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A Study on the Hybrid Heater Composed of a Temperature Sensitive Ferrite with Low Permeability for Hyperthermia

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Constant temperature regulation of a hybrid heater which is composed of a temperature sensitive ferrite with low permeability and a Cu tube is investigated for hyperthermia. The temperature sensitive ferrite is inserted into a Cu tube and its length and diameter are 10 mm and 3 mm. Below B=0.05 T, the measured temperature and the calculated one increased with the ratio of $B^{1/2}$ and agreed well with each other. Above B=0.05 T, the measured temperatures maintained constantly almost 50°C ± 1.5°C because of the influence of Curie temperature of the temperature sensitive ferrite. This result shows that the hybrid heater is able to regulate the temperature constantly at the rate of 50°C ± 1.5°C.

Keywords : high-temperature hyperthermia, tumor, Curie temperature, hybrid heater, ferrite

1. Introduction

Temperature sensitive ferrite has a wide range of application [1-4] because of its Curie temperature. Hyperthermia is performed for a patient with a cancer using the soft heating method which is a kind of inductive heating method. The soft heating method often uses a hybrid heater composed of a temperature sensitive magnetic material and a metal ring as a heating element. The metal ring radiates a heat by the hysteresis loss of magnetic material and a heat by the eddy current generated in time-varying magnetic field. In high-temperature hyperthermia [5-7], the exciting temperature at the center of tumor is needed to be higher than human body temperature because of a kind of cooling effect by a blood circulation around a tumor. It is important that the hybrid heater has the characteristics of constant temperature regulation. In this study, the characteristics of constant temperature regulation is investigated for the hybrid heater composed a temperature sensitive ferrite with comparatively low permeability and a Cu tube.

2. Experiment

Fig. 1 shows the hybrid heater used in this experiment. The hybrid heater was composed of a temperature sensitive ferrite and a Cu tube. The ferrite was inserted into the Cu tube. The length and the diameter of the temperature sensitive ferrite were 10 mm and 3 mm. The thickness of Cu tube was 1.5 mm. Fig. 2 shows the experimental setup having two E typed ferrite cores for ac magnetic field. The hybrid heater was located between two E typed ferrite cores. A high power signal generator (BP4610) was used to apply a high current to two E typed ferrite cores. A XYt recorder (PM8271) and a digital thermometer (DTM305) were used to measure the temperature of the temperature sensitive ferrite. To measure a mag-

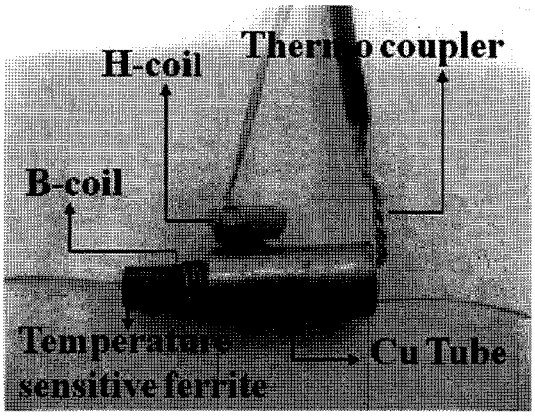

Fig. 1. Structure of hybrid heater with temperature sensitive ferrite and Cu tube.

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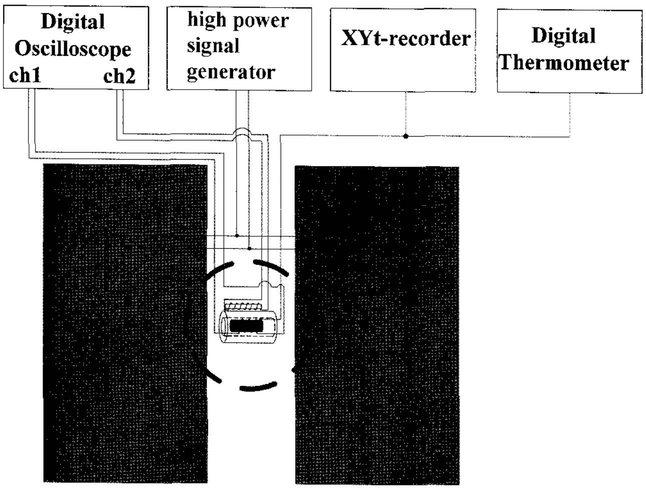

Fig. 2. Experimental setup.

Table 1. Composition of temperature sensitive ferrite.

