Analysis and Design of Applicator System for Regional Induction Heating 2.45 GHz

CHUMPON PATUMMAKASORN and CHANCHAI THONGSOPA
Department of Telecommunication Engineering
Suranaree University of Technology
111 Sranaree Road, Maung, Nakhonratchasima 30000
THAILAND
toy161@hotmail.com, chan@sut.ac.th

Abstract: - In this paper, the design of applicator system for regional induction heating at 2.45 GHz and using noninvasive method. The distribution of the lossy medium was analyzed using the finite difference time domain method(FDTD). The objective is to determine the area which the heat is uniformly distributed. The result from this paper was believed to be effectively when it was applied to the cancer treatment. The applicator utilized was the inducting spiral coils which were sets of two coils and four coils, and each coil has its own power-supply unit. It was fabricated by using magnetron sources operating at frequency of 2.45 GHz. The energy supplied to the induction coil was timely controlled. The results from the simulation and experimental of heating area from lossy medium were compared. Both simulation and experimental results showed good no conflict. The activation of supply units one at a time generated more heating wide area than the one when all units were activated at the same time. The results showed that the applicator with four coils generates more heating wide area than the one with two coils. Another interesting point is that the activation each power supply unit was turned on one by one generates more heating wide area than the activation all power supply units were turned on. In this study, both two coils and four coils were capable of producing a temperature rise of 7 Celsius degrees for 10 min. Moreover, the results from this investigation can be applied to various designs of heating wide area applicator and another advantage is its cost effectiveness.

Key-Words: - Applicator, Hyperthermia, Induction heating, lossy medium, finite difference time domain, agar phantom

1 Introduction

The treatment of cancer, such as Surgical excision, chemotherapy and radioactive treatment. Hyperthermia is a type of cancer treatment in which body tissue is exposed to high temperatures and recognized as an effective way to cure the cancer by applying the heat directly to the cancer cells. The heat distributions include the radio frequency induction, dielectric heating, microwave heating and ultrasonic wave heating. The heating temperature increased for 1.5 to 2.5 Celsius degrees per minute until it reached the value of 41 to 42 Celsius degrees, and it was kept constant for one hour. The operating frequency was varied between 73, 430, 2450 and 9000 MHz[1,2].

There are two methods of induction heating [3-5]. One method uses implants which produce local heating for regional heating. When the cancer cell was small and deep in the skin, e.g. the experiment and design of ferromagnetic implants, this approach was proved to be effective for the case that the cell was tiny or deep inside the skin[6]. Another example is that the implantation of micro-magnetic elements by following soft Heating approach, the result of this approach indicated that the temperature and heating wide area depend on the volume of magnetic elements[7]. The whole body heating method such as the experimental characterization of helical coils as hyperthermia applications show that this kind of device, in certain configurations, should be able to heat the deep portions of a human limb. [8]. Another example is that the VLF induction heating for cynical hyperthermia[9]. Two methods uses noninvasive external applicators for regional heating. When the cancer cell was large and not deep in the skin, so there was no need for the operation and it did not cause the pain. However, the arrangement for the right position of the applicator was important to the effective treatment of the cancer cells, e.g. the selective heating of cutaneous human tumors at 27.12 MHz . It is a modified diathermy unit which employs a “pancake” coil to induce the patients with up to 30 W of electromagnetic [10]. Another example is that the development of ferrite core applicator system for deep-induction hyperthermia, by used ferrite coils with the supply unit (4 MHz and 600 W) would increase the heating area when coils were equipped with the electrode[11]. The development of inductive regional heating system for breast hyperthermia, the result showed a temperature rise of more than 8 Celsius degrees at a depth of 8 cm[12]. From the study, the development applicator system for regional induction heating used noninvasive method. The operating frequency should not exceed 300 MHz and the big sized applicator was necessary. It is difficult to the arrangement for the appropriate position of the applicator.

In this paper, the study focuses on the heat distribution for a specific area at the frequency of 2.45 GHz and noninvasive approach was utilized. The external applicator with 700 supply units was powered by the magnetron tubes. The applicators are small sized. Moreover, a set of two coils and four coils applicator with independent power sources was used. The distribution of heating wide area was studied by timely controlling the turning on and off of the power supply units. The technique deployed to study the distribution of heat was the finite difference time domain method (FDTD) [13-17].

