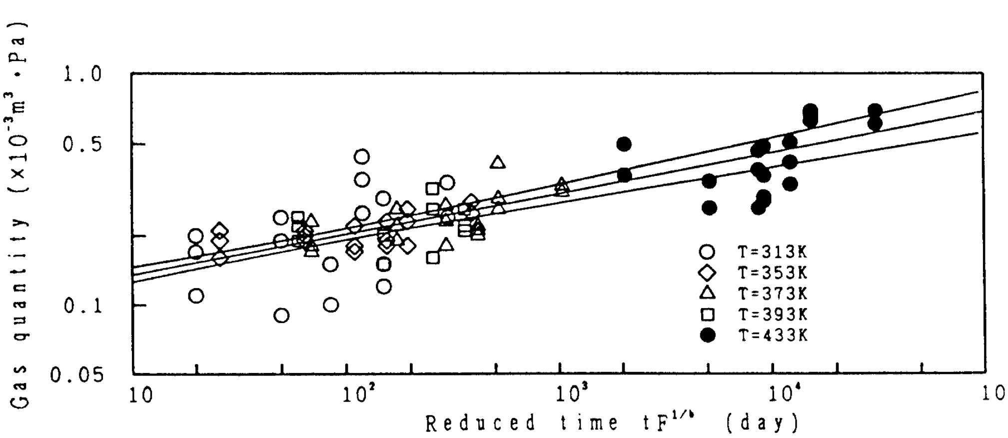


Fig. 4. Unified regression curve for gas quantity data and the 95% confidence limits for the true mean value of the gas quantity for a given reduced time, $tF^{1/b}$.

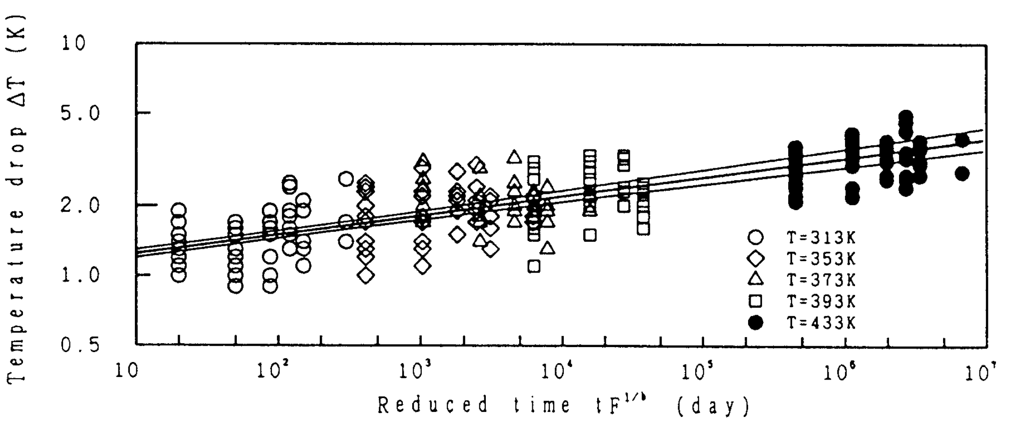


Fig. 5. Unified regression curve for temperature drop data and the 95% confidence limits for the true mean value of ΔT for given reduced time, $tF^{1/b}$.

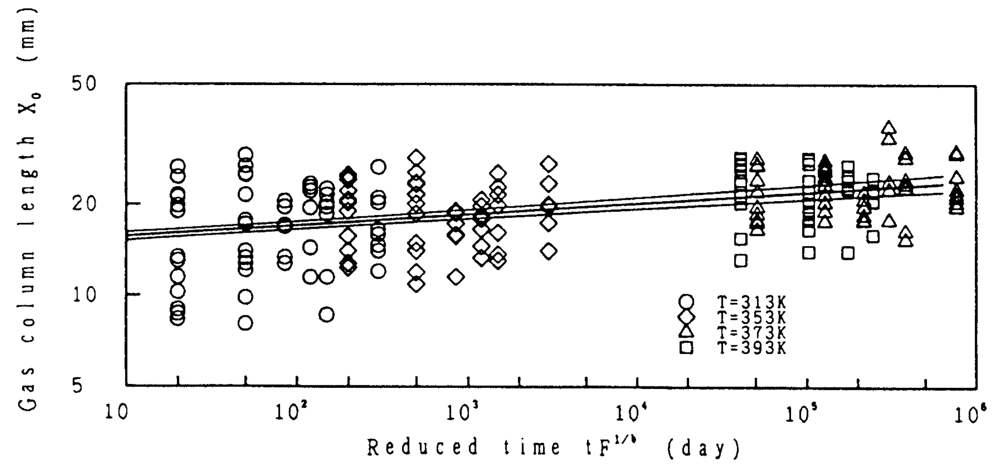


Fig. 6. Unified regression curve for gas column length data and the 95% confidence limits for the true mean value of x_0 for a given reduced time, $tF^{1/b}$.

