Evaluation on Chamber Volume and Performance for Simple Calorimetric Power Loss Measurement by Two Chambers

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***Abstract*—In this paper, a calorimetric power loss measurement (CPLM) which is low cost and a simple structure using two cheap chambers. A feature of the proposed method is that the power loss of the power converter is measured from the transient state of the rise in temperature. As a result, the measurement time of the power loss using heat conduction equation formulas is reduced by 86.1% compared with a conventional method which uses the steady state of the temperature due to the power loss. In addition, another method that can reduce the measurement time is discussed. In particular, the temperature in one of two chambers is controlled to follow the temperature in another chamber for the transient stat of the rise in temperature. As a result, the measurement time of the power loss is reduced by 87.5% in compared with the conventional method. In order to confirm the validity of the proposed method for actual applications, a switching power supply is used for an objective of the power loss measurement. Moreover, the relationship among the measurement error rate, the measurement time and the chamber volume. As a result, all of the maximum errors of the measured power loss were within 10%.**

I. INTRODUCTION

Recently, power converters become relatively high efficiency and high switching frequency due to wide-gap semiconductor devices, such as silicon carbide (SiC) and gallium nitride (GaN), and improved magnetic materials [1]. As a result, the power loss analysis of very high-efficiency power converters has been becoming difficult because very small power losses are buried in the measurement error. However, it is very important to measure the power loss of power converters precisely in order to improve the efficiency of power converters certainly.

Fig. 1 shows power loss measurement methods using an electrical power measurement (EPM) instrument. The most common method shown in Fig. 1(a) is to measure the input and output power using by EPM instrument. Especially, in case of very small power loss, the measurement results by EPM instrument are affected greatly by the delays between current probes and voltage probes, phase shifts between sampling channels of an oscilloscope and voltage offsets and so on [2]. In this method, the full scale error of the measurement range of the EPM instrument is included in measurement results because the power loss is calculated by using the measured input power and output power. In order to overcome these problems, there is another power loss measurement method, which uses two power converters are connected in parallel shown in Fig. 1(b) [3]. The first power converter is operated as a generator. The second power converter is used as a receptor. The power is circulated through two converters [4]. As a result, the input power is equal to power loss of two power converters due to the parallel connection. Therefore, the measurement range of the EPM instrument becomes smaller. As a result, the higher accuracy measurement result is obtained. However, since this method requires two power converters, consequently this method takes longer assembly time and causes high cost.

On the other hand, another power loss measurement method using the heat quantity of the power converter is known as the Calorimetric Power Loss Measurement (CPLM) [5], [6]. This system uses a thermostatic chamber in order to measure the heat quantity precisely. In addition, the circulatory organ is also used in order to circulate the water or air in the inside the thermostatic chamber [7]. This method can achieve high accuracy of power loss measurement because only the power loss is measured using the heat quantity is obtained from the temperature change of the circulating water or air. Additionally, the measurement accuracy is affected by the heat leakage through the walls of the chamber. Even if the power loss is very small, the thermostatic chamber and the circulatory organ are expensive. In addition, the structure of this method is complex due to these instruments. These instruments cannot be changed easily depending on the volume of the power converter, even if there are cases that the measurement time could be reduced when the power converter which has very small power loss is tested.

In this paper, a low cost and simple structure CPLM system using two chambers is described [8]. Two chambers are made from the expanded polystyrene, which are cheaper than instruments such as general thermostatic chambers and circulatory organs. By locating two chambers under the same environment, an effect of the heat leakage through walls of two chambers to the measurement accuracy can be reduced. This paper is organized as follows; first, the calorimetric principle is described, next, the proposed system is introduced and a theoretical behavior of the temperature in the chamber is discussed based on equations of heat conduction; thirdly, the measurement time and accuracy are evaluated when a resister and a switching power supply is used as the measured object of the proposed system. Finally, the relationship among the chamber volume, the measurement accuracy and the measurement time is verified by changing the chamber volume.