2 Construction of applicator system

In this paper, The applicator was fabricated copper wire with diameter of (w) 2.25mm. Outer diameter (Do) 70 mm. Distance between windings(s) 1 mm. Number of turns(N) 9 as shown in figure 1 and 2. The calculus of applicator as shown in equation(1) and(2),inductance (L) 1 uH. [18-20].

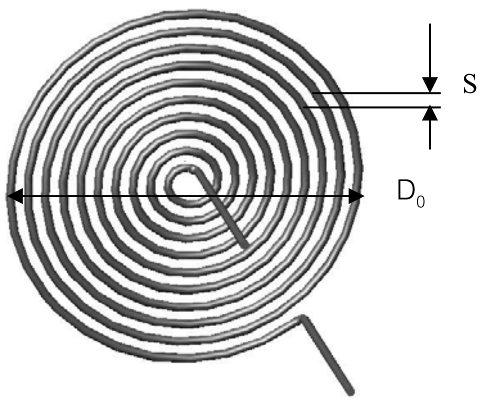


Fig.1 Construction of applicator (spiral induction coil)

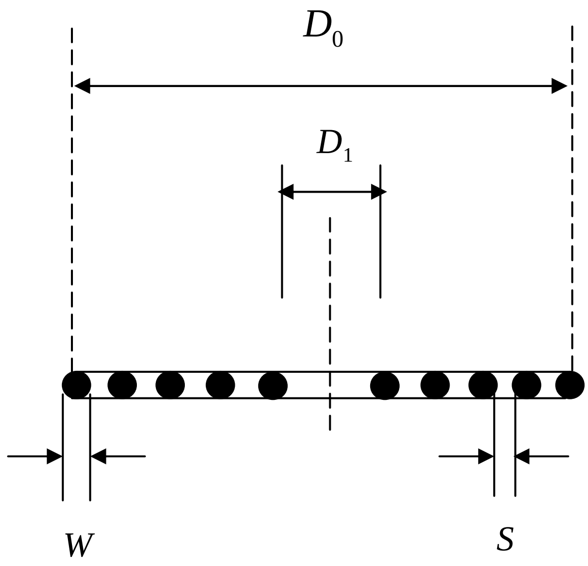


Fig. 2. The design of spiral induction coils.

$$L = \frac{N^2 \times A^2}{30R - 11D_1} \tag{1}$$

$$R = \frac{D_1 + N(W + S)}{2} \tag{2}$$

Where D_1 is inner diameter, N is Number of turns, W is wire diameter, S is turn spacing, L is inductance and D_0 is outer diameter

3 Temperature Distribution

In this section, the simulation of heat induction was conducted by analyzing eddy current distribution of the applicator and the following fundamental equation for vector potential A, which takes the eddy current into consideration, is used. Solving the above equation for A , the magnetic field and eddy current distribution are calculated as follows [21-26].

$$\nabla \times E = -j\omega\mu H \tag{3}$$

$$\nabla \times H = j_0 + j\omega\varepsilon E + \sigma E \tag{4}$$

$$\nabla . B = 0 \tag{5}$$

$$\nabla . D = \rho_s \tag{6}$$

$$\nabla \times (\nu \nabla \times A) = j_0 - j \quad (7)$$

$$\nabla \times (\nu \nabla \times A) = j_0 - \sigma \frac{\partial A}{\partial t} - \sigma \nabla \phi \quad (8)$$

Where ν is magnetic reluctance $(A.t/Wb)$, J_0 is forced current density (A/m^2), σ is conductivity $(\Omega^{-1}m^{-1})$, ϕ is electric potential (V), μ is permeability (H/m), ε is permittivity (Fm^{-1}), ω is radian frequency (rad/s), j is current density (A/m^2), E is the electric field (V/m), H is the magnetic field (A/m), B is magnetic flux density (Wbm^2), D is electric flux density (C/m^3)

The temperature distribution in lossy media can be calculated from bioheat transfer equation by assuming the lossy media is human tissue. It can be expressed as [27-37].

$$\frac{\partial T}{\partial t} = R_T \nabla^2 t + \frac{\varepsilon_v}{C_p} L_h \frac{\partial M_l}{\partial t} + \frac{P}{\rho C_p} \quad (9)$$

$$P = \frac{j.j^*}{\sigma} \quad (10)$$

$$j = -\sigma \frac{\partial A}{\partial t} - \sigma \nabla \phi \quad (11)$$

Where T is Temperature (^oC) t is heating time (s), R_t is distribution temperature $(m^2.s^{-1})$, ε_v is (kg^{-1}), M_l is liquid of mass ratio (kg), C_p is specific heat at constant pressure (jk/g^oC), ρ is the local physical density of the tissue $(kg.m^{-3})$, P is heat source distribution (W/m^3).

