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Technical Note

# Long-term reliability of the thermal performance of a flat-plate heat pipe using a prognostics method

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ABSTRACT

Fast development of electronic devices for satellites not only has led to integration of a large number of microchips in a confined area but also increased the heat flux dissipated by the electronic devices. So, it is challenge to achieve greater reliability as well as performance of the HRS (Heat-Rejection System) such as heat pipes, PFL (Pumped Fluid Loops), radiators, used for electronic devices installed to satellites. Moreover, the HRS needs to be evaluated with long-term reliability tests prior to being applied in the satellite. In this paper, accordingly, with a prognostics method that was recently performed with a particle filter, we focus on the long-term reliability of the thermal performance of a flat-plate heat pipe which is generally used as the HRS in a satellite. In addition, we predict the thermal performance trends for the heat pipe in use based on the measurement data. In particular, we take the thermal performance trends as estimated by the prognostics method with a particle filter using 30 days of experimental data from a 42-day period, and we compare these trends against the actual experimental data to validate the prognostics method with the particle filter. Based on the results, we show that long-term reliability of the thermal performance can be obtained with limited experimental data considered all failure causes.


## 1. Introduction

A heat pipe is a simple device that quickly and efficiently transfers heat from the hot area to a relatively low temperature area using the phase change of a working fluid in a metallic container. The heat pipe does not need another component to operate, nor does it need power. Also there are no limitations with respect to installing it in a small space due to its various geometric configurations such as cylinders and flat-plates. This is why heat pipes have been widely used to cool down the electronic devices installed in satellites. However, when a heat pipe is used for a long period, a non-condensable gas such as hydrogen can be generated due to the electrochemical reaction between the surface of the metallic container and the working fluid. Thus, the non-condensable gas which is typically hydrogen, can be accumulate at the end of the condensation section and make a non-condensable gas block that interrupts the heat transfer of the heat pipe. It is one of the important failure factors that can reduce the thermal performance and life time of a heat pipe [1]. Also, the performance of a heat pipe can be diminished by other factors such as leakage in space and mechanical damage in operation [1]. Therefore, to properly operate the heat pipe during the life time of the electronic devices installed in satellites, the long-term reliability of the heat pipe should be evaluated in use with consideration given to all known failure causes.

A number of studies on the long-term reliability and lifespan of heat pipes with consideration given to the compatibility of a metallic container and working fluids have been conducted by several researchers [2–7]. In 1973, with Arrhenius model, Baker [7] firstly investigated an accelerating life test of heat pipes to estimate the thermal performance considering only one factor which is a non-condensable gas. However, the prediction of the thermal performance of the heat pipe can be changed according to operating conditions such as the surrounding humidity and working temperature. Therefore a real time diagnosis and prognosis for a heat pipe as HRS used in satellites should be required by observing the thermal performance of a heat pipe considered all failure causes of the heat pipes when in use.

In this paper, to predict the long-term reliability of the thermal performance of a flat-plate heat pipes in real time, we measured the surface temperature of a flat-plate heat pipe during 42 days under the sever working condition instead of a normal operating condition and experimentally observed the thermal performance using the thermal resistance model with measurement data. Also with the limited measurement data from 30 days we numerically

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**Nomenclature**

| | |
|---|---|
| $A$ | model parameter of intercept |
| $B$ | model parameter of slope |
| $f$ | transition function |
| $h$ | measurement function |
| $i$ | sample index |
| $k$ | time index |
| $L$ | likelihood function |
| $p$ | probability |
| $q$ | applied heat [W] |
| $R$ | thermal resistance [K/W] |
| $T$ | temperature [°C] |
| $t$ | time [days] |
| $v_k$ | process noise |
| $w_k$ | measurement noise |
| $x_k$ | state variable |
| $y_k$ | measured data |
| *Greek Symbols* | |
| $\sigma$ | standard deviation |
| $\theta$ | unknown parameter vector |

estimated the trend of the thermal performance using a prognostics method, which was recently used with a particle filter. So we compared the thermal performance trends estimated by the prognostics method using 30 days of experimental data with the experimental results to validate the prognostics method. Finally we show that long-term thermal performance reliability can be obtained with limited experimental data considered all failure causes using the prognostics method.

