신뢰성응용연구 신뢰성기술
제9권, 제2호. pp.149-163, 2009

A Study on Thermal Characteristics for Hand Carried Ultrasound System

Jong-Gu Kim, Young- Jin Cho, and Kae-Dal Kwack*

Dept. of Electronic Engineering, Graduate school of engineering, Hanyang University,
17 Haengdang-dong, Seongdong-gu, Seoul 133-791, Korea

Abstract

This paper intends to suggest a design to reduce the thermal load of a hand-carried ultrasound (HCU) system, with the aim of increasing the product life. To design ways to reduce the heat load, the surface temperatures of key parts of an HCU system were measured as the 4 system cooling fans, which have a direct relation to the system life, were operated normally. When the derating rate of 80% was applied while the fans of the HCU system were operated abnormally, it was observed that the key image processing parts exceeded the surface temperature (TC) with consideration to derating. Since the part surface temperature did not exceed the derated level when the regulated voltage was derated from 12V to 9V, it is expected to lower the operating voltage of the fans to 9V to increase the fan and HCU system lifetime by 1.8 times.

1. INTRODUCTION

With economic and technological advances enabling higher quality of life and better medical services, the average human lifespan has increased, and countries around the world are becoming aging societies. To cope with the resulting issues, the health care industry has been required to adapt. Accordingly, the market for ultrasound systems has continued to grow, and new markets have been expanding due to the introduction of mobile ultrasound systems Kwang-Hoe Kim(2007). For the purposes of this paper, the mobile ultrasound system will be called the hand-carried ultrasound system (HCU system). The HCU system is shaped like a compact notebook computer for the purpose of mobility. Its market is growing, and is expected to reach more than 37,474 units in 2012 IMS Research(2008).

Despite the rapid growth in the market, the mobile unit is vulnerable in terms of thermal reliability, as it is designed with a compact structure for the purpose of mobility, which can degrade the durability of the product. Therefore, it is necessary during the design process to study whether the structural change employed to reduce the form factor of the HCU system can lead to Thermal reliability problems.

This study describes the surface temperture measurement of main parts while operating the RHE fan and system fan of the HCU system developed by company 'A', and suggests derating measures to improve thermal reliability.

2. DERATING DESIGN

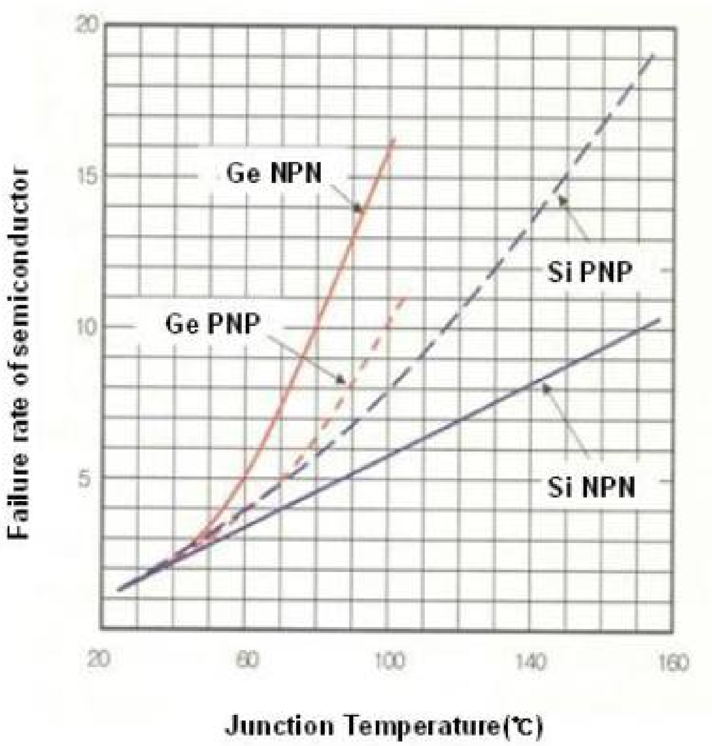
2.1 Definition and Types of Derating

Derating is a method of reducing stress and/or making quantitative allowances for a part's functional degradation. Consequently, derating is a means of reducing failures, extending part life, and increasing reliability (not quality). In addition, derating helps protect parts from unforeseen application anomalies and overstresses SD-18(2004).