The applicator systems was fabricated by using magnetron sources operating at frequency of 2.45 GHz and a maximum output power of 700 w. Each of four microwave magnetrons are mounted into a 9×20×3 cm^3 cavity which is coupled by a $\lambda/4$ probe to each applicators through a RG 8/U coaxial cable. This applicator was radiate to lossy medium (phantom),as shown in Fig. 3 [38].

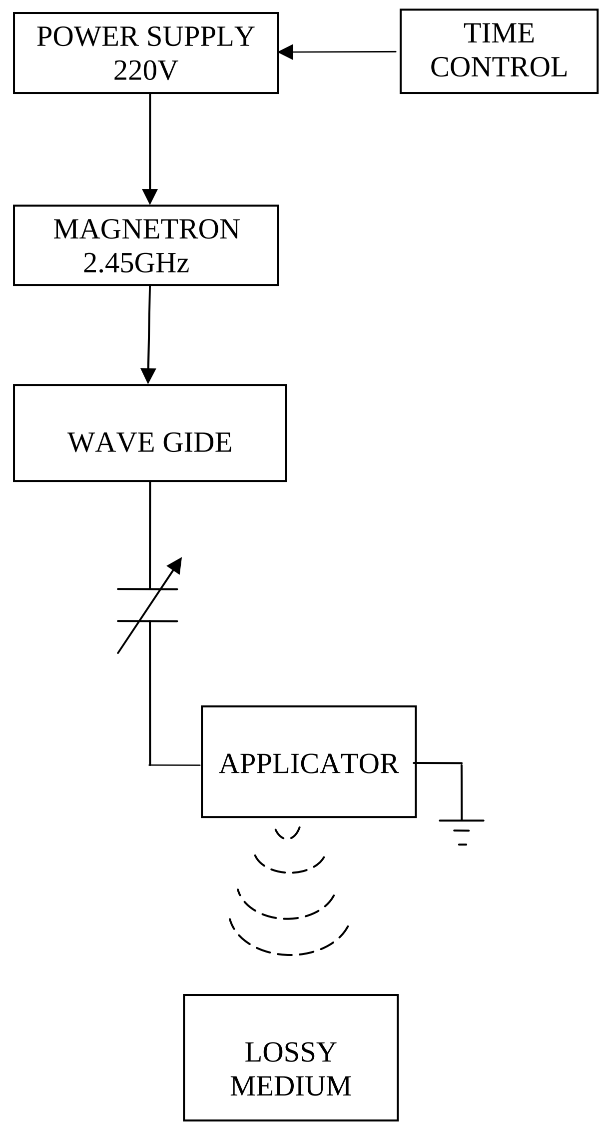


Fig.3. Construction of applicator systems.

4 Measurement and Result

The lossy medium temperature distribution was analyzed by using the finite difference time domain method (FDTD). It with diameter of (G) 9 cm, hight(H) 7 cm, Distance between lossy medium to applicator(s1) was 1,2,3,4,5,6,7,8,9 and 10 mm respectively, as shown in Fig. 4(a) The initial temperature of lossy media was 37 Celsius degrees which is the human temperature. The temperature at the surface of lossy medium was keep a constant 27 Celsius degrees. The Fabrication of lossy medium imitates skin layer, fat layer and agar phantom, as shown in Fig. 4(b). The results from the simulation and experimental of heating area from lossy medium were compared, as show fig. 5.