II. CALORIMETRIC PRINCIPLE

The measurement error ε of the power loss in the power converter can be expressed by (1),

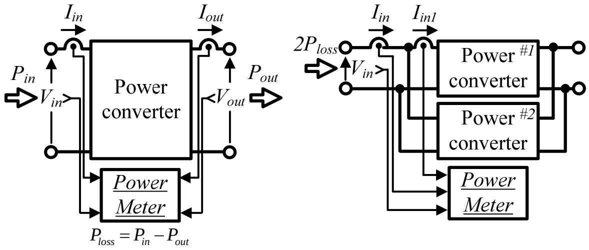
$$\varepsilon = \Delta P_{loss} / P_{loss} = \left(\Delta P_{in} + \Delta P_{out}\right) / P_{loss} \tag{1}$$

where, ΔP_{loss} is the measured power loss of power converter, P_{loss} is the power consumption of the power converter, ΔP_{in} is the measured input power and ΔP_{out} is the measured output power. If the power loss of a power converter which has the efficiency of 99% is measured by using a power meter which has an accuracy of 0.15%, the worst case of the measurement error is 29.85%. Besides, a measurement method does not provide high accuracy due to the limited bandwidth and dynamic frequency response. Therefore, it is required to measure the power loss directly.

The power consumption of the power converters is exchanged to heat. Therefore, the calorimetric method controls water or air in order to take over the heat from the power converters. P_{loss} can be described by (2),

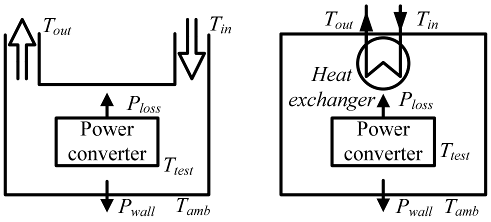
$$P_{loss} = \rho c_p V (T_{out} - T_{in}) \tag{2}$$

where, ρ is the mass density, c_p is the specific heat capacity of the fluid, V is the flow rate of the coolant, and T_{in} and T_{out} are the temperature of the inlet and outlet water.

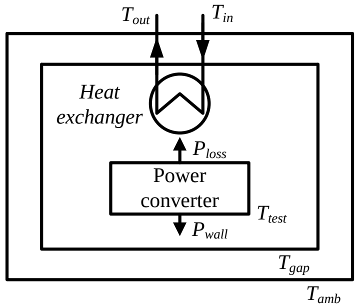


(a) Input and output powers measurement. (b) Opposition method.

Figure 1. Electrical methods of power loss measurement.



(a) Open type. (b) Closed type, single-cased.



(c) Closed type, double-cased.

Figure 2. Conventional calorimeter systems.

Fig. 2 shows several types of the conventional calorimeters have been proposed so far [9-11]. Fig. 2 (a) shows an open type calorimeter system. In this system, a power converter is placed directly in a measurement chamber. Using air for the coolant, this system is a simple construction. In addition, measurement time of this system is short. However, this system has significant defect that it is difficult to measure heat capacity, the temperature rise and the volume flow of the air. Air is very sensitive to environmental changes such as the humidity, the temperature and density. Additionally, the measurement accuracy is affected by the heat leakage through the walls of the calorimeter P_{wall} because the temperature in the chamber T_{test} is different from the ambient temperature T_{amb}. Therefore, the accuracy of this system is very affected from the environment. This calorimeter type is often used for measuring induction machines with power losses up to several kilowatts.

On the other hand, Fig. 2 (b) shows closed and single-cased type calorimeter system. This system employs a separate cooling loop for the heat exchange with the ambient. Using water for a coolant, this system is higher accuracy than the open type calorimeter. However, the measurement time becomes long because heat capacitance of water is higher compared with that of air.