Typical factors considered for derating when designing electrical parts are thermal stress and electrical stress. Derating of electrical stress is the operation of a part at a lower electrical level than its specification. Thermal derating is the operation of a part at a temperature lower than its specified temperature or junction part temperature.

2.2 Thermal Derating

Approximately 70% of failures occurring on electrical devices consisting of electronic parts are known to be directly or indirectly caused by overheating. As such, thermal derating measures to restrain the operating temperature or junction part temperature to below a certain level must be considered in the design stage in order to ensure stable operation.



<Figure 1> Temperature vs. Failure Rate of Semiconductor Parts

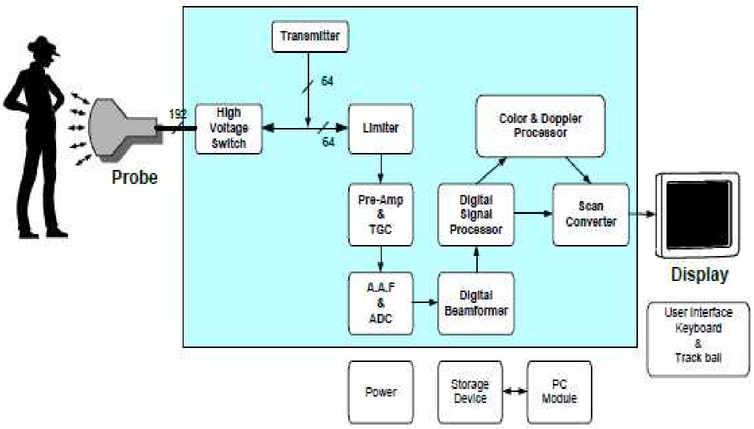
3. HAND CARRIED ULTRASOUND SYSTEM

The reason why thermal derating design is needed is because when the temperature of the semiconductor part rises, the failure rate quickly increases, and thus product life is reduced. <Figure 1> shows the correlation between the IC junction part temperature and the failure rate. It clearly shows that the failure rate rapidly increases as temperature rises Myeong-Soo Kim(2007).

Therefore, a design that applies a 15~20% derating from the maximum specified temperature of the part junction is typically used to reduce thermal load.

3.1 Structure of HCU System

<Figure 2> HCU System



<Figure 3> HCU System Internal Structure

<Figure 2> and <Figure 3> show the exterior and internal structure, respectively, of the HCU system studied. It has a similar appearance to a notebook computer, and dimensions of 40cm(W) * 30cm(D) * 10cm(H).

To briefly describe the operation of an HCU system, a focused, high-voltage, ultrasonic pulse signal is transformed to an ultrasound signal through a signal transformer that is called a probe, and is then transmitted to the human body.

The signal is then returned after a certain time, depending on the part of the human body that has received the signal, is then amplified and converted to a digital signal by the analog-to-digital converter, and is beamformed. The beamformed digital signal is then image processed and scan converted to be displayed on the monitor.

3.2 Cooling System of the HCU System

The strength of an HCU system is that it is portable, while offering a level of performance equivalent to a conventional ultrasound system. Since mobility is the key to the HCU system, it must be designed in a compact structure. As such, all components must be miniaturized and designed for high concentration, integration and low power consumption.

As the compact design structure of the HCU system makes it vulnerable to overheating, the fixture and cooling system must be designed to cope with this issue. The case material of the HCU system is a composite of magnesium alloy and PC offering outstanding shock and thermal resistance. <Figure 4> shows the detailed heat cooling system of an HCU system. Since the airflow space is narrow because of the small internal space, it induces heat diffusion to a heat plate made of aluminum material with high heat diffusion, and forcefully cools the diffused heat using a heat pipe and fan in order to quickly emit the heat generated by the parts.