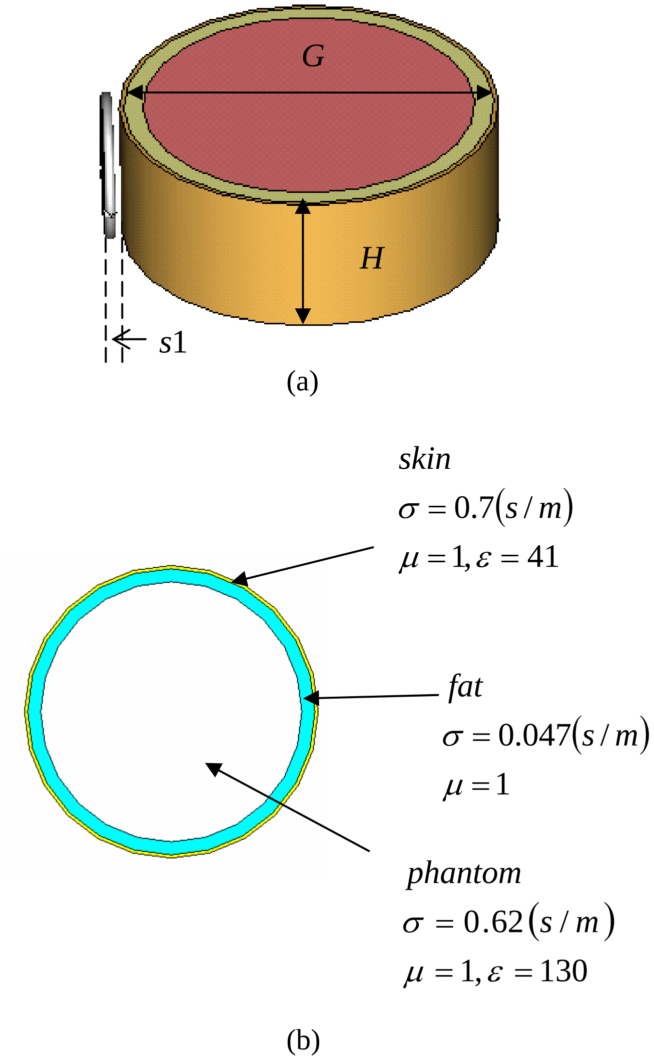


Fig.4 The lossy medium (a) Distance between lossy medium to applicator(s1) (b)The lossy medium consist

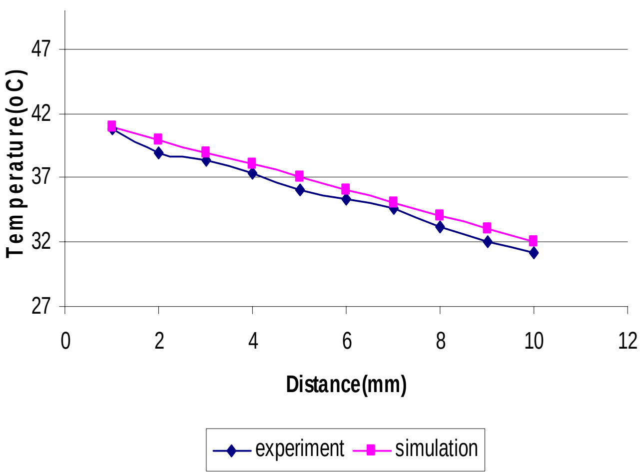


Fig.5 Relationship between temperature and distance between medium and lossy medium (s1)

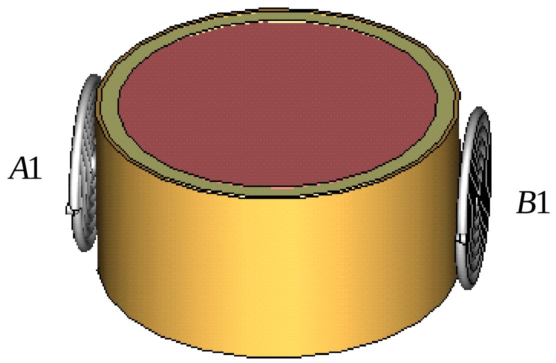


Fig.6. The arrangement for position of the applicator (two coils)

Table 1. The activation all power supply units were turned on (two coils)

Applicator A1	ON	ON
Applicator B1	ON	ON

Table 2. The activation each power supply unit was turned on one by one (two coils)

Applicator A1	ON	OFF
Applicator B1	OFF	ON

Table 3. The activation all power supply units were turned on(four coils)

Applicator A2	ON	ON	ON	ON
Applicator B2	ON	ON	ON	ON
Applicator C2	ON	ON	ON	ON
Applicator D2	ON	ON	ON	ON

Table 4. The activation each power supply unit was turned on one by one (four coils)

