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Calculation of heating power generated from ferromagnetic thermal seed (PdCo-PdNi-CuNi) alloys used as interstitial hyperthermia implants

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Abstract High quality heating device made of ferromagnetic alloy (thermal seed) was developed for hyperthermia treatment of cancer. The device generates sufficient heat at room temperature and stops heating at the Curie temperature T_c. The power dissipated from each seed was calculated from the area enclosed by the hysteresis loop. A new mathematical formula for the calculation of heating power was derived and showed good agreement with those calculated from hysteresis loop and calorimetric method.

Introduction

Hyperthermia is raising the tissue temperature between 41.5–46°C to kill cancerous cells while preserving normal cells. Initial attempts to make advantage of anti cancer activity of hyperthermia involved the use of pyrogens for the induction of high fevers in patients with malignancies. Perhaps the best known of these studies was that of Coley in 1893 [1], who used bacterial toxins to raise the temperature in patients. In hyperthermia the temperature of the tissue is elevated artificially with the aim of receiving therapeutic benefits. It is considered an adjunct to other treatments [2–4]. One of the common methods for heating small tissue volumes was suggested firstly by Burton *et al.* in 1971 [5] using self-regulating implants. These implants are usually needle-shaped ferromagnetic thermoseeds.

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The physical process of seed heating is based on eddy current induced by an oscillating magnetic field or by magnetic hysteresis loss [6]. Then, the temperature of the cancer tissue is raised until the curie temperature of the implants is reached. Previous work have developed thermal seed of binary alloys or ferrite [6–9] for interstitial hyperthermia. On the other hand, the power absorption of ferromagnetic seeds have been measured experimentally using a calorimetric method [9] and static magnetic hysteresis loop [6]. Moreover, a theoretical calculation of heating power based in linear theory rather than the calorimetric measurements was investigated by many authors [10, 11].

In this article we developed for the first time in Egypt a manufacture of PdNi, PdCo and NiCu ferromagnetic thermoseeds in order to increase the sharpness of Curie temperature T_c. These thermoseeds show sharp decrease in magnetic susceptibility and the heat production at T_c. However, computations performed by Atkinson *et al.* (1984) [11] indicated that a heat production rate of 200 mw/cm is adequate for most clinical application. The characteristics of the prepared seeds have been measured as a function of temperature, and magnetic field strength.

In the present study we have measured a heating power using the area of the hystresis loss. A simple model for the calculation of the power dissipated from ferromagnetic thermoseeds is constructed aimed on the combination of the Curie Wiess law and the electromagnetic induction law below T_c. The calculated values of heating powers are compared with the experimental results.

Experimental

Thermal rods were prepared from a mixture of magnetic and nonmagnetic elements. The rod implants were developed with palladium nickel (Pd_xNi_{100-x}), palladium cobalt (Pd_xCo_{100-x}) and copper nickel (Cu_xNi_{100-x}) alloys with different concentrations x (x ranging from 10 to 30 wt.%). Constituent elements of at least 99.85% purity were alloyed into ingot form in an induction furnace. They were cold worked into approximately 0.9 mm diameter wire and cut to 5.5 cm length seeds. As significant cold work destroys the normal lattice structure, inhibits formation of magnetic domains and impedes Bloch wall movement. A recrystallization heat treatment at 1000°C was necessary to improve bulk magnetic properties and homogeneity of the alloys. The sharpness of a ferromagnetic transition T_c in these alloys depends on the homogeneity of the samples. A second annealing at 1000°C, 1000°C, 800°C for PdNi, PdCo and Cu Ni respectively in an inert atmosphere was performed to relieve any mechanical stresses resulting from the cold working, and also to provide magnetic uniformity to the alloys.

Since the value of the inductance L is directly proportional to a.c susceptibility ($\chi_{a.c}$), an experiment is constructed for fast detecting T_c by measuring L instead of a.c susceptibility ($\chi_{a.c}$). A copper wire was wound around the rod shape sample and the coil was connected to an inductance bridge. The inductance L of the samples was measured in the temperature range 20–100°C at 100 kHz.

To calculate the heating power generated from the ferromagnetic thermoseeds, the magnetic hysteresis loops of each sample at different temperatures below the T_c were measured. Direct measurements of magnetization M at different magnetic fields H and temperatures T were made using Oxford Faraday magnetometer [12]. The area of the hysteresis loop of each sample is decreased with increasing temperature. According to Shimizu *et al.* [6], the heating power can be deduced from the area of the recorded hysteresis loop using;

$$P = f \oint MdH \qquad (1)$$

where, P is the measured heating power per unit length under applied magnetic field, f is the assumed frequency of the applied a.c magnetic field and $\oint MdH$ is the area of the d.c hysteresis loop.

