Temperature Control of High Temperature and High Voltage Device by Fluid Loop Insulation and Cooling System Using Fluorinated Inactive Liquids

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Abstract

Miniaturization and high performance are always required for space equipments. To cite a case, for the Ion-propulsion engine which contributed to the asteroid sample return mission by “Hayabusa” spacecraft, it is required to drive at higher voltage in order to get higher specific impulse. However, if the operating voltage becomes higher, the probability of discharge between electronic devices rises and thus the equipment inevitably grows in size to keep sufficient gap between the devices. In addition, as there is no convectional heat transfer in space, the temperature locally becomes very high if the equipment is downsized. So, it can be said that miniaturization and high performance are generally contradictory requirements. In this research, a fluid loop insulation and cooling system was built as a means of realizing both miniaturization and high voltage. For the working fluid of the system, fluorinated inactive liquids were used which can provide high electrical insulation and thermal conductivity. In this paper, to begin with, the electrical insulation property of the fluorinated inactive liquids was verified by an experiment. Then the dynamics model of the constructed insulation and cooling system was derived by a system identification experiment. Finally, a control low for temperature control was constructed using the estimated model and cooling performance of the system was examined by both numerical simulations and experiments.

フッ素系不活性液体を用いた流体ループ式絶縁冷却システムによる高温高電圧機器の温度制御

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摘要

宇宙用機器は，トータル質量の軽減，コストの削減，先端ミッションへの貢献など様々な観点から，常に機能の高性能化と小型化が要求される．小惑星探査機はやぶさで大きな成果をあげたイオンエンジンを例に挙げると，より高い比推力を得るためにはより高電圧での駆動が必要である．しかし，電源を高電圧化した場合，電圧が加わる電子素子間の放電発生確率が高まるため，一般に大型化が必要になる．また，宇宙では対流熱伝達がないため，小型化しようとすると局所的に非常に高温になり，機器を小型化するのは難しい．

機器を大型化せずにこれらの問題を解決する一つの手段として，本研究ではフッ素系不活性液体を用いた絶縁冷却システムを構築した．フッ素系不活性液体とは電気絶縁性や熱伝達率に優れている，化学的に安定な液体である．本研究では，まずフッ素系不活性液体の絶縁性を実験により検証した．また，システム同定実験により絶縁冷却システムのモデルを導出した．そして作成したモデルを用いて温度制御のための流量制御則を構築し，数値シミュレーションと実験の双方により絶縁冷却システムの冷却性能を検証した．

1. Introduction

Miniaturization and high performance are always required for space equipments. To cite a case, for the Ion-propulsion engine which contributed to the asteroid sample return mission by “Hayabusa” spacecraft, it is required to drive at higher voltage in order to get higher specific impulse. However, if the operating voltage becomes higher, the probability of discharge between electronic devices rises and thus the equipment inevitably grows in size to keep sufficient gap between the devices. In addition, as there is no convectional heat transfer in space, the temperature locally becomes very high if the equipment is downsized. So, it can be said that miniaturization and high performance are generally contradictory requirements.

In this research, a fluid loop insulation and cooling system was built as a means of realizing both miniaturization and high voltage. For the working fluid of the system, fluorinated inactive liquids(1) were used which can provide high electrical insulation and thermal conductivity (Table 1). In this paper, to begin with, the electrical insulation property of the fluorinated inactive liquids was verified by an experiment. Then the dynamics model of the constructed insulation and cooling system was derived by a system identification experiment. Finally, a control low for temperature control was constructed using the estimated model and cooling performance of the system was examined by both numerical simulations and experiments.

2. Verification Experiment of Insulation Property

2-1 Purpose of Verification Experiment

In this research, a kind of fluorinated inactive liquids, fluorinert(2) FC-3283 is used for the working fluid of the insulation and cooling system. This experiment is intended for the actual proof of the insulation property of fluorinert FC-3283, and experimental setup is designed and made for the experiment (Fig. 2 and Fig. 3). And, the setup is designed to pressurize the experimental vessel inside to decrease bubbles which are generated by heating of fluorinert. Even if the insulation properties of fluorinert are verified by an experiment, there are possibilities that electric discharge occurs from the bubbles. So, it is verified that the generated bubbles are controlled by this experimental setup.