As shown in <Figure 5>, the key modules are positioned in 3 groups to ensure seamless airflow and increase the efficiency of heat cooling. Heat generated by the ultrasound and PC module is diffused by the remote heat exchanger (RHE), while that generated by the power module is diffused using the system fan. The main modules are grouped in 3 types,

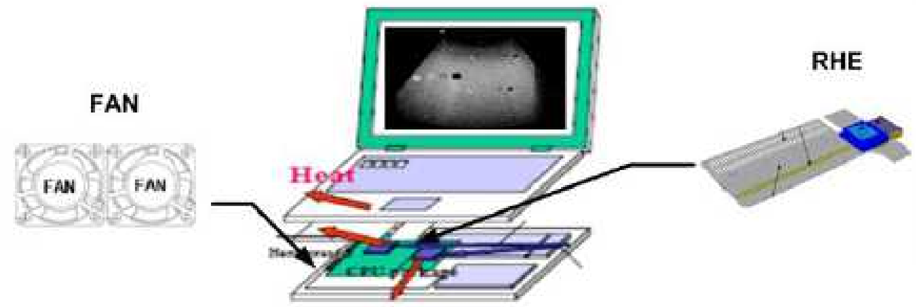
as follows:

① Concentration of heat source by modules
(Prevention of temperature rise of other parts)

② Quick diffusion of heat generated to aluminum heat plate
(Prevention of temperature rise of heat generating parts)

③ Quick exhaust of diffused heat using the heat pipe and fan

The cooling system used by the ultrasound module and PC module, consisting of the aluminum heat plate, heat pipe and fan, is called the remote heat exchanger (RHE).



<Figure 4> Structure of cooling system for HCU System

The structure of the RHE for the HCU System is the same as that of an RHE used in a notebook computer. The RHE concentrates the heat diffused from the heat source to the heat plate using the heat pipe, and then emits it through the heatsink pin. It diffuses the heat generated by the key parts and PC modules of the ultrasound image function.

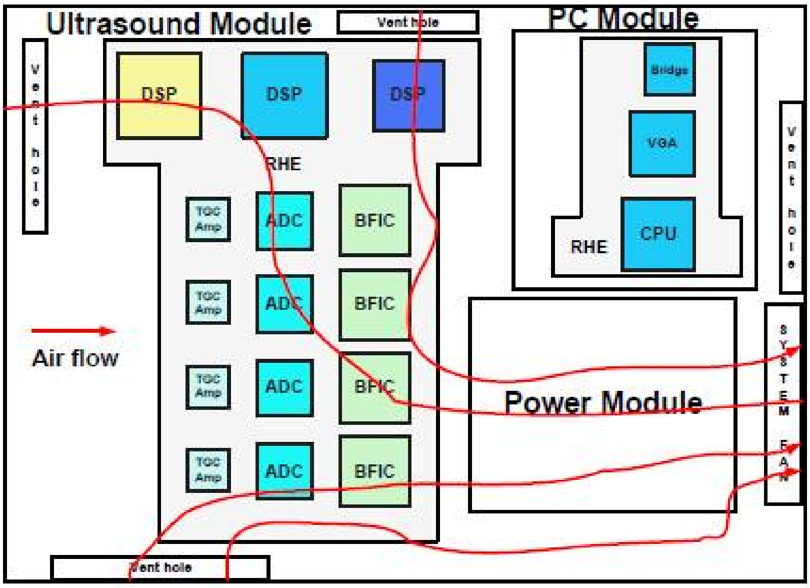
The cooling system of the HCU consists of the RHE between the ultrasound module and PC module, and two system fans in parallel. 4 vent holes are used for air intake.

The RHE and system fans are operated at the specified voltage of 12V. Another important component of the HCU system is the system cooling fan. The fan induces the overall heat of the system to the vent hole for ventilation. It plays an important role in diffusing the heat generated by the power module.

The system fans used by the HCU system are a type of variable airflow axial flow fan, and use a high speed BLDC (brushless DC) motor fan.

The BLDC motor is ideal for medical devices or mobile units because of its low vibration and noise. Its energy consumption can be reduced by controlling the speed. As the speed of the BLDC motor is controlled by the PCB module that is housed inside the motor, and the motor and PCB module are structured in a sealed body together, PCB module problems can result if the heat generated by the motor and PCB module is not seamlessly diffused, which leads to the interruption of fan operation Tae-Gu Lee et al(2005).

In the previous studies, it was observed that the heat generated during BLDC motor operation is proportionate to the fan operation voltage, and that as the operating voltage increased, the failure rate increased, thus reducing the product life.