Fig. 2 (c) shows a closed and double-cased type calorimeter system can increase the measurement accuracy. T_{gap} is the air temperature in the gap between the inner chamber and outer chamber. In this method, T_{gap} is controlled to be equal to T_{test}. Therefore, the power consumption for the heat leakage through the walls of the inner chamber P_{wall} can be zero. Therefore, the double-cased calorimeter is the highest accuracy in the three types as mentioned above. However, this system uses the circulatory organ for the coolant, complex control circuits and sensor. As a result, these systems are expensive. Moreover, this method is also required to take the long measurement time due to high heat capacitance of water.

III. CPLM SYSTEM USING TWO CHAMBERS

Fig. 3 shows the control block diagram of proposed system which is composed by two chambers and a heater. The chambers which are made from insulator materials, are illustrated as the chamber A and chamber B in Fig. 1. A power converter as the measured object of the proposed system is placed in the chamber A. The temperature in the chamber A T_{inA} is increased by the power loss of the power converter. T_{inA} saturates when the amount of heat consumption from heater equals to the amount of heat consumption from the chamber surface.

The temperature in the chamber B T_{inB} is controlled by a feedback control using the PI regulator. It should be noted that a heater in the chamber B is controlled by the buck converter. T_{inA} is set to the command temperature of chamber B. When T_{inB} reaches the command value that is the saturated temperature in the chamber A, the power consumption of the heater in the chamber B equals to that which is generated from the power converter in the chamber A.

Fig. 4 shows the prototype of the proposed CPLM system. The measurement accuracy is evaluated using the prototype. Table I shows the used materials for the calorimeter. Two chambers are made from the expanded polystyrene. The heater cement resistor of 10 Ω is used. For simplicity of the experiment, a heater is used instead of the power converter. The power converter runs in the chamber A. The power loss measurements with the power consumption between 5 W and 25 W are demonstrated. The volume of the chamber is V_{chamb1} = 3.17×10^{-2} m^3 (inner dimension of chamber; long 447 mm, width 322 mm, height 220 mm). The error rate set up within 10% based on the power consumption between 5 W and 25 W. The power loss of the power converter is evaluated from the power consumption of a heater in chamber B. The temperatures of the air in the two chambers are affected by the same ambient temperature because two chambers are placed in same place.

IV. THEORETICAL DISCUSSION

In this section, the relationship between the chamber volumes and measurement time is discussed using the theoretical equation of heat conduction. The power converter is operated in the chamber A. The temperature of the air in the chamber A rises, due to the heat quantity produced by the power loss of the power converter. The air in the chamber A is circulated by a fan. Based on the heat conduction equation, the heat quantity Q_{in} (W) is led to

$$\rho c_p V \frac{dT_{inA}}{dt} = Q_{in} - Q_R - Q_{cool} \qquad (3)$$

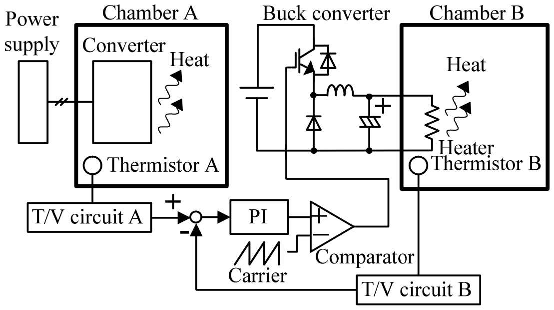


Figure 3. System configuration of proposed CPLM using two chambers.

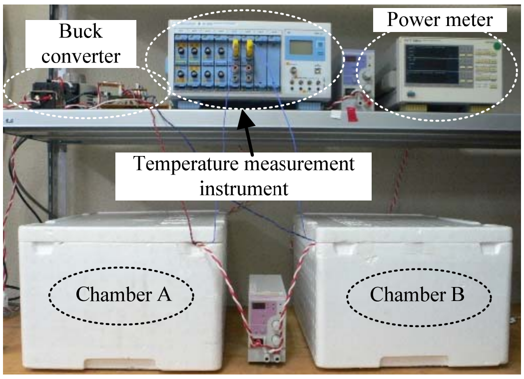


Figure 4. Prototype of proposed CPLM using two chambers.