Fe (wt%)	Ni (wt%)	Cu (wt%)	Zn (wt%)	Si (wt%)	O (wt%)
50.95	6.23	2.83	18.01	1.07	20.90

netic flux density and a magnetic field according to the variation of temperature, B coil was wound around the temperature sensitive ferrite and H coil was set under Cu tube or the temperature sensitive ferrite. The room temperature was maintained to 20°C throughout this experiment. Table 1 shows the composition of temperature sensitive ferrite.

3. Relations between magnetic flux density and temperature

The power consumption in the Cu tube was caused by an electric field due to time-varying magnetic field shown in Eq. (1)-Eq. (4), where E, B, p, σ_{cu}, P_{ave} and P are electric field, magnetic flux density, power density, conductivity, time average power and power, respectively.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

$$p = \sigma E^2 \tag{2}$$

$$P_{ave} = \frac{1}{T}\int_0^T p \, dt \tag{3}$$

$$P = \int P_{ave} dv \tag{4}$$

The temperature increased with a power consumed in the Cu tube as shown in Eq. (5). Eq. (5) shows the lumped constant model and accordingly the heat generated in the Cu tube is assumed to transfer from the inside of the tube toward the outside of tube. R is the heat

Table 2. Parameters used in the temperature calculation.

f (kHz)	r_i (mm)	r_0 (mm)	L (mm)	ρ_H (m/W)	σ_{cu} (10^7 mhos/m)
5	3.6	5	11	0.0105	5.8

resistance defined by Eq. (6), where ρ_H, R_G, l, r_o and r_i are heat resistance rate of Cu tube, geometric heat resistance of Cu tube, the length of the Cu tube, outer diameter and inner diameter of the Cu tube. Eq. (7) was obtained by substituting Eq. (6) into Eq. (7), where ω is angular frequency and shows a temperature variation of Cu tube depending on the maximum flux density B of temperature sensitive ferrite. Table 2 shows the parameters used in the calculation of temperature.

$$\Delta T = RP \tag{5}$$

$$R = \rho_H R_G = \frac{\rho_H}{2\pi l}\ln\frac{r_0}{r_i} \tag{6}$$

$$\Delta T = \frac{\rho_H}{2\pi}\frac{\sigma_{cu} w^2 r_i^4 B_0^2}{4}\left(\ln\frac{r_0}{r_i}\right)^2 \tag{7}$$

4. Results and Discussion

Fig. 3 shows the dependence of initial permeability of the temperature sensitive ferrite on a temperature. The permeability was obtained by LCR meter measurement. The temperature decreased up to room temperature by cooling naturally a silicon oil which was heated above 100°C. The initial permeability was as low as 4 in the room temperature and decreased rapidly above 50°C. Fig. 4 shows a B-H curve measured for only the temperature sensitive ferrite. The maximum flux density was about 0.35 T when the magnetic field of 50 kA/m was applied. During this measurement, there is no temperature vari-

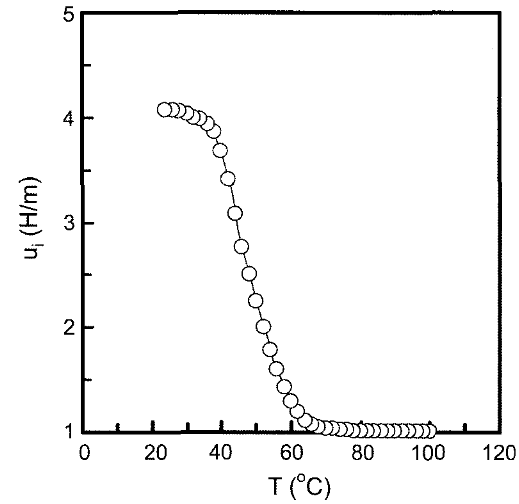

Fig. 3. Dependence of initial permeability on temperature.

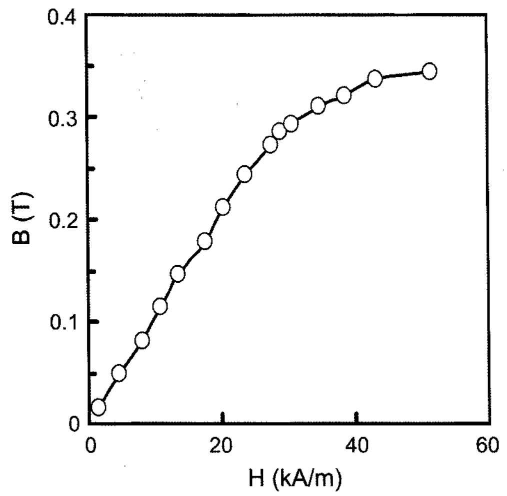

Fig. 4. B-H curve of temperature sensitive ferrite.