<Figure 5> Main Module Arrangement and Air Flow Diagram of HCU System

4. REVIEW OF THERMAL CHARACTERISTICS OF HCU SYSTEM

4.1 Test Plan

This study addresses the question of whether the key parts of an HCU system will maintain the derated part surface temperature when the system is normally operated. It also addresses the question of whether said key parts will maintain the derated part surface temperature using only the heat plate and heat pipe when the RHE and system fan operations are interrupted. <Table 1> shows the test cases of RHE fan and system fan operation.

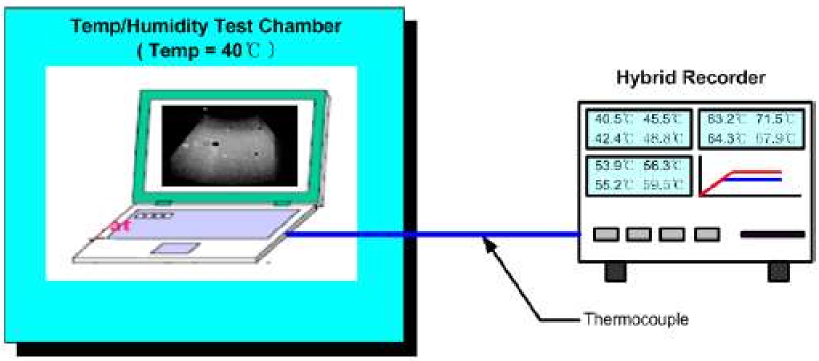
<Table 1> Test Cases of Fan Operation

Test Case	RHE FAN	System FAN
Case 1	ON	ON
Case 2	OFF	OFF
Case 3	ON	OFF
Case 4	OFF	ON

4.2 Test Equipment and Test Method

As shown in <Figure 6>, the test system consists of a temp & humidity test chamber, a hybrid temperature recorder, and an HCU system to test the cases listed in <Table 1> As shown in <Figure 5>, the thermocouple of the hybrid temperature is attached to the surface of 15 ultrasound module parts and 3 PC module parts.

The surface temperatures of the parts are measured under normal operation and in the test conditions listed in <Table 1> The measured results are reviewed to determine whether the cooling system maintains the derated part surface temperatures under both optimum and worst-case conditions.



<Figure 6> Experiment Equipment for Surface Temperature Measurement

4.3 Test Result Comparison

To compare the cooling performance of the HCU system, the part surface temperatures of 4 cases are measured and compared with the normal operation temperature. To determine whether the measured part surface temperatures remain within normal operation temperature range, the maximum junction temperature (T_j) is calculated and compared with the specification in the datasheet.

In this study, Tj is calculated with Equation (1) below, using the part surface temperature (T_c), thermal resistance (θ_{jc}) in the datasheet, and power dissipation (P_D) of the part.

$$T_j = T_C + \theta_{jc} * P_D (℃) \quad (1)$$

<Table 2> shows the summary of the temperature specification of main parts. In the table, the compared values are divided into absolute maximum value and derating value.

In general, temperatures 15~20% lower than Tj are used for evaluation to increase the product life of the semiconductor parts. There is no definite standard for this figure, and different companies use different levels. For this study, a reduction of 20% is applied to define the derating rate, as in Equation (2) below.

$$T_j = (T_j - \max * 0.7) + 15(℃) \quad (2)$$

<Table 2> Specification of Main Parts of HCU System

Module	Major Compoent	Datasheet specification (Absolute Maximum Value)					Derating Value	
		P_D(W)	Θjc (℃/W)	T_J(℃)	T_A(℃)	T_C(℃)	T_J(℃)	T_C(℃)
Ultrasound Part	BF1	1.00	10.0	125.0	90.0	115.0	102.5	92.5
	BF2	1.00	10.0	125.0	90.0	115.0	102.5	92.5
	BF3	1.00	10.0	125.0	90.0	115.0	102.5	92.5
	BF4	1.00	10.0	125.0	90.0	115.0	102.5	92.5
	ADC1	0.80	20.0	105.0	70.0	89.0	88.5	72.5
	ADC2	0.80	20.0	105.0	70.0	89.0	88.5	72.5
	ADC3	0.80	20.0	105.0	70.0	89.0	88.5	72.5
	ADC4	0.80	20.0	105.0	70.0	89.0	88.5	72.5
	TGC AMP1	0.95	4.3	150.0	85.0	100.0	120.0	85.0
	TGC AMP2	0.95	4.3	150.0	85.0	100.0	120.0	85.0
	TGC AMP3	0.95	4.3	150.0	85.0	100.0	120.0	85.0
	TGC AMP4	0.95	4.3	150.0	85.0	100.0	120.0	85.0
	DSP1	1.50	10.0	100.0	72.5	85.0	85.0	70.0
	DSP2	1.50	10.0	100.0	72.5	85.0	85.0	70.0
	DSP3	1.00	4.9	85.0	70.0	80.1	74.5	69.6
PC Part	CPU	5.50	3.0	100.0	70.0	85.0	85.0	68.5
	VGA	7.00	3.5	125.0	70.0	100.0	102.5	78.0
	BRIDGE	3.00	8.3	125.0	70.0	100.0	102.5	77.6