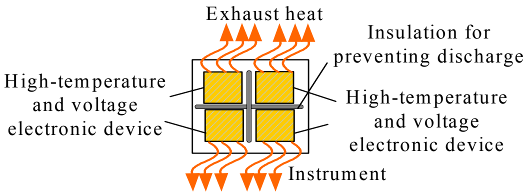


Figure 1 Imagery of Thermal Control and Insulation

Table 1 Fluorinert and Typical Insulation Oil

	Fluorinert (FC-3283)	Typical insulation oil
Firing point（℃）	Incombustibility	148
Flow point（℃）	-50	-30.3
Breakdown voltage（kV）	43	60
Kinetic viscosity（st）	0.008（at 25℃）	8（at 40℃）
Heat transfer coefficient（W/mK）	0.067	0.15

2-2 Experimental Methodology of Verification

[Experiment 1]

Verification Experiment of Insulation Property

To begin with, it is determined if the electric discharge occurs in air using high voltage generator set at 14kV. Next, high voltage generator is set in the experimental setup of verification of insulation property of fluorinert like Fig. 3, and the experimental vessel is filled by fluorinert. Finally, high voltage generator is turned on power, and it is checked that electric discharge does not occur.

[Experiment 2]

Observation of Pressurized Bubbles

In experiment 2, a heater is replaced by the high voltage generator. The heater is turned on power, and bubbles are generated. Next, a piston which is put in the experimental vessel is slid down, and the experimental vessel inside is pressurized. As a result, the behavior of bubbles is observed.

2-3 Result of Verification Experiment

[Experiment 1]

Fig. 4 (a) shows the result of discharge test in air. Looking at Fig. 4 (a), discharge occurs from the high voltage generator to a cupper plate. This result shows that discharge occurs in air. And Fig. 4(b) shows the result of discharge test in fluorinert. Looking at Fig. 4(b), discharge does not occur in fluorinert. This result shows that when temperature of fluorinert is 25.0℃, dielectric strength of fluorinert is more than 14kV (3.5mmGap).

[Experiment 2]

Fig.5 shows the behavior of bubbles before pressurization and after pressurization. Looking at Fig.5, the mass bubbles are generated before pressurization, but the bubbles are decreased after pressurization. This result shows that it is determined if the bubbles generated by heating of the heater can be decreased by pressurizing of fluorinert. It is thought that because the pressure which is more than vapor pressure is assigned to the experimental vessel, this phenomenon occurs. As a result, when the bubbles are generated, the probabilities of discharge in the spaces increase, but the bubbles can be controlled by pressurizing fluorinert. It is shown that if the bubbles can be decreased, the bubbles can be eliminated from a target of discharge because the bubbles are moved forcibly by the pump.

3. Linear Model of Insulation and Cooling System

3-1 Insulation and Cooling System

Fig.6 shows insulation and cooling system which is composed by this study and allows insulation and cooling at the same time and Fig.7 shows the brief overview of the insulation of cooling system. In this system, high temperature and high voltage electric devices are imitated by a heater which is placed at the middle of the experimental vessel, and fluorinert is filled in the system.