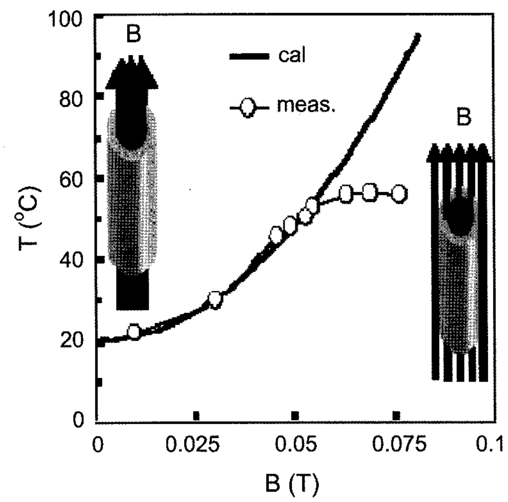

Fig. 6. Dependence of temperature on magnetic flux density.

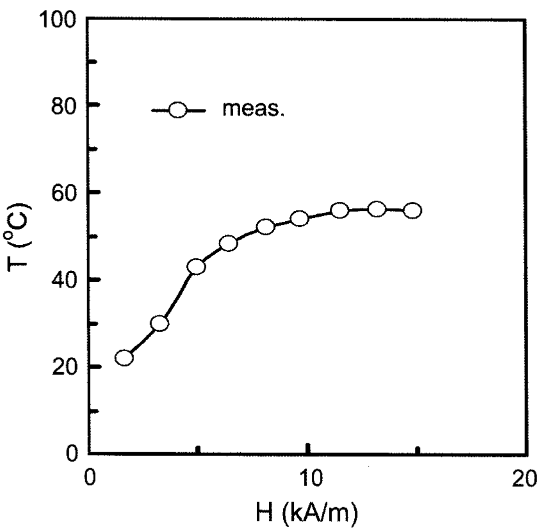

Fig. 5. Dependence of temperature on magnetic field.

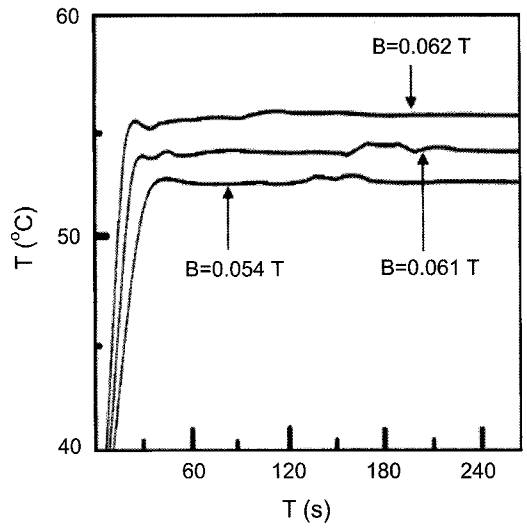

Fig. 7. Dependence of temperature on time.

ation due to the hysteresis loss of the temperature sensitive ferrite.

Fig. 5 shows the dependence of the temperature for the hybrid heater on ac magnetic field. The increasing tendency of a temperature to ac magnetic field above 5 kA/m was greatly different from the one below $H = 5$ kA/m. Fig. 6 shows the dependence of the calculated temperature and the measured one on ac magnetic flux density for the hybrid heater. Below $B = 0.05$ T, the measured temperature and the calculated one increased with the ratio of $B^{1/2}$ and agreed well with each other. Above $B = 0.05$ T, the measured temperatures maintained constantly because of the influence of Curie temperature. Fig. 7 shows the dependence of the temperature on time at $B =$ 0.054 T, 0.061 T, 0,062 T. The temperature reached to the steady state within 40 s and maintained 54.5°C ± 1.5°C with the time increased. The error of ± 1.5°C was caused by ac magnetic field penetrating directly through the Cu tube. This result represents that the hybrid heater composed of the temperature sensitive ferrite with low permeability and Cu tube is able to regulate the temperature constantly at the rate of 54.5°C ± 1.5°C.

5. Conclusion

In this study, we investigated the temperature regulation of a hybrid heater at the 5 kHz. The hybrid heater was composed of a temperature sensitive ferrite with very low permeability at the room temperature and a Cu tube. The hybrid heater showed the regulation characteristics to keep the temperature constantly at the rate of 50°C ± 1.5°C.

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