TABLE I. USED MATERIALS FOR THE CALORIMETER.

Senser	Temperature	SL1000 :Thermocouple (type K)
	Power meter	WT1800 : Accuracy 0.15%
Chamber	Expanded polystyrene : Dimensions :447 mm × 322 mm × 220 mm Wall Thickness : 200 mm, Volume : 31700 cm^3	
Heater	Cement resistor :Resistance 10 Ω Dimensions :190 mm × 550 mm × 20 mm	

where, ρ (kg/m^3) is the density of the air, c_p (J/gK) is the specific heat of air, V (m^3) is the inner volume of the chamber A, T_{inA} (K) is the temperature of the air in the chamber A, Q_{in} (W) is the heat quantity from the inside of the power converter to the converter surface in the chamber A, Q_R (W) is the heat quantity from the converter surface to the measurement point of the air temperature in the chamber A, Q_{cool} (W) is the heat discharge from the chamber A. Q_R and Q_{cool} is expressed by (4) and (5).

$$Q_R = (T_R - T_{inA}) / R_r \quad (4) \qquad Q_{cool} = (T_{inA} - T_{amb}) / R_{chamb} \qquad (4)$$

Here, Eq. (3) is also expressed by Eq. (6).

$$\rho c_p V \frac{dT_{inA}}{dt} = Q_{in} - \{(Q_{in} \cdot R_r + T_{inA}) - T_{amb}\} / R \qquad (5)$$

where, T_R (K) is the inner temperature of power converter, R_r (K/W) is the thermal resistance from inside of the power converter to the measurement point of the room temperature,

T_{amb} (K) is the ambient temperature, R_{chamb} (K/W) is the thermal resistance of the chamber A, R (K/W) is the total thermal resistances (=R_r +R_{chamb}).

Eq. (5) is transformed with Laplace transformation and presented as

$$\rho c_p V\left(sT_{inA}(s)-T_o\right)=\frac{Q_{in}}{s}\left(1-\frac{R_r}{R}\right)-\frac{T_{inA}(s)}{R}-\frac{T_{amb}}{sR} \tag{6}$$

where, T_o is the initial temperature in the chamber A. The heat quantity of the power converter is assumed as the step input. Eq. (6) is derived in term of the T_{inA}, and then it is applied with inverse Laplace transformation, which is shown in (7).

$$T_{inA}=\left(Q_{in}R_{chamb}+T_{amb}\right)\left(1-e^{-\tau t}\right)+T_o e^{-\tau t} \tag{7}$$

where R_{chamb} (K/W) is the thermal resistance of the chamber A, T_{amb} (K) is the ambient temperature and τ is the time constant. τ is expressed by (8).

$$\tau=1/\left(\rho c_p V_{ch} R\right) \tag{8}$$

If the parameters are known except Q_{in}, (9) is derived by differentiating (7) and translating into logarithm.

$$\ln\left(\frac{dT_{inA}}{dt}\right)=\ln\frac{Q_{in}\left(R-R_r\right)+T_{amb}-T_o}{\rho_{air}c_{pair}V_{ch}R}-\frac{1}{\rho_{air}c_{pair}V_{ch}R}t \tag{9}$$

As a result, the Q_{in} can derive by (9) before the temperature is saturated. The rise of the measured temperature is differentiated and both sides of equation are expressed logarithmically. Moreover, the regression curve is analyzed from the experimental results. The measurement results are expressed by 1st order equation. The R and the R_r is showed by (10) and (11) by using the slope a and the intercept b, respectively.

$$R=-1/\left(\rho_{air}c_{pair}V_{ch}a\right) \tag{10}$$

$$R_r=R-\left\{\rho_{air}c_{pair}V_{ch}R\exp(b)\right\}/Q_{in} \tag{11}$$

From (10) and (11), when the chamber volume V_{ch} is small, the surface area of the chamber is decreased. Then, the time constant of the temperature rise is increased by increasing of R_{chamb}. Therefore, the measurement time will be long because the time of the temperature saturations becomes long when the chamber volume V_{ch} is small.