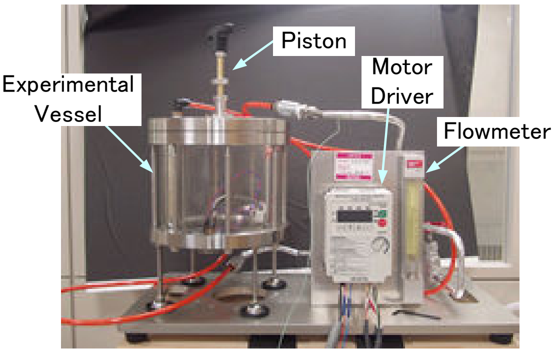


Figure 2 Appearance of Experimental Setup

(Verification Experiment of Insulation Property)

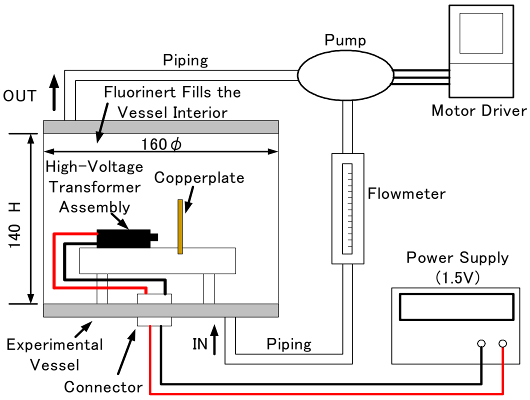


Figure 3 Brief Overview of Experimental Setup

(Verification Experiment of Insulation Property)

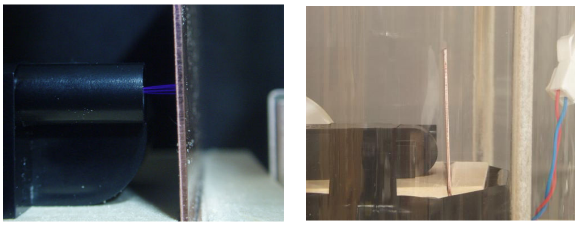
Temperature of the target of cooling can be controlled by a pump. Fluorinert heated by the heater is cooled by passing a radiator. The supply capability of heater and flow of fluorinert is variable. Flow of fluorinert is control input, and the temperature of heater which imitates high temperature and high voltage electric devices is controlled.

3-2 System Identification

In this study, system identification is performed using input and output data to derive an analytical model of the insulation and cooling system. Input is flow of fluorinert and output is the temperature of the middle of the experimental vessel here. For system identification, ARX (Auto-Regressive eXogeneous) model(3) is assumed. When white noise is determined using ω_k, it is assumed identification target is described as that the relation of input and output of

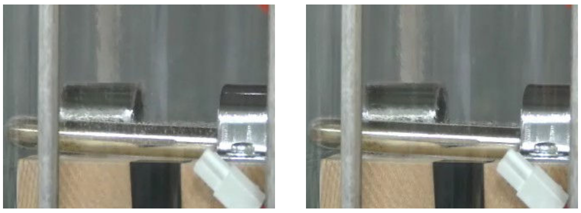
$$\begin{aligned} y(k)+a_1y(k-1)+\cdots+a_{n_a}y(k-n_a) \\ =b_1u(k-1)+\cdots+b_{n_b}u(k-n_b)+\omega(k) \end{aligned} \tag{1}$$

Following approximations are ushered into (1)



(a) in air (b) in fluorinert

Figure 4 Result of Discharge test



(a) before pressurization (b) after pressurization

Figure 5 Observation of the bubbles

$$\begin{aligned} A(q)&=1+a_1q^{-1}+\cdots+a_{n_a}q^{-n_a} \\ B(q)&=1+b_1q^{-1}+\cdots+b_{n_b}q^{-n_b} \end{aligned} \tag{2}$$