Results and discussion

Figure 1 shows measurements of the inductance L as a function of temperature T for the annealed seeds $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$. As can be seen from the plot, there is a sharp transition of Curie temperature T_c for $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$ at 52°C, 57°C and 49°C respectively.

The magnetization of the samples is temperature and magnetic field dependent. From hysteresis loop, the total magnetization M can be represented by $M = \pm\sigma + \chi(T)H$, where, σ is the remanant magnetization and $\chi(T)$ is termed the susceptibility of the material of the sample. The negative sign represents the value of the remnant magnetization when the field is swept from the negative value back towards zero fields. The hysteresis loops were measured using maximum static magnetic field ±0.8T for the selected samples of $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$.

Figure 2 shows the hysteresis loops of $PdNi_{27.0}$ at temperatures below the Curie point. It can be seen from the figure that σ, the saturation magnetization M_s and the area of hysteresis loop were found to decrease with increasing temperature. This leads to a decrease in the value of the power loss with increase of temperature. Similar behaviour was found for the other prepared seeds. From Fig. 2, the area of the hysteresis curve is proportional to the energy dissipated in the form of power heating loss. The power heating loss decreases with decreasing the area of the hysteresis loop and stopped automatically when the Curie temperature is reached.

The area under the hysteresis loop was evaluated using a numerical analysis method [13–15] using the following relation;

$$\int_0^H M(H)dH = h\int_0^n f_q dq = h\left[f_o + q\nabla f_o + \frac{q(q+1)}{2!}\nabla^2 f_o + \frac{q(q+1)(q+2)}{3!}\nabla^3 f_o + \cdots\right]_0^n \qquad (2)$$

where, h is the step of integration between each two points of H (here $h = 0.1$), f_q is the magnetization function of H, n is the integral terminator and q is constant near values of n. From equation (1), the calculated values of the heating power evaluated from the area of the hysteresis loops for $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$ seeds as a function of temperature at frequency 100 kHz, are shown in Fig. 3.

It is clear from the figure that, the heating power of samples decreases with increasing temperature. This leads to a disappearance of power produced from these seeds near the Curie temperature. For this reason the ferromagnetic thermoseed material is the best localized self-regulated temperature control system.

Theoretical calculation of heating power

It this section, a simple theoretical model for the calculation of heating power produced from any ferromagnetic seed placed under *a.c* magnetic field is derived.

When a high frequency magnetic field is applied on a ferromagnetic seeds, an eddy current is induced. This current converted to energy dissipated in the form of heat [16]. From