The calculated T_j is used to calculate T_c in Equation (1). <Table 2> shows the results of the calculation.

4.3.1 Cases 1 and 2 Measurement Results and Comparison

<Table 3> shows the measured part surface temperatures and

Module	Major Compoent	Ambient Temperture = 40℃ ,Operation 2hours		
		System & RHE FAN All Operation(℃) (Best Condition)	System & RHE FAN All Not Operation(℃) (Worst Condition 1)	Temperture difference (℃)
Ultrasound Part	BF1(CH1)	59.9	74.4	14.5
	BF2(CH2)	67.7	81.3	13.6
	BF3(CH3)	65.4	80.2	14.8
	BF4(CH4)	60.3	76.3	16.0
	ADC1(CH5)	58.7	*74.6*	15.9
	ADC2(CH6)	57.6	*74.2*	16.6
	ADC3(CH7)	58.7	*75.7*	17.0
	ADC4(CH8)	56.7	*73.8*	17.1
	TGC AMP1(CH9)	64.6	78.3	13.7
	TGC AMP2(CH10)	62.8	78.7	15.9
	TGC AMP3(CH11)	61.4	77.5	16.1
	TGC AMP4(CH12)	62.7	78.5	15.8
	DSP1(CH13)	56.9	*73.2*	16.3
	DSP2(CH14)	55.2	*71.6*	16.4
	DSP3(CH15)	58.9	*73.4*	14.5
PC Part	CPU(CH16)	65.1	*79.4*	14.3
	VGA(CH17)	69.1	*85.6*	16.5
	BRIDGE(CH18)	69.1	*81.8*	12.7

The result shows that the surface temperatures are increased by 12.7~17.1℃. It also shows that derating T_c is exceeded for 10 parts.

4.3.2 Cases 1 and 3 Measurement Results and Comparison

<Table 4> shows the measured part surface temperatures and comparison of cases 1 and 3 as well as the calculated derating T_c to determine whether the temperatures are appropriate.

<Table 4> Comparison of Cases 1 and 3

Module	Major Compoent	Ambient Temperture = 40℃ ,Operation 2hours		
		System & RHE FAN All Operation(℃) (Best Condition)	Only RHE FAN Operation (℃) System FAN Fail (Worst Condition 2)	Temperture difference (℃)
Ultrasound Part	BF1(CH1)	59.9	64.7	4.8
	BF2(CH2)	67.7	72.6	4.9
	BF3(CH3)	65.4	71.1	5.7
	BF4(CH4)	60.3	65.8	5.5
	ADC1(CH5)	58.7	64.0	5.3
	ADC2(CH6)	57.6	62.9	5.3
	ADC3(CH7)	58.7	64.4	5.7
	ADC4(CH8)	56.7	62.2	5.5
	TGC AMP1(CH9)	64.6	69.7	5.1
	TGC AMP2(CH10)	62.8	69.1	6.3
	TGC AMP3(CH11)	61.4	67.4	6.0
	TGC AMP4(CH12)	62.7	68.0	5.3
	DSP1(CH13)	56.9	61.8	4.9
	DSP2(CH14)	55.2	59.8	4.6
	DSP3(CH15)	58.9	63.4	4.5
PC Part	CPU(CH16)	65.1	68.3	3.2
	VGA(CH17)	69.1	74.2	5.1
	BRIDGE(CH18)	69.1	74.6	5.5

The result shows that the surface temperatures are increased by 3.2 ~ 6.3℃. It also shows that derating T_c is acceptable for all parts.