Then, (1) is described as

$$A(q)y(k)=B(q)u(k-n_k)+\omega(k) \tag{3}$$

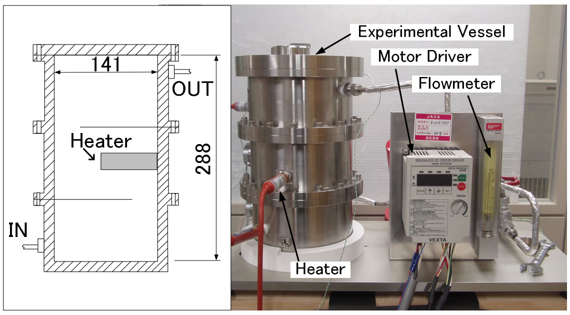


Figure 6 Insulation and Cooling System

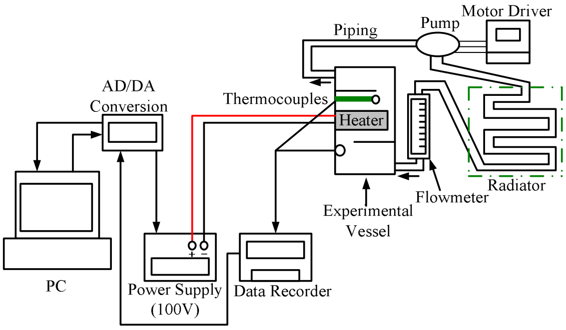


Figure 7 Brief Overview of Insulation and Cooling System

A model which can be described like this is called ARX model. The analysis model of the insulation and cooling system is derived using ARX model and linearization around some flow. The conditions of the system identification are shown below:

- Supply capability of the Heater : 300W (Constant)
- Flow of fluorinert : Max. 454.4ml/min, Min. 263.5ml/min, 2.78×10^{-4}Hz (1 cycle per hour) ~ 1.67×10^{-3}Hz (1 cycle per 10 minutes), sweep input

3-3 Result of System Identification

Fig. 8(a) shows the input (flow of fluorinert) and output (temperature of the middle of the experimental vessel) in the conditions which are referred in section 3-2, and Fig. 8(b) shows the comparison between experimental result and result of system identification. Then, temperature and flow of fluorinert in Fig. 9 is the value where direct current component is removed.

Looking at Fig. 8(b), the experimental result and the result of system identification almost correspond with each other. As this result, a transfer function of discrete time system of the system is

$$G(q)=\frac{B(q)}{A(q)}=\frac{-4.31\times10^{-5}}{1.00-q^{-1}} \tag{4}$$

and, a transfer function of continuous time system of the system is

$$G(s)=\frac{-4.31\times10^{-4}}{s+7.60\times10^{-3}} \tag{5}$$

4. Temperature Control Experiment of the System

4-1 Summary of Temperature Control Experiment

In this section, temperature control experiment of the heater which imitates high temperature and high voltage electric devices is performed using the experimental system shown in Fig.7, and the result of this experiment is compared with the result of numerical simulation using linear analysis model which is derived by system identification. Then, adequacy of the model in linear range is validated.

4-2 Control method for the Experiment

This experiment system is orienting system, and the system is thought of as its response is fast and there is almost no dead time. So, the differential action is not necessary. Then, PI control is performed for the temperature control experiment. Its control input is flow of fluorinert, and temperature of the middle of the experimental vessel is fed back.

4-3 Experimental Methodology of the Experiment

First, the insulation and cooling system is filled by fluorinert, and the heater placed at the middle of the experimental vessel is driven at 300W. Then, the pump is driven till the temperature of the middle of the experimental vessel is static state. PI control starts When the temperature is static state, and each data are obtained. In this experiment, target temperature of the middle of the experimental vessel is x_m+4 ℃ (x_m=39.5℃).

4-4 Result of Temperature Control Experiment

Fig.9 shows the comparison between result of the experiment and numerical simulation. Focused on Fig.9 (a), the result of the experiment and numerical simulation correspond to each other, and both results converge on target temperature. However, Looking at Fig. 9 (b), they correspond to each other qualitatively, but experimental result is bigger than the result of numerical simulation. But this difference is about 6% thinking of actual flow rate (direct current component is removed.), so the adequacy of the analytical model which is represented as equation (5) is validated on some level.