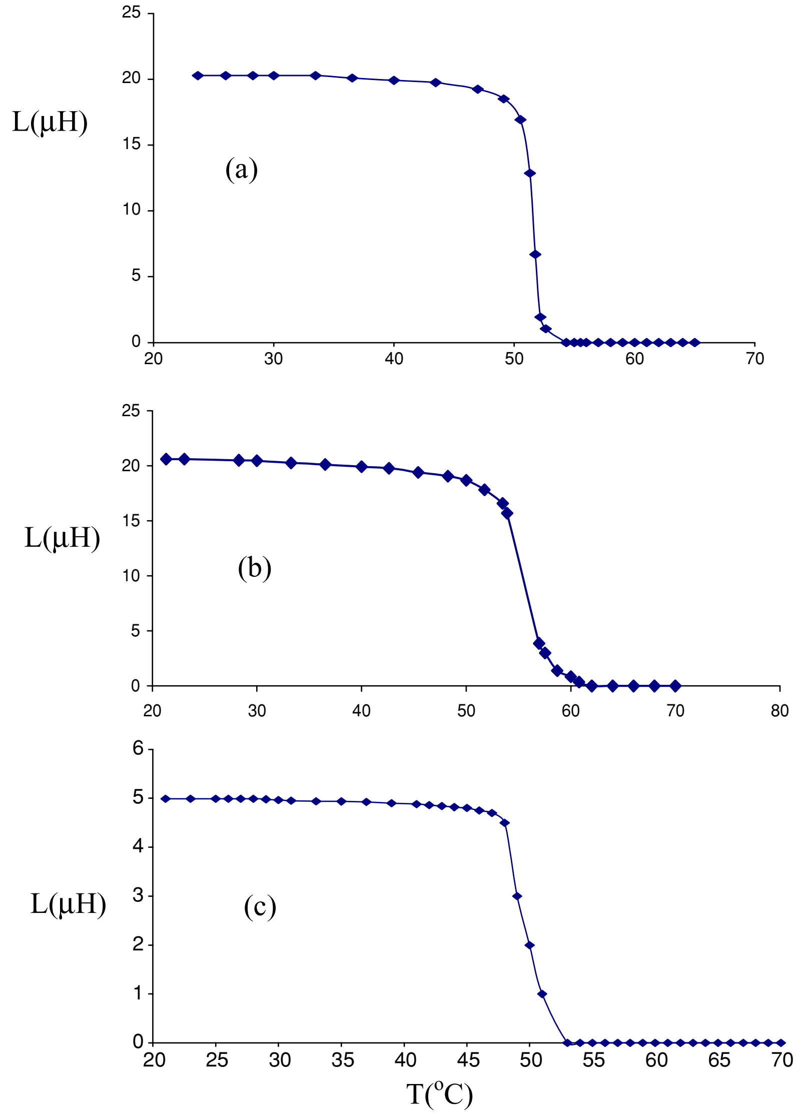

Fig. 1 Temperature dependent of the inductance for ferromagnetic seeds at 100 kHz, (a) $PdNiB_{27.0}$, (b) $PdCo_{10.8}$ and (c) $CuNi_{29.0}$.

the electromagnetic induction law, the power loss per unit volume is given by;

$$P = \frac{r_o^2}{2\rho}\left(\frac{dM}{dt}\right)^2 \cdot \frac{\mu_o^2}{\chi^2} \tag{3}$$

where r_o is the radius of the seed, μ_o is the permeability of air, and ρ is the resistivity of the seed. From Curie-Weiss law,

$$M = \frac{C}{T - T_c} H \tag{4}$$

where, C is the Curie constant and T_c is the Curie temperature. Substituting equation (4) into equation (3), one gets,

$$P = \frac{r_o^2}{2\rho}\left[\frac{d}{dt}\left(\frac{C}{T - T_c}\right) H\right]^2 \frac{\mu_o^2}{\chi^2} \tag{5}$$

From equation (5), one can write for the maximum total power per unit volume (watt/m^3), which is emitted from a ferromagnetic material placed in a.c magnetic field,

$$P_{\text{total}} = P(H) + P(T) \tag{6}$$

where, $P(H)$ is the part of power at constant temperature, it is a function of H^2 and $P(T)$ is the part of power at constant a.c magnetic field, it is a function of T^2.

First at $H = H_o =$ constant, then equation (5) becomes,

$$P(T) = \frac{r_0^2 \mu_0^2 C^2 H_0^2}{2\rho\chi^2} \cdot \frac{1}{(T - T_c)^4}\left(\frac{dT}{dt}\right)^2 \tag{7}$$

By taking the square root of equation (7),

$$\sqrt{P(T)} = \frac{r_o \mu C H_o}{\sqrt{2\rho}\chi} \cdot \frac{1}{(T - T_c)^2}\left(\frac{dT}{dt}\right) \tag{7-a}$$