V. EXPERIMENTAL RESULTS

In order to valid the theoretical analyses of the proposed method, experiments are conducted by using prototype experimental setup.

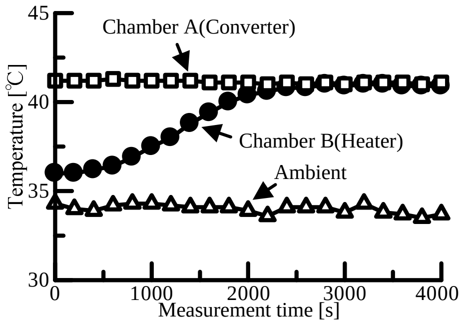


Figure. 5. Temperature control results for constant temperature command using PI control.

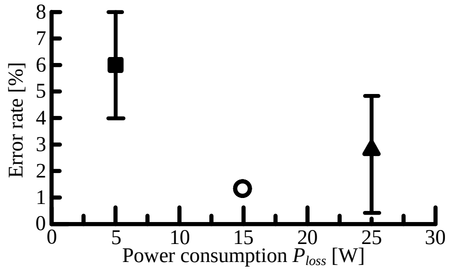


Figure. 6. Measurement error rate of the power loss measurement based on steady state condition. When power consumption is 5 W and 25 W, measurements were done three times.

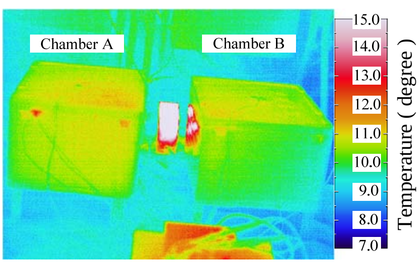
A. *Power loss measurement based on steady state condition*

Two chambers are made from the expanded polystyrene. For simplicity of the experiment, a heater is used instead of the power converter in the chamber A.

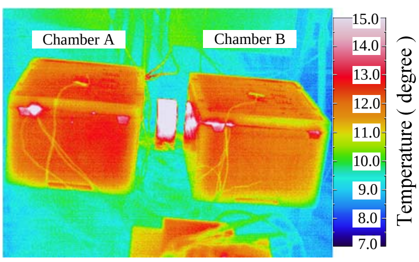
Fig. 5 shows the experimental result of the temperature control by using PI regulator at P_{loss} = 5 W. From Fig. 5, it is confirmed that the temperature in the chamber B is equaled to the temperature in the chamber A by using PI control.

Fig. 6 shows the fluctuation band of the power loss measurement error rate when the temperature is saturated on the steady state. The power consumption of the power converter is measured three times at the each power consumption. From Fig. 2, it is confirmed that the maximum error of power loss is 8.0% at P_{loss} = 5 W. In this case, all measurement accuracy becomes within 0.08% when the converter that has the efficiency of 99% at 1kW. In theory, when the temperature deviation of the chamber A and chamber B is 0 degrees Celsius, the heater power consumption in the chamber B perfectly agrees with the power loss in the chamber A in the proposed system. However, there are measurement errors in the experimental results. This reason is the difference of the ambient temperature between the chamber A and the chamber B.

Fig. 7 and Fig. 8 show the surface temperature of the chambers. Before the measurement, it is confirmed that it is low. In the steady state after them temperature was saturated, the surface temperature becomes around 13 degree Celsius. From the results, it is seen that there are variations of the surface temperatures of the chambers. However, from the results of Fig. 6, Fig. 7 and Fig. 8, the measurement error is within 8% even if there are variations of the temperature.

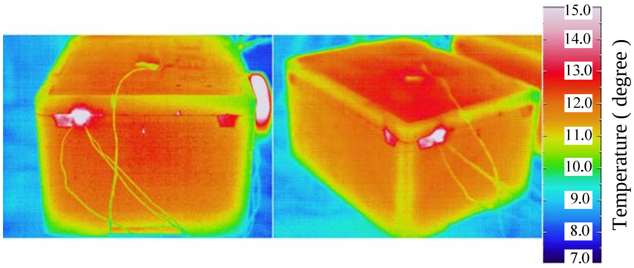


(a) Before a measurement.