5. Bilinear Model of Insulation and Cooling System

5-1 Modeling of Insulation and Cooling System

In this research, it is assumed that insulation and cooling system is mounted in spacecraft, and temperature control is performed whose control input is flow of fluorinert and state quantity is temperature of the place where insulation and cooling is necessary. In the preceding chapter, the insulation and cooling system is modeled linearized around some flow as early consideration, but in the case of actual spacecraft, the control input is varied in a wide range, and it is necessary to perform temperature control in a wide range.

Then, the insulation and cooling system is modeled with idealizing, so the system is described as

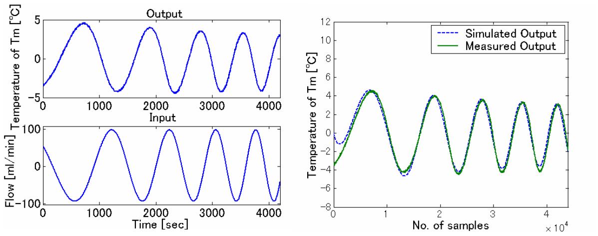
$$C_1\frac{d(x_1-x_0)}{dt}=-u(x_1-x_0)+Q-\frac{x_1-\alpha}{R_1} \tag{6}$$

$$C_2\frac{d(x_2-x_0)}{dt}=u(x_1-x_2)-\frac{x_2-\alpha}{R_2} \tag{7}$$

x_1, x_2 represent temperature of the middle of the experimental vessel and temperature of lower stand of the experimental vessel. x_0 represents temperature of fluorinert flowing in the middle of the experimental vessel, and C_1, C_2 represent heat capacity of the middle of experimental vessel and lower stand of experimental vessel, and Q is heat flow from heater, R_1, R_2 represent overall heat transfer resistance of the middle of the experimental vessel and lower stand of experimental vessel, α is ambient temperature of experiment room. The equation of state is described as

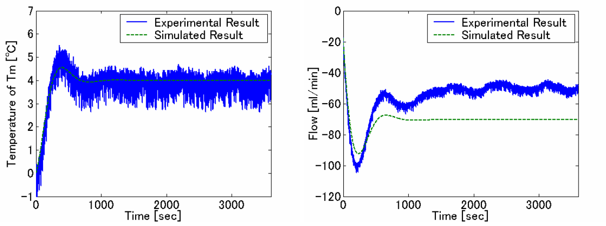
$$dx/dt = Ax+Bux+Cu \tag{8}$$

As above, the equation of state can be represented using



(a)Input and Output (b)Result of System Identification

Figure 8 Result of System Identification



(a)Temperature History (b)Flow History

Figure 9 Comparison between result of the experiment and numerical simulation

the product of input u and state x(4). The system like this is called bilinear system. The theoretical model is derived in this way, but the constructed system is very complex structure because flow path is set using dividing walls shown in Fig. 6 and 7 to cool the target certainly. For this reason, it is thought that there are nonlinearity because of flow which can not be expressed by equation (6) and (7). In the case that insulation and cooling system is mounted in actual spacecraft, it is assumed that the system is very complex also. So, in this study, the parameters of analytical model which can use the determination of control gain is obtained by system identification, and the analytical model of insulation and cooling system is constructed.

Then, equation (6) is deformed using $1/C_1R_1 = a$, $1/C_1 = b$, $x_0/C_1 = c$, $(QR_1 + \alpha)/C_1R_1 = K$ as

$$\dot{x}_1 = -ax_1 - bux_1 + cu + K \tag{9}$$

It is linearized around $x_1 = x_m$, $u = u_m$, and organized as

$$\Delta\dot{x} = -(a + bu_m)\Delta x - (bx_m - c)\Delta u \tag{10}$$

Furthermore, it is described using $\Delta x \to x$, $\Delta u \to u$, as

$$\dot{x} = -(a + bu_m)x - (bx_m - c)u \tag{11}$$

Equation (11) is Laplace transformed as

$$X(s) = \frac{-(bx_m - c)}{s + (a + bu_m)}U(s) + \frac{1}{s + (a + bu_m)}x(0) \tag{12}$$

System identification is performed with the equilibrium temperature and flow of fluorinert varied, and obtained transfer function is compared with equation (12), and the constant terms of equation (12) is derived. So, the analytical model of the system is constructed.