Applicator A2	ON	OFF	OFF	OFF
Applicator B2	OFF	ON	OFF	OFF
Applicator C2	OFF	OFF	ON	OFF
Applicator D2	OFF	OFF	OFF	ON

The simulation and experiment was conducted in two stages: turning on all power supply units(20 minutes), as shown in table 1,3. And turning on each power supply one by one(each for 20 sec). That set of coils was composed of two coils which transfer energy from A1 to B1 and can also switch to opposite directions, as shown in table 2. and For four coils applicator, the energy was transferred from A2 to B2 and C2 to D2, as shown in table 4. The arrangement for position of the applicator are two coils and four coils as shown as fig. 6 and 7.

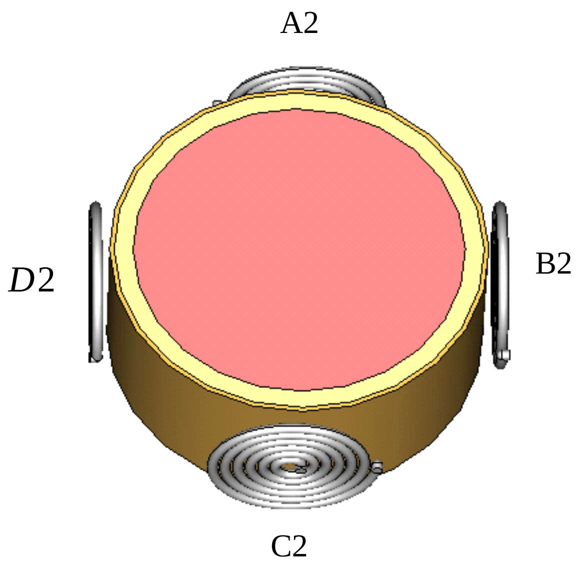


Fig.7. The arrangement for position of the applicator (four coils)

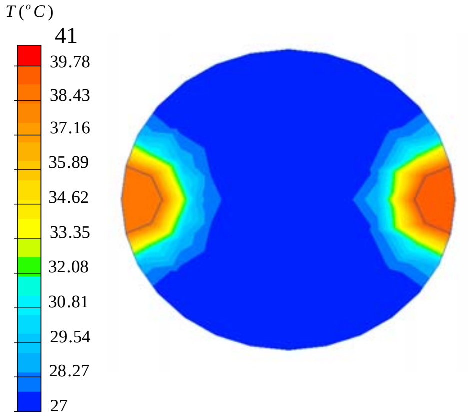


Fig. 8 The temperature distribution in the lossy medium (two coils applicator) after all power supply units were turned on for 20 minutes.

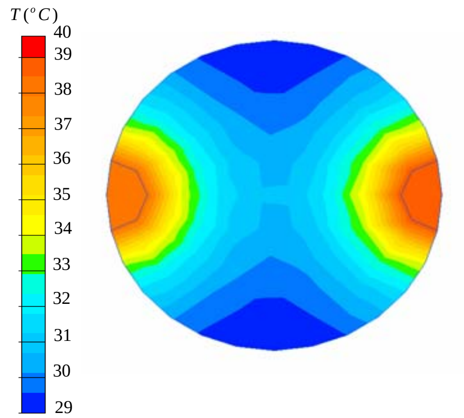


Fig. 9 The temperature distribution in the lossy medium (two coils applicator) after each power supply unit was turned on one by one (each for 20 sec).

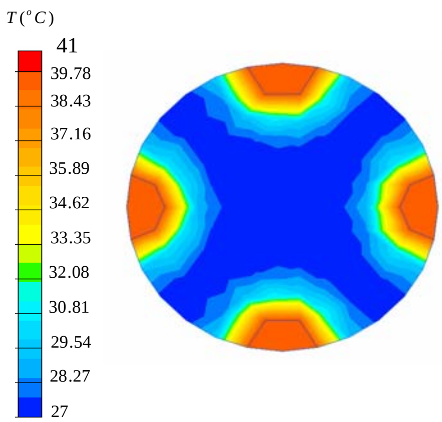


Fig. 10 The temperature distribution in the lossy medium (four coils applicator) after all power supply units were turned on for 20 minutes.