5. Results and Discussion

(1) Arrhenius Plot

It is quite evident from Figs. 4, 5 and 6 that b_{0i}'s and thus F_i's are functions of T_{test}. Many mechanisms involving rate processes fit the Arrhenius model. If the gas (CO_2) generation is such a process, the acceleration factor, F_i, reflecting the effect of T_{test} can be expressed by the equation,

$$F_i = C\ exp(-E/kT_i). \qquad (8)$$

Here E is the activation energy of the reaction generating CO_2 for the present case, k is the Boltzmann constant and C is a constant. The condition as a reference state that $F_i=1$ for $T_i=T_{test}=313$ K is sufficient to decide the constant C. In Fig. 8, F_i values obtained in the unified regression analysis for three data sets are respectively plotted against $1/T_{test}$. It may be regarded as the data points of each kind of experiment to be

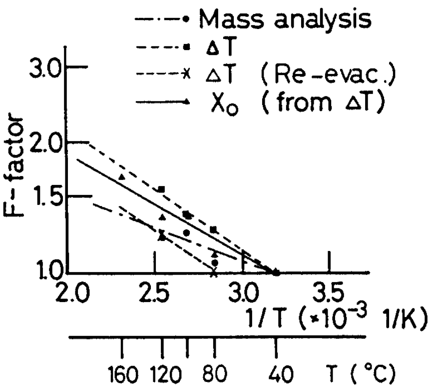


Fig. 7. Arrhenius plots for gas quantity data, ΔT-data and x_0 data. The acceleration factor, F, is calculated by the unified regression analysis.

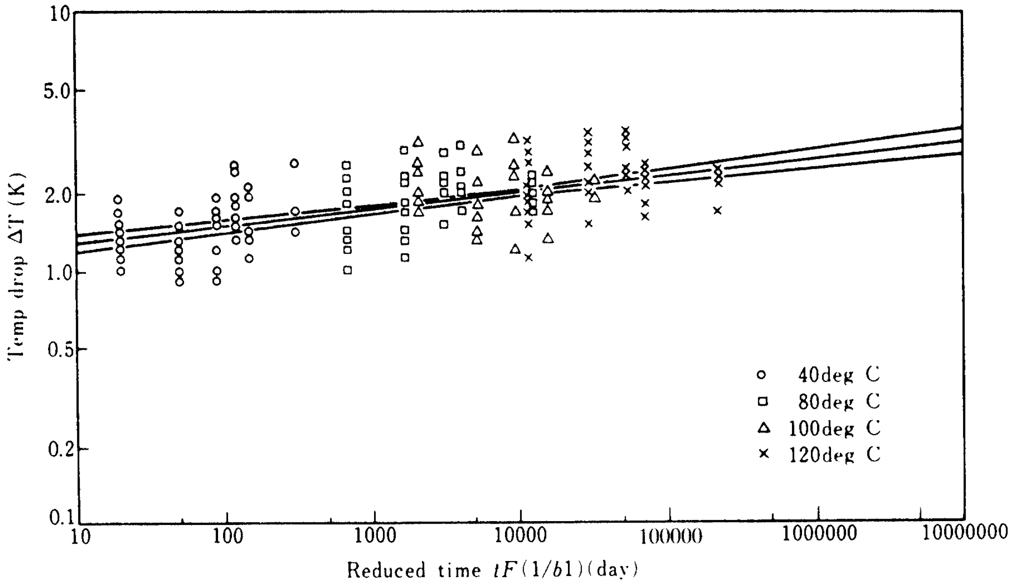


Fig. 8. Unified regression curve for temperature drop data except the 433 K data and the 95% confidence limits for the true mean value of ΔT for a given reduced time, tF^{1/b_1}. Compare with Fig. 5.