4.3.1 Case 1 and 4 Measurement Results and Comparison

<Table 5> shows the measured part surface temperatures and a comparison of cases 1 and 4 as well as the calculated derating T_c, to determine whether the temperatures are appropriate.

<Table 5> Case 1 and 4 Measurement Results and Comparison

Module	Major Compoent	Ambient Temperture = 40℃ ,Operation 2hours		
		System & RHE FAN All Operation(℃) (Best Condition)	Only System FAN Operation (℃) RHE FAN Fail (Worst Condition 3)	Temperture difference (℃)
Ultrasound Part	BF1(CH1)	59.9	69.5	9.6
	BF2(CH2)	67.7	76.4	8.7
	BF3(CH3)	65.4	74.4	9.0
	BF4(CH4)	60.3	70.0	9.7
	ADC1(CH5)	58.7	69.2	10.5
	ADC2(CH6)	57.6	68.6	11.0
	ADC3(CH7)	58.7	69.7	11.0
	ADC4(CH8)	56.7	67.7	11.0
	TGC AMP1(CH9)	64.6	73.1	8.5
	TGC AMP2(CH10)	62.8	72.8	10.0
	TGC AMP3(CH11)	61.4	71.7	10.3
	TGC AMP4(CH12)	62.7	72.3	9.6
	DSP1(CH13)	56.9	66.8	9.9
	DSP2(CH14)	55.2	65.6	10.4
	DSP3(CH15)	58.9	67.7	8.8
PC Part	CPU(CH16)	65.1	*75.5*	10.4
	VGA(CH17)	69.1	*79.2*	10.1
	BRIDGE(CH18)	69.1	*80.1*	11.0

The result shows that the surface temperatures were increased by 8.5~11℃. It also shows that derating T_c was exceeded for all parts of the PC module.

5. LIFETIME INCREASE MEASURES OF HCU SYSTEM

5.1 Cooling System Evaluation

The cooling system of the HCU system satisfies temperature derating of all main parts in all 4 test cases when RHE and fan are operating normally. However, temperature derating of some parts is exceeded if the RHE fan stops operating. Therefore, it is deemed necessary to design the product with consideration of the possibility of fan failure, and to add the function of displaying warning messages if fan operation is interrupted.

5.2 Lifetime Increase Measures of HCU System

The lifetime of an HCU system can be increased if it is designed with consideration to fan derating so that it will be operated stably. As fan life is directly related to operating voltage, the RHE and system fans were tested by derating the operating voltage to 12V, 9V and 5V, as shown in <Table 6>.

<Table 9> and <Table 10> show the results of the test. Although derating T_c was not satisfied when the fan operating voltage was below 9V, it was satisfactory as long as the system was operated at 9V or above. The results of the relationship between the fan and RPM Lifetime for D0512A Series, predicted based on Equation (3), are shown in <Table 7> and <Table 8> Therefore, if the voltage is reduced to 9V from the specification, the product life of the fan and HCU system will be increased by 1.8 times, while offering a satisfactory level of heat diffusion.

$$MTTF_0 = 1.037^{(\triangle R/100)} * MTTF_1 \quad (3)$$

<Table 6> Test Cases of Fan Voltage

Test Case	FAN Operating Voltage(V)
Case 5	12
Case 6	9
Case 7	5

<Table 7> Fan Life Expectancy according to RHE FAN Operating Voltage

Operating Voltage(V)	Speed (RPM)	Prediction Life time(hours), when Ambient Temperture = 40℃	Life time growth(multiple)
12	4250	30,000	
9	3400	40,855	*1.4*
5	1870	71,229	1.7

<Table 8> Fan Life Expectancy according to System Fan Operating Voltage

Operating Voltage(V)	Speed (RPM)	Prediction Life time(hours), when Ambient Temperture = 40℃	Life time growth(multiple)
12	6900	30,000	
9	5320	53,263	1.8
5	2370	155,560	2.9