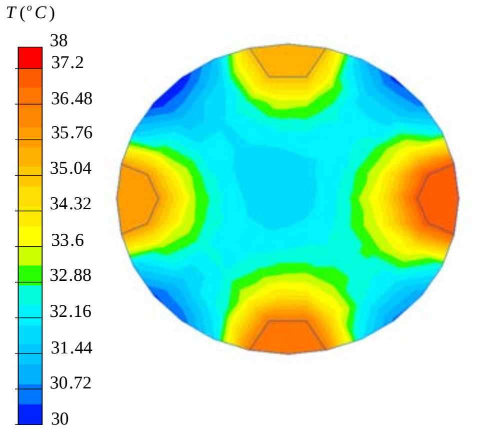
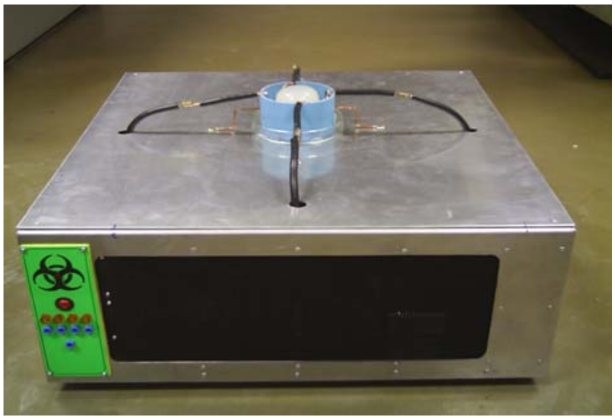


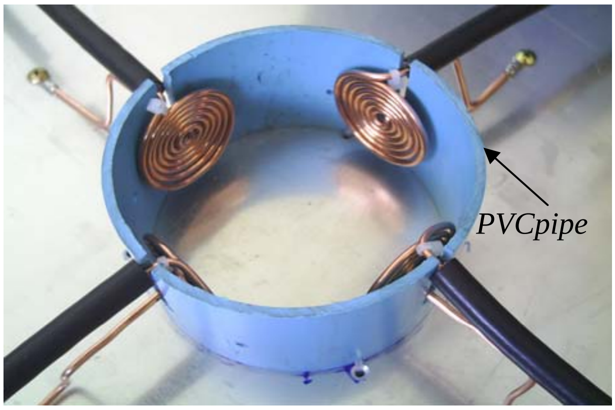
Fig. 11 The temperature distribution in the lossy medium (four coils applicator) after each power supply unit was turned on one by one (each for 20 sec).

Figure 8 and 9 showed the simulation results of heating area in the lossy medium when two coils applicator was used. The energy was fed to both coils by turning on all power supply units with the maximum temperature of 41 Celsius degrees and areas of temperature distribution are 19 cm^2. When turning on power supply unit one by one, the maximum temperature was set at 40 Celsius degrees and areas of temperature distribution are 50 cm^2. The result showed that the activation each power supply unit was turned on one by one generates more heating wide area than the activation all power supply units were turned on.

Figure 10 and 11 showed the comparison results of heating area in the lossy medium in case of four coils applicator. The feeding energy was applied to both coils when turning on all power supply units and the target of maximum temperature was 41 Celsius degrees and areas of temperature distribution are 38 cm^2. However, when the energy was fed to both coils after turning on each power supply one by one, the maximum temperature was set at 38 Celsius degrees and areas of temperature distribution are 60 cm^2. The interesting result is that the activation each power supply unit was turned on one by one generates more heating wide area than the activation all power supply units were turned on. The applicator was fabricated by using magnetron sources operated at the frequency of 2.45 GHz as shown in Fig. 10. According to the result, the specimen had two layers, and the upper layer was 2.5 cm in depth and diameter was 9 cm. The distance between applicator and the specimen was 1 mm. so it was easily monitored by using the thermal imager. The temperature of the specimen at the beginning of the measurement was 27 Celsius degrees.



(a)



(b)

(c)

Fig. 12 (a) Construction of applicator systems (b) Fabricator of applicator systems. (c) Inside the applicator.