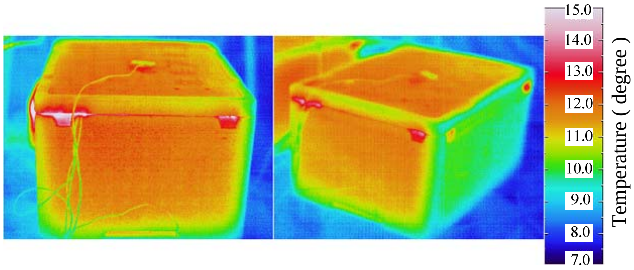


(b) After temperature was saturated.

Figure. 7. Surface temperature of two chambers.



(b) Chamber A



(b) Chamber B

Figure. 8. Surface temperature of two chambers after temperature was saturated.

B. *Power loss measurement using heat conduction equation formula*

Fig. 9 shows the error rate of the power consumption of the heater between the measurement value of the calculated values which is obtained by (10) and (11). As a result, it is confirmed that the error rate of the power consumption is within 10%. In addition, it is confirmed that the measurement time is shortened by 86.1% compared with the method based on the steady state condition.

C. *Power loss measurement by transient response of temperature rise*

In this section, the temperature in the chamber B is controlled to follow in the temperature in the chamber A for the transient state of the temperature rise.

Fig. 10 shows that the temperature of the chamber B T_{inB} is controlled to the temperature of the chamber A T_{inA} in a short time. Note that the power consumption of the power converter is 25 W. According to Fig. 3, it is confirmed the temperature in the chamber B reaches to the temperature in the chamber A in the transient states of the temperature rise.

Fig. 11 shows the power consumption of the power converter and the heater when the temperature of the chamber B is controlled as shown in Fig. 11. The power consumption of the heater is equaled to the power consumption of the converter on 1350 s. As a result, it is confirmed that the measurement time is shortened by 87.5% compare with the power loss measurement based on the steady state.

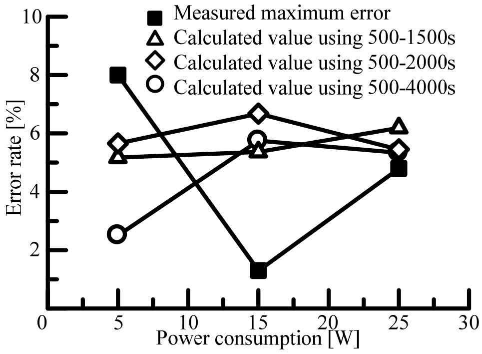


Figure. 9. Error rate of the power consumption between the measurement values and the calculation values.

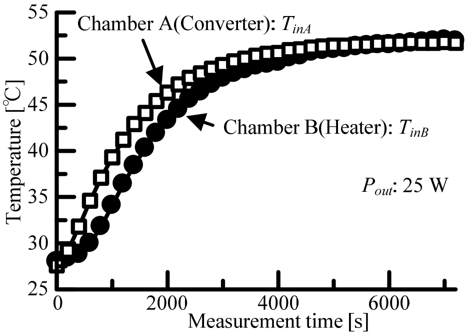


Figure. 10. Temperature of the chamber B is controlled to the temperature of the chamber A in a short time.

D. *Measurement accuracy in comparison with EPM*

In this section, the prototype system is experimentally tested using a switching (SW) power supply that has the maximum efficiency of 67% which was measured by the EPM. The power loss of the SW power supply used in this experiment can be measured by the EPM at high accuracy because the full scale error is small. Thus, the measured value with an EPM can be used as a reference value to evaluate the accuracy of the proposed CPLM. Output power of the SW power supply P_{out} is set to 1, 5, 20, 30 and 40 W. The power losses of the SW power supply P_{SW} are measured by the prototype three times at each P_{out}.