<Table 9> Cases 5 and 6 Measurement Results and Comparison

Module	Major Compoent	Ambient Temperture = 40℃ ,Operation 2hours		
		System & RHE FAN All Operation at 12 V (℃) (Normal Condition)	System & RHE FAN All Operation at 9 V (℃) (Derating Condition)	Temperture difference (℃)
Ultrasound Part	BF1(CH1)	59.9	59.8	-0.1
	BF2(CH2)	67.7	67.9	0.2
	BF3(CH3)	65.4	65.9	0.5
	BF4(CH4)	60.3	60.6	0.3
	ADC1(CH5)	58.7	59.6	0.9
	ADC2(CH6)	57.6	58.5	0.9
	ADC3(CH7)	58.7	60.0	1.3
	ADC4(CH8)	56.7	57.5	0.8
	TGC AMP1(CH9)	64.6	64.4	-0.2
	TGC AMP2(CH10)	62.8	64.5	1.7
	TGC AMP3(CH11)	61.4	63.2	1.8
	TGC AMP4(CH12)	62.7	63.4	0.7
	DSP1(CH13)	56.9	56.7	-0.2
	DSP2(CH14)	55.2	55.3	0.1
	DSP3(CH15)	58.9	59.2	0.3
PC Part	CPU(CH16)	65.1	65.3	0.2
	VGA(CH17)	69.1	69.2	0.1
	BRIDGE(CH18)	69.1	69.4	0.3

<Table 10> Cases 5 and 7 Measurement Results and Comparison

Module	Major Compoent	Ambient Temperture = 40℃ ,Operation 2hours		
		System & RHE FAN All Operation at 12 V (℃) (Normal Condition)	System & RHE FAN All Operation at 5 V (℃) (Derating Condition)	Temperture difference (℃)
Ultrasound Part	BF1(CH1)	59.9	65.1	5.2
	BF2(CH2)	67.7	73.1	5.4
	BF3(CH3)	65.4	71.1	5.7
	BF4(CH4)	60.3	65.9	5.6
	ADC1(CH5)	58.7	64.9	6.2
	ADC2(CH6)	57.6	64.0	6.4
	ADC3(CH7)	58.7	65.6	6.9
	ADC4(CH8)	56.7	63.2	6.5
	TGC AMP1(CH9)	64.6	69.2	4.6
	TGC AMP2(CH10)	62.8	69.7	6.9
	TGC AMP3(CH11)	61.4	68.6	7.2
	TGC AMP4(CH12)	62.7	68.8	6.1
	DSP1(CH13)	56.9	62.1	5.2
	DSP2(CH14)	55.2	60.8	5.6
	DSP3(CH15)	58.9	64.3	5.4
PC Part	CPU(CH16)	65.1	70.4	5.3
	VGA(CH17)	69.1	74.3	5.2
	BRIDGE(CH18)	69.1	74.7	5.6

6. CONCLUSIONS

This study tested the performance of the cooling system of HCU, and confirmed that it efficiently cooled the heat generated by the internal parts.

When the derating rate of 80% was applied while the case of 4 fans of the HCU system were operated normally, it was observed that the key image processing parts met the surface temperature(T_c) with consideration to derating.

By derating the operating voltage of the fan of the cooling system from the specified 12V to 9V, the lifetime of the fan and the HCU system is expected to increase by 1.8 times, while equivalent cooling performance is maintained. A subsequent study will predict the fan product life when the operating voltage is reduced.

If the cooling system is designed with a focus on thermal derating, it is expected that the product life of an HCU system can be increased.

REFERENCES

[1] Kwang-Hoe Kim(2008), "Video Diagnosis System", Korea Institute of Science and Technology Information, pp. 1~8, December.

[2] IMS Research(2008), "The World Market For Ultrasound Imaging Equipment 2008 Edition -Version 2.0", p. 12, November.

[3] SD-18(2004), "Part Requirement & Application Guide", August.

[4] Myeong-Soo Kim(2007), "Derating, Reliability Innovation Center, The University of Suwon", pp. 307~316 October.

[5] Tae-Gu Lee, Jong-Sun Moon, Ho-Seon You, Jae-Heon Lee(2005), "Thermal Reliability Analysis of BLDC Motor in High Speed Axial Fan by the Accelerated Life Test" pp.1170, September.

[6] Lifetime for D0512A Series, "Relationship equation of FAN RPM", Orient Telecom Co.,Ltd

[7] http://www.crane.navy.mil/sd18/FoundationPartReliability.pdf

[8] http://www.orientel.co.kr/product/product06_02.html