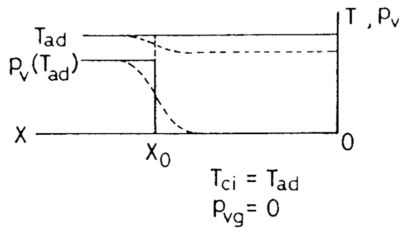
situated on each straight line, if those at 433 K are excluded. The slope of each line decided as the best fit to data excluding 433 K ones gives E to be 6×10^{-21} J for gas quantity data, 9×10^{-21} J for ΔT-data and 7×10^{-21} J for x_0-data. It is worth pointing out that these values are all comparable in the order of magnitude. This result is quite natural, because these three data sets result from a common phenomenon, that is, CO_2 generation in Cu-water heat pipes. Thus, the application of the Arrhenius model to the phenomenon is justified. The magnitude of E thus obtained indicates that CO_2 generation is diffusion- or similar kind of transport-process- controlled reaction. The activation energy for usual chemical reactions is typically larger than this figure by an order [*6*].

The reaction occurred during the test at $T_{test}=433$ K seem to be different from the other because E for above 410 K is larger than that for lower temperatures. This is also seen from microscopic observation of the surface state of the inner pipe walls, what will be described in the forthcoming report. This is the reason why data points for T=433 K are considerably apart from those for lower temperatures as seen in Figs. 4 and 5. The analysis is repeated for the data except those of 433 K in order to see the effect of the exclusion. The result is given in Fig. 8 for ΔT-data. Only a little appreciable difference is found by comparison with Fig. 5 in which data for 433 K are included. The reason for this is that the number of data for 433 K is at most 1/5 of the total number. It may be concluded that the inclusion of the 433 K data has a little effect on the regression curves but the reduced time allocated to the 433 K data is incorrect due to the wrong value of E. The test conducted at 433 K is inadequate to the accelerated test for operation at lower temperatures, that is for example, 353 K, because the reaction at such higher temperatures may be different from that at lower temperatures.

(2) Estimation of Gas Column Length

Both the non-condensible gas quantity and the temperature distribution along a heat pipe are independently measured, but both kinds of data must be mutually correlated. It is, of course, possible to solve a set of simultaneous equations which give relations between the gas quantity and the temperature distribution [9, 10]. However, such an approach is tedious and is not always suitable for statistical treatments. A straightforward but signijficant measure to correlate them is the gas column length x_0. The method obtaining x_0 from the temperature distribution was described in the previous section. A difficulty arising in the calculation of x_0 from the gas quantity is the estimation of the vapor pressure in the inactive condenser section, P_{vg}, as illustrated in Fig. 2. If the column length is enough long as in the cases of significant

I Perfect gas column model



II Imperfect gas column model

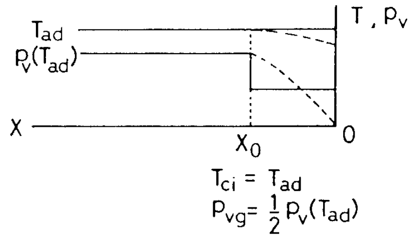


Fig. 9. Models to estimate the vapor pressure in the inactive condenser section; the perfect gas column model (model I) and the imperfect gas column model (model II). (see the text for explanation).

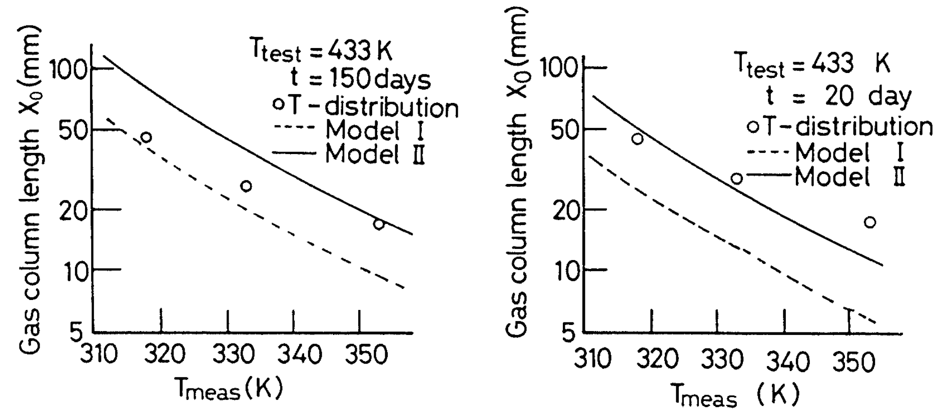


Fig. 10a and b. Comparisons of estimates x_0 from gas analysis data based on the models I and II with the data directly from temperature distribution measurement.