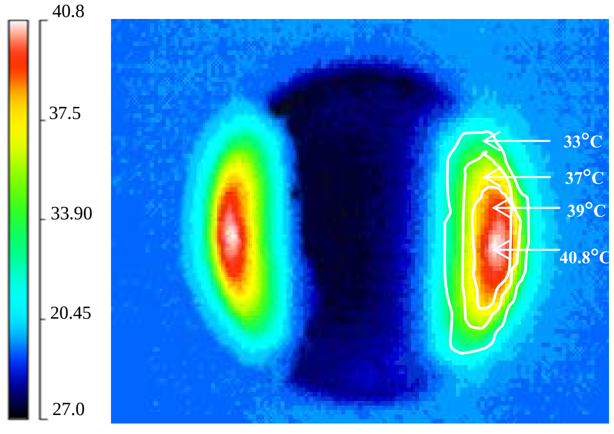


Fig. 13 The temperature distribution in the lossy medium (two coils applicator) after all power supply units were turned on for 20 minutes.

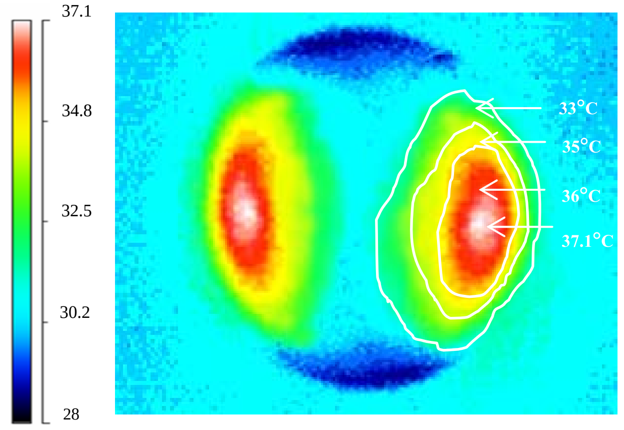


Fig. 14 The temperature distribution in the lossy medium (two coils applicator) after each power supply unit was turned on one by one (each for 20 sec)

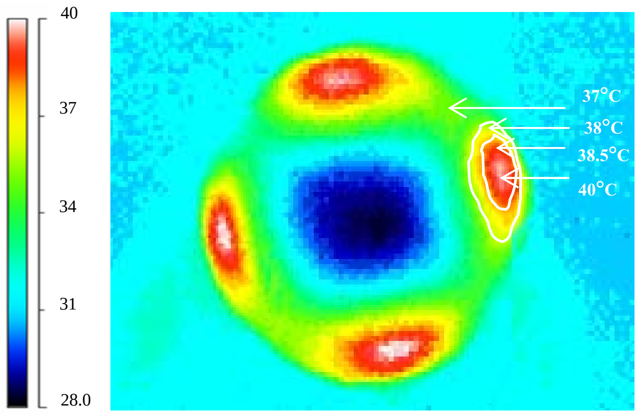


Fig. 15 The temperature distribution in the lossy medium (four coils applicator) after all power supply units were turned on for 20 minutes.

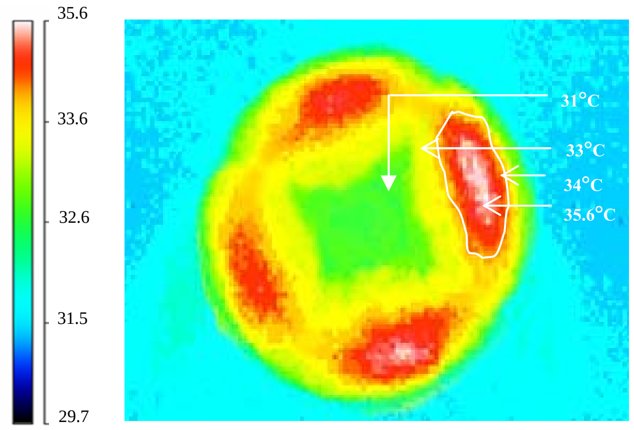


Fig. 16 The temperature distribution in the lossy medium (four coils applicator) after each power supply unit was turned on one by one (each for 20 sec)

Figure 13 and 14 showed the experimental result of heating area in lossy medium (for two coils applicator). The energy was fed to both coils when turning on all power supply at 48.8 Celsius degrees. and areas of temperature distribution are 25 cm^2. Alternatively, the feeding energy was transmitted to both coils by turning on each power supply one by one when the temperature was set at 37.1 Celsius degrees and areas of temperature distribution are 60 cm^2. In conclusion, the activation of supply units one at a time generated more heating wide area than the one when all units were activated at the same time.