The experimental conditions of system identification are shown below. 10 set experiments are performed with supply capability of heater and flow of fluorinert varied. Where, the sampling time is 100ms.

[Experimental Condition 1]

- Supply capability of heater : 150 ~ 500W (every step is 50 W, 8 types, constant)
- Flow of fluorinert : Max. 454.4ml/min, Min. 263.5ml/min, 2.78×10^{-4}Hz (1 cycle per hour) ~ 1.67×10^{-3}Hz (1 cycle per 10 minutes), sweep input

[Experimental Condition 2]

- Equilibrium temperature of the middle of the experimental vessel : 39.5℃ (constant)
- Flow of fluorinert : 358.9 ~ 549.8ml/min and 168.0 ~ 358.9 ml/min, 2.78×10^{-4}Hz(1 cycle per hour) ~ 1.67×10^{-3}Hz (1 cycle per 10 minutes), sweep input

5-2 Result of System Identification and Consideration

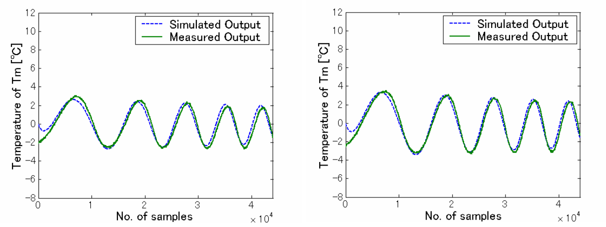
In this section, the results of system identification which 1 dimension ARX model is assumed are shown. It is easy to compare with theoretical model represented by equation (12). Fig. 10 (a) ~ (h) and Fig. 11 (a) ~ (b) show the comparison between experimental results and results of system identification under experimental condition 1 and 2. Then, temperatures in Fig. 10 (a) ~ (h) and Fig. 11 (a) ~ (b) are the values where direct current component is removed. Looking at Fig. 10 (a) ~ (h) and Fig. 11 (a) ~ (b), the experimental results and the results almost correspond with each other in any cases. As these results, a transfer function of continuous time system of the system is derived. The relation of the equilibrium temperature and the numeration of the transfer function are shown in Fig. 12, and the relation of the average flow and denomination of the transfer function are shown in Fig. 13. As these results, the constant terms of equation (12) are described as

$$\begin{cases} a = -3.03 \times 10^{-3} \\ b = 9.55 \times 10^{-6} \\ c = -6.57 \times 10^{-5} \end{cases} \tag{13}$$

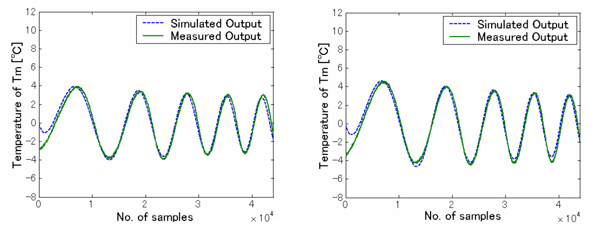
And equation (9) is described as

$$\begin{aligned} \dot{x} = (3.03 \times 10^{-3})x_1 - (9.55 \times 10^{-6})ux_1 \\ - (6.57 \times 10^{-5})u + (9.55 \times 10^{-6}Q - 3.03 \times 10^{-3}\alpha) \end{aligned} \tag{14}$$

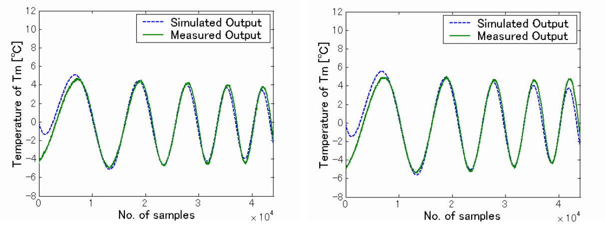
As this result, bilinear analysis model of insulation and