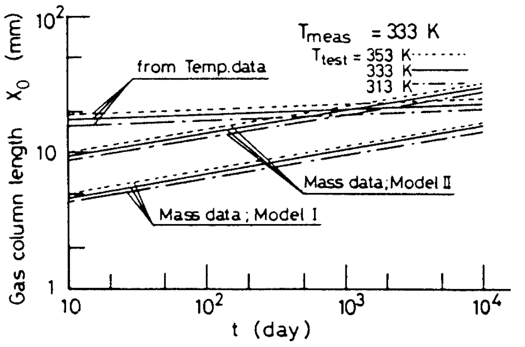


Fig. 11. Estimation of the gas column length x_0 from the temperature distribution measurement and the gas analysis data. The measuring temperature, T_{meas}, is assumed to be 333 K. The operation temperature is indicated by T_{test}.

gas accumulation or of very low vapor pressure $p_v(T_{ad})$ just as illustrated in Fig. 9, the perfect gas column model (model I) where the temperature and the vapor pressure in the inactive section are approximated by T_{ad} and 0 respectively must be applicable. On the other hand, in some situations where p_{vg} nearly linearly decreases from $p_v(T_{ad})$ to zero at the pipe end, another model (model II) that they are done by T_{ad} and $p_v(T_{ad})/2$ respectively may well describe the phenomenon as shown in Fig. 9. In fact, the estimate on the basis of the model I for the case of T_{test}=433 K, t=150 days and the measuring temperature T_{meas}=313 K well agrees with x_0 obtained from the temperature distribution measurement, and so does that estimated on the basis of the model II for T_{test}=433 K, t=20 days and T_{meas}=333 K as seen in Fig. 10-a and b, respectively. The prediction based on both models are compared with x_0 data directly obtained from the temperature distribution measurement in Fig. 11, where x_0 values are referred to those of heat pipes operated and measured at 333 K (solid lines). In addition, other two cases in which pipes are operated at both 353 K and 313 K and measured at 333 K are also plotted for comparison.

(3) Initial CO_2 Generation

The facts that appreciable amount of CO_2 accumulates in the condenser section

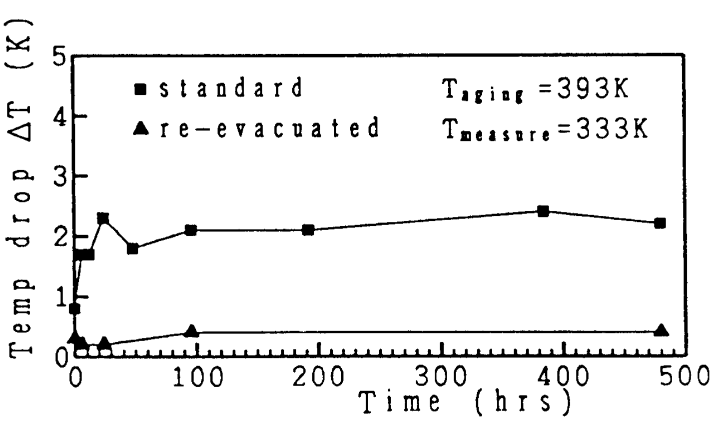


Fig. 12. Variations of the temperature drop, ΔT, during initial 20 days. The result for a standard heat pipe is compared with that for a re-evacuated pipe.

after life test but the increase rate is quite small suggest that initial CO_2 generation is responsible for the performance degradation after that. Therefore, all the same test procedure as the life test were repeated for other 40 heat pipes to investigate the gas generation during the initial 20 days. The initial variation of the temperature drop of the same heat pipe as that for the life test denoted by 'standard' is shown in Fig. 12, where the pipe is operated at 393 K ($=T_{aging}$) and is measured at 333 K ($T_{measure}$). There is a rapid increase in ΔT for initial several days, and the increase rate after that is close to that found in the life test. For the heat pipe that is re-evacuated after the initial phase, only very small total temperature drop is observed, though small but same increasing rete in ΔT is still found. In Fig. 13 the result from the accelerated life test for re-evacuated heat pipes is given for comparison with that of standard heat pipes. The effect of the re-evacuation process is quite clear in this figure. The Arrhenius plot for the re-evacuated heat pipes is also given in Fig. 7, where the data is indicated by x's and the reference temperature is taken as 353 K. It is quite reasonable that the same value of E is again obtained from the plot. Several preliminary examinations were carried out to investigate the cause of initial gas (CO_2) generation. An addition of baking process prior to the fill charge is found to give a little effect on CO_2 generation. No evidences of corrosion or pitting are observed on inner surfaces after the completion of the life test. However, black oxidized layers on them, which are formed with the aim of improving the heat transport or, more specificially, the surface wetting performance, are found to be completely scraped off and pure material surfaces are exposed after the test. Thus, the initial CO_2 generation is considered to originate from the decomposition of the layer which contains any hydrocarbon compound due to imperfect degreasing process proir to the oxidized layer formation. This subject will be discussed in more detail in the forthcoming report.