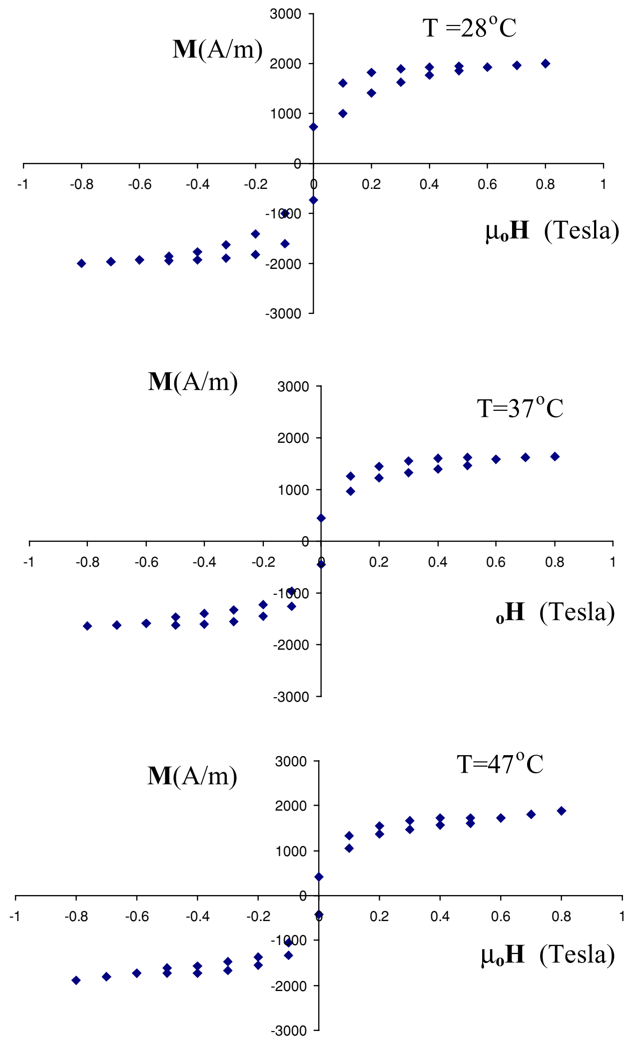

Fig. 2 The magnetic hysteresis loops for $PdNi_{27.0}$ alloy at different temperature below T_c.

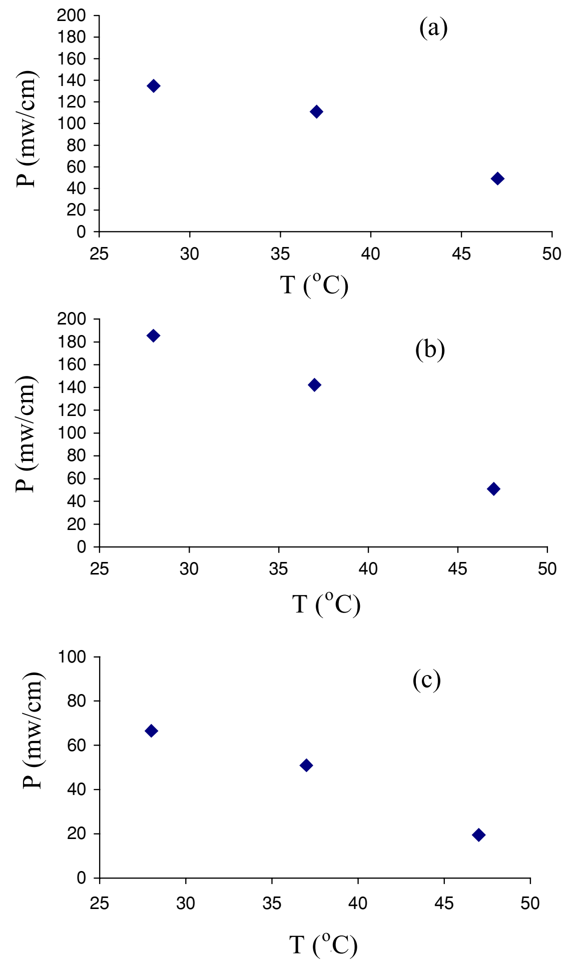

Fig. 3 The power heating loss as a function of temperature for (a) $PdNi_{27.0}$, (b) $PdCo_{10.8}$ and (c) $CuNi_{29.0}$, calculated from the area under the hysteresis loop using the numerical analysis methods and assuming that the frequency of the applied a.c magnetic field is 100 kHz.

By integrating equation (7-a),

$$\int_0^T (T - T_c)^{-2} dT = \frac{\chi\sqrt{2\rho P(T)}}{r_0 C \mu_o H_o} \int_0^t dt \tag{7-b}$$

Then,

$$(T - T_c)^{-1} = \frac{\chi\sqrt{2\rho P(T)}}{r_0 C \mu_o H_o} t \tag{7-c}$$

Squaring equation 7-c, we get

$$P(T) = \frac{\mu_0^2 r_0^2 C^2 H_0^2}{2\rho\chi^2} \cdot \frac{1}{(T - T_c)^2} \cdot \frac{1}{t^2} \tag{8}$$

The power $P(T)$ at constant a.c magnetic field through one cycle is given by

$$P(T) = \frac{f^2 \mu_0^2 r_0^2 C^2 H_0^2}{2\rho\chi^2} \cdot \frac{1}{(T - T_c)^2} \tag{9}$$

At constant temperature T and since $H = H_o \cos\omega t$, then, from equation (4),

$$\frac{dM}{dt} = \frac{C}{T - T_c} \cdot \frac{dH}{dt} = \frac{C\varpi}{T - T_c} H_o \sin\varpi t \tag{10}$$