Figure 15 and 16 showed that heating area in the lossy medium in case of four coils applicator. The energy was fed to both coils by turning on all power supply with maximum temperature at 40 Celsius degrees and areas of temperature distribution are 45 cm^2. Another approach is to feed energy to both coils by turning on each power supply one by one power supply with maximum temperature at 35.6 Celsius degrees and areas of temperature distribution are 62 cm^2. Similar to the previous results, the activation each power supply unit was turned on one by one generates more heating wide area than the activation all power supply units were turned on.

Figure 17 show graph is compare times to temperature from experimental and simulations. For lossy medium of two coils applicator on 20 minutes ago. The simulation and experiment results all power supply units were turned on are simulation1 and experiment1 respectively. The simulation and experiment results of each power supply unit was turned on one by one(each for 20 sec) are simulation2 and experiment2 respectively. That graph can be observed temperature rise of lossy medium more 7 Celsius degrees on 10 minutes. All power supply units were turned on has more temperature than each power supply unit was turned on one by one.

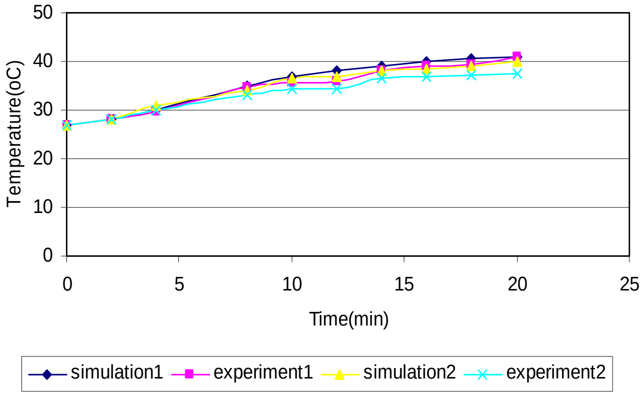


Fig.17. The results from the simulation and experimental of heating area from lossy medium were compared for 20 minutes.(two coil)

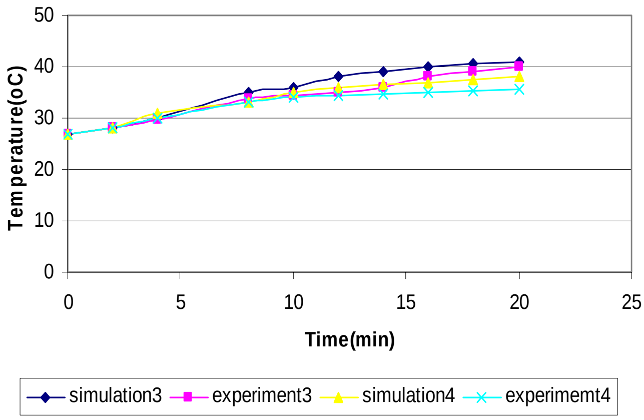


Fig.18. The results from the simulation and experimental of heating area from lossy medium were compared for 20 minutes (four coil)

From figure 18 show graph is compare times to temperature from experimental and simulations. For lossy medium of four coils applicator on 20 minutes ago. The simulation and experiment results all power supply units were turned on are simulation3 and experiment3 respectively. The simulation and experiment results of each power supply unit was turned on one by one(each for 20 sec) are simulation4 and experiment4 respectively. That graph can be observed temperature rise of lossy medium more 7 Celsius degrees on 10 minutes. All power supply units were turned on has more temperature than each power supply unit was turned on one by one.

4 Conclusion

The applicator system for regional induction heating was fabricated using noninvasive method. For a large tumor of size more than 6 cm in diameter, it was easily fabricated by using magnetron sources operated at the frequency of 2.45 GHz and small sized applicator was preferred. The timing circuit was controlled to turn on the supply unit for generating heating wide area. The simulation and experimental results of heating wide area distribution in the lossy medium was investigated. Both simulated and experimental results show good agreement. The result showed that the activation of supply units one at a time generated more heating wide area than the one when all units were activated at the same time. The result reveals that four coils applicator generated more heating wide area than the one with two coils. The activation each power supply unit was turned on one by one generates more heating wide area than the activation all power supply units were turned on. Moreover, both two coils and four coils applicator were capable of producing a temperature rise of 7 Celsius degrees for 10 minutes. The results from this investigation can be applied in the design process of applicator and it is costly effective.

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