Fig. 12 shows the measurement error of the P_{SW} at each P_{out}. The maximum measurement error is 6.1% at P_{SW} = 10.7 W (P_{out} = 1 W). On the other hand, the minimum measurement error is 0.6% at P_{SW} = 16.8 W (P_{out} = 30 W).

E. Relationship among the chamber volume, measurement accuracy and measurement time

The measurement accuracy and measurement time are determined by the chamber volume in CPLM methods. The chamber volume is approximately 30 times the volume of the SW power supply used in the previous section. In this section, the chamber with twice volume is used for measuring the P_{SW}.

Fig. 13 shows the measurement accuracy and the measurement time when the chamber volume varies at P_{SW} is 10.7 W. When the V_{chamb2} is used, the maximum measurement error is 3.74%. However, the measurement time is extended from 4380 s to 6600 s.

The high measurement accuracy is obtained by decreasing the chamber volume. In contrast, the measurement time becomes longer. The thermal resistance R_{chamb} increases due to the decreasing of a surface area. From (8), the value of the time constant is increased by increasing of R_{chamb}. It means that the period of the temperature saturation also becomes long. As a result, the decrease of the chamber volume helps to achieve the high measurement accuracy because the temperature dispersion in the chamber is decreased by decreasing the chamber volume.

VI. CONCLUSION

In this paper, the low cost CPLM system for a high efficiency converter is proposed. The proposed system is constructed at a low cost without the thermostatic chambers which cause a high cost of the CPLM system. The method for measurement of the power loss by the temperature rise with the loss of power converter is discussed. The maximum error of the measured power consumption was within 6.1%. Moreover, the relationship between the measurement accuracy and the measurement time was experimentally verified by using the prototype with the reduced volume of the chamber. As the result, it was confirmed that the measurement accuracy and time becomes higher and longer by decreasing the chamber volume.

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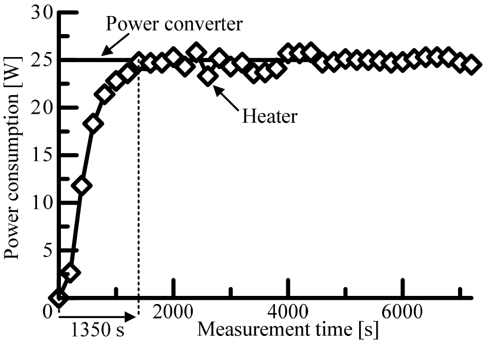

Figure. 11. Power consumption of converter and heater when the temperature of the chamber B is controlled as show in Fig. 10.

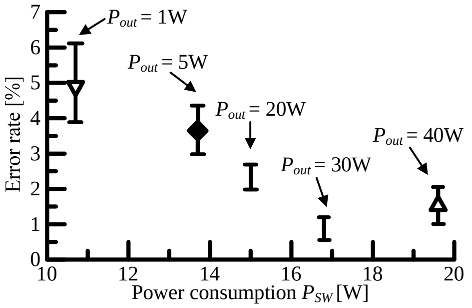

Figure. 12. Measurement error rate of the power consumption of a switching power supply with the proposed CPLM system based on transient response of temperature rise. Measurements were done two times or three times at each power consumption.

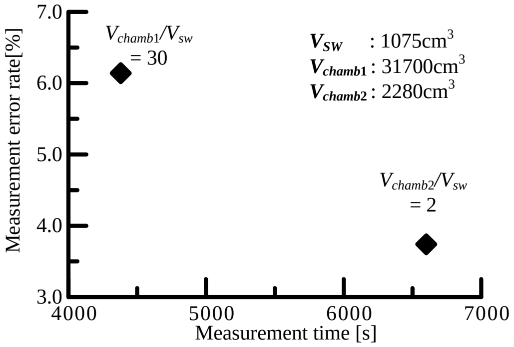

Figure. 13. Relationship among the measurement error rate, the measurement time and the chamber volume.

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