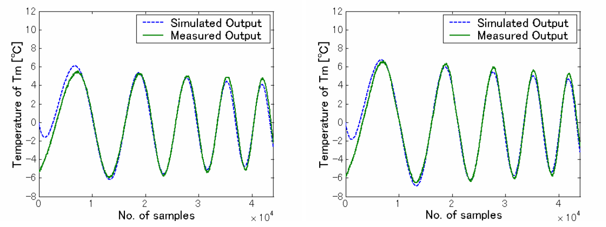
(a) 150W（x_m =23.5[℃]） (b) 200W（x_m =28.8[℃]）



(c) 250W（x_m =34.0[℃]） (d) 300W（x_m =39.5[℃]）

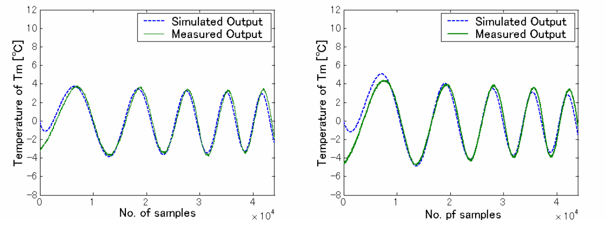


(e) 350W（x_m =44.1[℃]） (f) 400W（x_m =49.0[℃]）



(g) 450W（x_m =54.1[℃]） (h) 500W（x_m =59.5[℃]）

Figure 10 Results of System Identification under condition 1



(a) 168.0～358.9 ml/min (b) 358.9～549.8ml/min

Figure 11 Results of System Identification under condition 1

cooling system is constructed. For the future, the adequacy of this analytical model will be validated, and it is necessary to construct the control law of the system as bilinear system.

6. Conclusion and Future Works

In this study, insulation and cooling system is constructed using fluorinated inactive liquid. First, insulation property of fluorinert is validated by experiments. Next, linear analytical model of the system is validated by comparison between the results of numerical simulation and experimental results as early deliberation. Then, it is shown that actual insulation and cooling system is bilinear system, and bilinear analytical model of the system is derived by the comparison between theoretical model and the results of system identification.

For the future, the temperature control law will be invented using bilinear analytical model of the system, and it is necessary to validate the adequacy of the bilinear analytical model with comparison between results of numerical simulation and experimental results in a wide range. Also, it is necessary to design and construct experimental setup to perform experiment alike actual space craft in experiment, size, and structure.

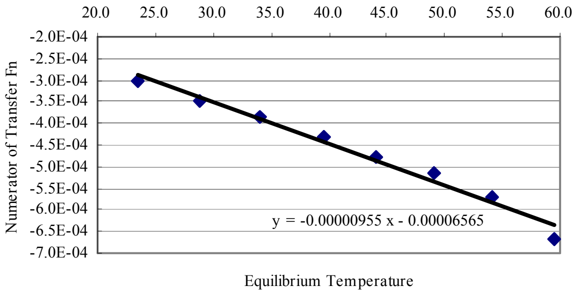


Figure 12 Relation of the Equilibrium Temperature and the Numeration of the Transfer Function

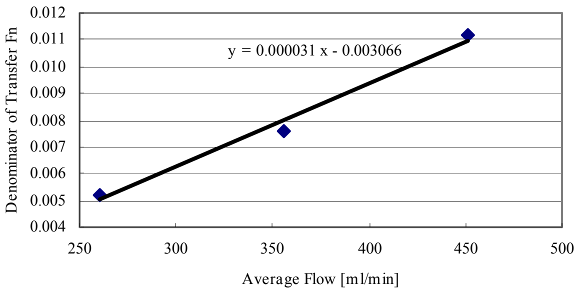


Figure 13 Relation of the Average Flow and Denomination of the Transfer Function

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