## 2. Experimental apparatus and prognostics method with a particle filter

The experimental system consists of a flat-plate heat pipe, a power supply for heating, a container for insulating the evaporation section of the heat pipe and a data acquisition, respectively. The container of the flat-plate heat pipe is made of aluminum with a groove wick, and acetone is chosen as the working fluid to minimize container corrosion. As shown in Fig. 1(a), the inside of the heat pipe is divided into 12 channels, and the groove wicks are manufactured to improve the movement of working fluid by capillary force. To measure the surface temperature of the flat-plate heat pipe, T-type thermocouples are used, as depicted in Fig. 1(b). The Fig. 1(b) shows that the temperature of the evaporation section and adiabatic section are each measured with one thermocouple (T-type), and four additional thermocouples (T-type) are used to accurately measure the temperature in the condensation section. With the measurement data, we define the thermal performance of the heat pipe using the thermal resistance as given by

$$R = \frac{T_{Evaporation} - T_{Condensation}}{q} \quad (1)$$

where $q$, $R$, $T_{Condensation}$ and $T_{Evaporation}$ are applied heat, thermal resistance, temperature at condensation and evaporation, respectively. The thermal resistance refers to the degree of obstruction for a heat transfer and is inversely proportional to the thermal performance of the heat pipe. Thus, the degradation of thermal performance can be observed through the increase of the thermal resistance of heat pipes. In the experiment, the heat pipe is operated in a severe working condition (>100 °C) instead of a normal operating condition (50 °C) so as to rapidly observe the degradation of the thermal performance of the flat-plate heat pipe.

To estimate the thermal performance trends of the heat pipe based on the measured data in real-time, the particle filter method is used. This method is a novel, useful technique used to analyze the observed data in real-time and to predict data trends [8]. Ultimately, the remaining useful life of dynamic systems such as engines and turbo machineries in real time can be evaluated based on the given predictions [8]. Since this method can be applied in non-linear systems with non-Gaussian process noises unlike the classical Kalman filter, it has a lot of applications in the science and engineering fields, including with respect to crack growth [8–9] and battery degradation [9]. Particularly, compared to the conventional Monte-Carlo simulation, the particle filter is a very fast and efficient way of dealing with the observed data in real-time by providing a sequential framework for the long-term reliability [8–10]. The particle filter uses a statistical approach based on the following Bayes' theorem [11].

$$P(\boldsymbol{\theta}|\boldsymbol{y}) \propto L(\boldsymbol{y}|\boldsymbol{\theta}) \cdot p(\boldsymbol{\theta}) \quad (2)$$

where, $\boldsymbol{\theta}$ is an unknown parameter vector, $\boldsymbol{y}$ is the measurement data, $L(\boldsymbol{y}|\ \boldsymbol{\theta})$ is the likelihood function or the conditional probability density function (PDF) of $\boldsymbol{y}$ at a given $\boldsymbol{\theta}$, $p(\boldsymbol{\theta})$ is the prior PDF of $\boldsymbol{\theta}$, and $p(\boldsymbol{\theta}|\ \boldsymbol{y})$ is the posterior conditional PDF of $\boldsymbol{\theta}$ at a given $\boldsymbol{y}$. If new measured data are present in real-time, the particle filter estimates and updates the state variables of the system and unknown parameters recursively with "particles" (or samples) based on the Bayes' theorem. The general process is as follows [8].

$$x_k = f(x_{k-1}, \theta_k, v_k) \quad (3)$$

$$y_k = h(x_{k-1}, w_k) \quad (4)$$

where $f$, $h$ and $k$ are the transition function, the measurement function and the time index. In addition, $x_k$ and $y_k$ are the state variable and measured data, and $v_k$ and $w_k$ are the process and measurement noise, respectively. In this study, the thermal resistance, Eq. (1), for a flat-plate heat pipe is chosen as the state variable $x_k$. Based on the observations, the degradation model for the thermal performance can be assumed as a linear function in terms of time as follows.

$$R = A + bt \quad (5)$$

where $A$ and $b$ are the model parameters, and $t$ is the used time, respectively. The transition function for the present study is then derived as follows.

$$x_k = (A + b_k \Delta t) x_{k-1} \quad (6)$$

where $\Delta t$ is the time step size. For the sake of simplicity, we can fix one of the model parameters, namely $A = 0.5$, which is the initial value of the thermal resistance based on the observation. Also, process noise $v_k$ is ignored because it can be handled through the uncertainty in the model parameter $b_k$. The measurement noise $w_k$ is assumed as normally distributed with unknown standard deviation $\sigma$.

The process begins with the drawing of an arbitrary set of samples for the parameters $x$, $b$ and $\sigma$ at step $k = 1$. Then the following three steps are employed. First is the prediction step in which the posterior distribution of $b$ at the previous step $k-1$ is used as the prior at the current step $k$, and the state variable at the current step is predicted using Eq. (6). Next is the updating step of the parameters using the likelihood when new measurement data $y_k$ is intro-