(4) Life Estimation

The particular life requirement presented by communication system customers is 20 years under the operation temperature at 333 K. If tolerable levels of x_0 or ΔT are specified, the answer is obtained from Figs. 5 or 6, or from Fig. 13 for the re-evacuated

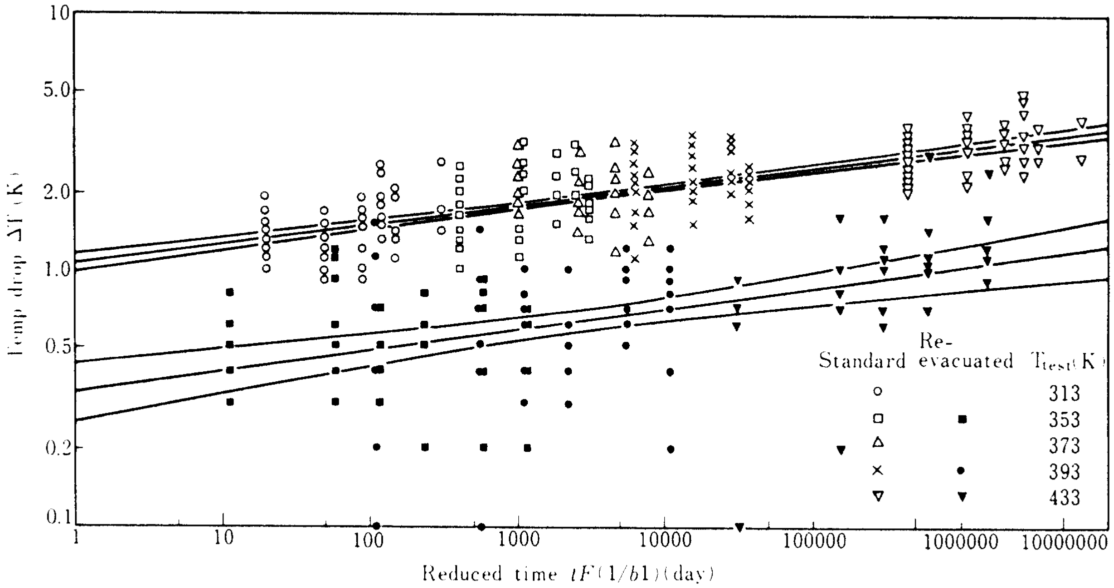


Fig. 13. Comparison of ΔT data between the standard and the re-evacuated heat pipes.

pipes. If, for example, the tolerable level determine the reduced time t_r by referring to the figures, the required accelerated test duration t at the temperature T_k to simulate the operation at T_j is calculated by the formula.

$$t=t_r(F_k/F_j)^{-1/b_l} \tag{9}$$

Here, F_k and F_j are the acceleration factors corresponding to T_k and T_j, respectively, and b_l is given in the unified regression analysis. The result obtained from ΔT data indicates that 20-years-operation at 333 K is simulated by an accelerated test at 393 K for about 470 days. The prediction curves are reformed in Fig. 11, where the abscissa expresses the time instead of the reduced time (tF^{1/b_l}). It is also seen in Fig. 11 that the model II gives a fair estimate of x_0 after 20 years. It is clear that for the practical application of this kind of heat pipes for over 20 years the re-evacuation process would solve the long-term degradation problem.

6. CONCLUSIONS

The following conclusions are drawn from the present study.

1) A method of unified regression analysis to take account of the acceleration factor resulted from the elevated life test temperature is successfully applied to CO_2 generation phenomena in commercially available Cu-water heat pipes.

2) The Arrhenius model can be applied to the data and identifies the CO_2 generation as a diffusion-like reaction.

3) A model that the temperature and the vapor pressure in the inactive condenser section are approximated by those in the active condenser section and by half of the vapor pressure at the temperature, respectively, can give fairly good estimate of the

gas column length from the gas quantity data for 20-years-operation.

4) Initial CO_2 gemeration is primarily responsible for the performance degradation. The re-evacuation process completely resolves the degradation problem.

5) This type of Cu-water heat pipe may be employed for 20-years-operation provided that re-evacuation is performed in the initial stage.

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