The maximum value of dH/dt is given at $\omega t = 90$, then

$$\frac{dM}{dt} = \frac{C}{T - T_c} H_0 \varpi \tag{11}$$

Substituting equation (11) into equation (3), the power at constant temperature,

$$P(H) = \frac{r_0^2}{2\rho} \cdot \frac{\mu_0^2 C^2 4\pi^2 f^2}{\chi^2 (T - T_c)^2} H_0^2 \tag{12}$$

Substitute equations (9) and (12) in equation (6), one gets for the total power,

$$P_{total} = \frac{r_0^2}{2\rho\chi^2}\left[\frac{\mu_0^2 C^2 4\pi^2 f^2}{(T-T_c)^2}H_0^2 + \frac{\mu_0^2 C^2 f^2}{(T-T_c)^2}H_0^2\right]$$

$$P_{total} = \frac{r_0^2}{2\rho\chi^2}(4\pi^2+1)\frac{\mu_0^2 C^2 f^2}{(T-T_c)^2}H_0^2$$

$$P_{total} \approx \frac{40 r_0^2 \mu_0^2 C^2 f^2 H_0^2}{2\rho\chi^2}\cdot\frac{1}{(T-T_c)^2}$$

Multiply the above equation by the area of the seed (πr_o^2), the power per unit length becomes;

$$P_{\text{total}} \approx \frac{40\pi r_0^4 \mu_0^2 f^2 H_0^2}{2\chi^2\rho\gamma^2}\cdot\frac{1}{(T/T_c-1)^2} \tag{13}$$

where, γ is the intermolecular field presents the total heating power emitted per unit length of the ferromagnetic seeds.

The theoretical calculation of the temperature dependence of the heating power for $PdNi_{27.0}$, $Co_{10.8}$ and $CuNi_{70.4}$ seeds at different frequencies is shown in Fig. 4. It can be seen that the power reaches minimum value near T_c. At 100 kHz,

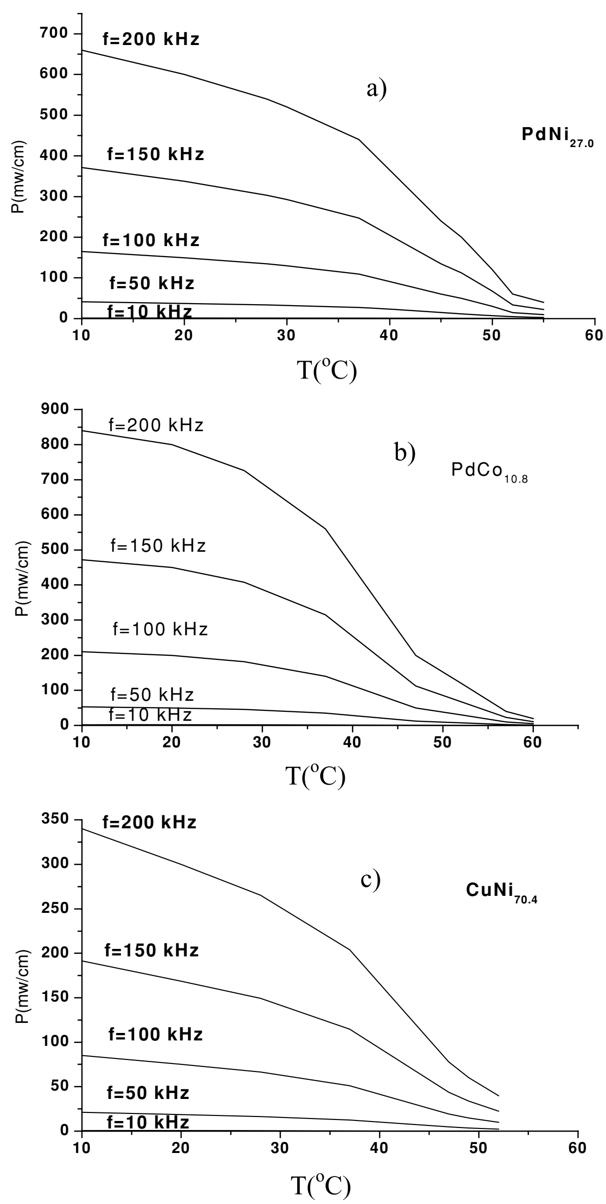

Fig. 4 Temperature dependent of the heating power at different frequencies for (a) $PdNi_{27.0}$, (b) $PdCo_{10.8}$ and (c) $CuNi_{70.4}$ calculated from the theoretical model of equation (13).

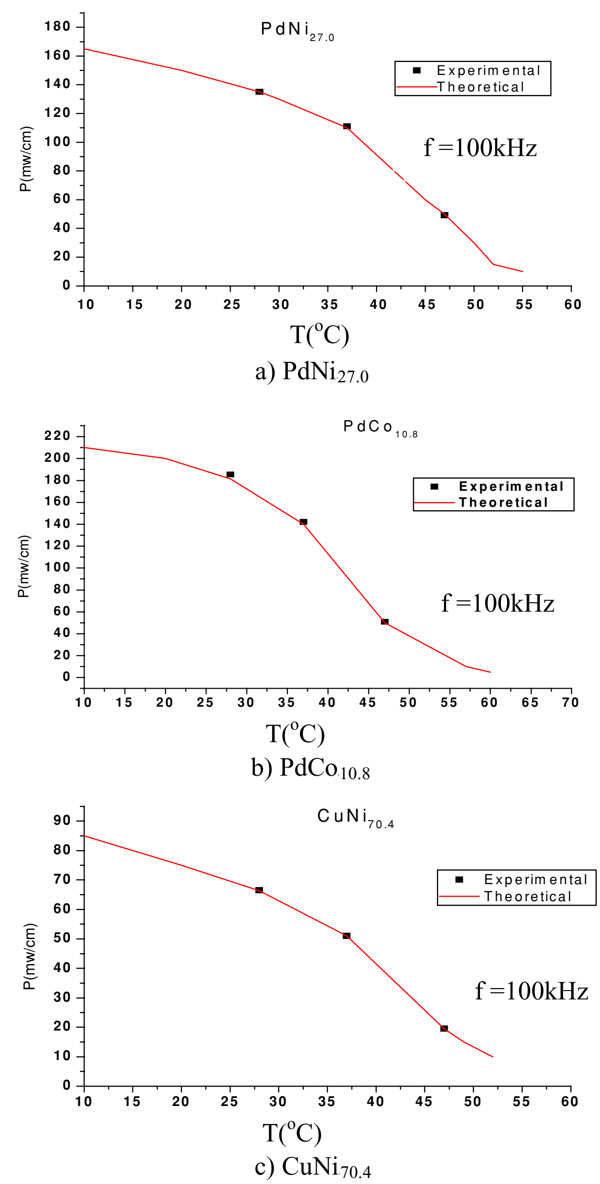

Fig. 5 The heating power as a function of temperature for (a) $PdNiB_{27.0B}$, (b) $PdCoB_{10.8}$ and (c) $CuNiB_{70.4}$ at 100 kHz. Solid line represents the theoretical calculation of power according to equation (13).

Fig. 4 shows that, the heating power is about 200 mw/cm for $PdNi_{27.0}$, and $PdCo_{10.8,}$ which is sufficient for most clinical applications [10]. On the other hand, $CuNi_{70.4}$ seed shows the heating power of about 85 mw/cm. In this case, the use of CuNi seeds need to use the frequency of a.c. magnetic field greater than 150 kHz. Figure 5 shows the theoretical line representing the power calculated from equation (13) together with the experimental points, which are recorded from the hysteresis loops and equation (1), (see Fig. 3), for $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$ thermoseeds, at 100 kHz.

In Conclusion, $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$ ferromagnetic thermoseeds have been prepared for interstitial hyperthermia in cancer treatment. The $PdNi_{27.0}$, $PdCo_{10.8}$ and $CuNi_{70.4}$ seeds show sharp ferromagnetic to paramagnetic transition temperatures at 52°C, 57°C and 49°C respectively. These seeds provided power output at 20°C of about 150, 200 and 75 mw/cm respectively, as measured from the hysteresis loops, which are in good agreement with the values measured by the calorimetric method [8–11]. Temperature dependence of seeds power have been computed from a combination of curie and induction laws. Our computations show good agreement with those calculated from the area under hysteresis loop at a.c magnetic field of frequency 100 kHz and field strength of 4 kA/m. It is also clear that the power is automatically stopped when T_c is reached, indicating that the seeds have self limiting temperature control. Therefore, The above mentioned seeds are clinically useful in treating localized tumors in the next work.

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