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MAGNETIC FIELD OF ELECTRICAL RADIANT HEATING SYSTEM

Abstract: *In this paper magnetic field of electrical radiant heating system (ERHS) is considered. Typically, cable system of ERHS is planar, and it can be built into the floor, wall or ceiling. The magnetic field generated by ERHS depends on the intensity of the current, which in turn depends on the size of the heating area. According to our results, single wire ERHS can generate magnetic field considerably higher than the background field.*

Key words: Electrical radiant heating system, magnetic field, magnetic field exposure.

INTRODUCTION

Rising number of electrical devices increases the level of magnetic field at our homes. Electrical heaters may generate considerable part of it. The European recommendation for magnetic flux density reference level at 50 Hz is 100 μT for the general public [1]. Serbian national rulebook [2] established the reference level of 40 μT, which is 2.5 times lower than the European recommendation. There is ongoing discussion whether the magnetic flux density below the reference level causes any health effects. However, some epidemiological studies reported a possible association between prolonged exposures to magnetic field higher than typically found at homes, although well below the reference level. Findings reported in [3] are related to increased rates of childhood leukaemia. According to [3], increased risk starts at level several hundred times lower than the reference level. Studies reported in [4] indicate that increased risk starts as low as 0.4 μT or even lower.

According to [5], [6], the average level of magnetic flux density ranges from 0.025 μT to 0.07 μT at homes and typically is ten times higher at workplaces.

In this paper magnetic flux density generated by an electrical radiant heating system (ERHS) is considered. Heating element of ERHS typically consists of electric cables built into the floor. Other ERHS may also include wall or ceiling mounted radiant panels, see Fig. 1.

The magnetic field of an ERHS depends on the current in the system, which may be up to 15 A, see e.g.[7]. The intensity of the current depends on the power of the ERHS, which is closely related to the size of heating area. Furthermore, the layout of the conductors varies with shape and size of the room. An ERHS can be realized as a single wire or a twin wire system. It is well known that the magnetic field produced by a twin wire ERHS is considerably lower than the magnetic field produced by a single wire ERHS. However, the single wire ERHS is popular due to its lower price. In what follows a single wire ERHS is considered.

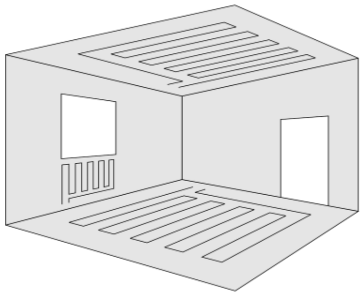

Figure 1. *Examples of an ERHS built into the floor, wall and ceiling mounted*

CALCULATIONS

The magnetic field calculations are performed both analytically and numerically. The analytical calculations are based on Bio–Savart law, where the conductors are modelled with current filaments in the air. Numerical calculations are based on finite element method (FEM) and performed in Comsol 3.5 software package. These two methods are compared on an example of EHRS heating element built into the floor, in a room of size 4 x 4 m, with the layout illustrated in Fig. 2.

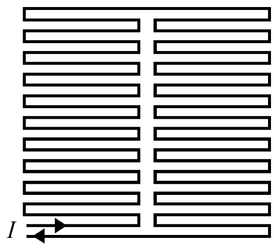

Figure 2. *The example of ERHS heating element. Reference direction of the current is indicated by arrows*

The results for magnetic flux density distribution at height 30 cm above the conductors is presented in Figs. 3(a) and 3(b). Fig 3(a)is obtained starting from Bio-Savart low, whereas Fig. 3(b) is obtained by FEM. Presented results are in very good agreement, thus giving the advantage to the analytical method which is less time consuming and requires less computer memory. Accordingly, in what follows, only analytical method is used. The calculated values of the magnetic flux density correspond to the current of $I = 1$ A. Since magnetic flux density is linearly proportional to the current, the results obtained for $I = 1$ A can be easily scaled up or down for arbitrary current. For example, for the layout presented in Fig. 2, the current of 10 A generates ten times stronger magnetic flux density, that is, up to 5 μT.

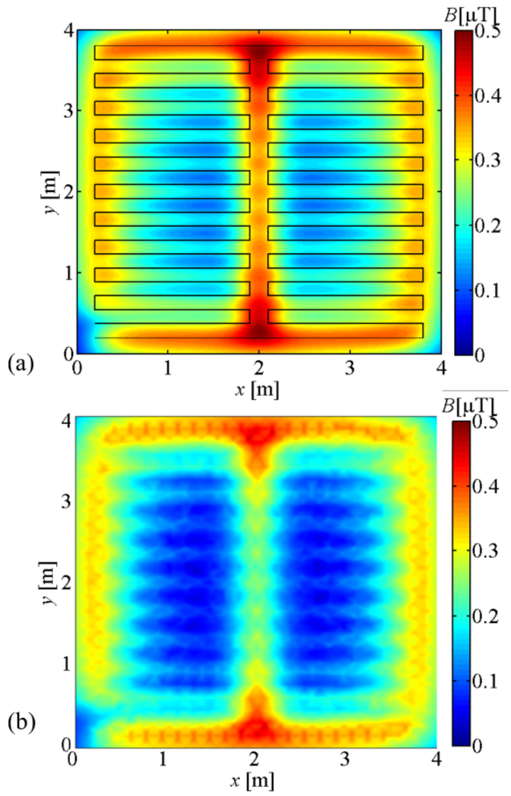

Figure 3. *Magnetic flux density 30 cm above the conductors, I=1 A, obtained by (a) analytical calculations and (b) FEM*

Magnetic flux density of the heating element

One of the types of heating elements for underfloor ERHS is realized with aluminium strip. In such type of the heating system, the aluminium strip is placed on the floor area and in a big loop returns to the connection point. In this section, we describe the procedure for the magnetic field calculation in vicinity of such type of the heating element. For others types of heating elements, which include the wall mounted or ceiling mounted heating elements, these procedure for magnetic field calculation is also applicable.

In order to cover the floor, aluminium strips should be bended and folded usually according to some regular pattern. Typically, the layout of the strip repeats some basic motif on the floor. Therefore, the major part of the heating element can be described by repeating the same basic motif. In what follows, such basic motif is referred to as a unit cell.

Thus, in order to simplify the description of the heating element, the strip is divided into unit cells. Each unit cell consists of four parts numbered with $n+1$, $n+2$, $n+3$ and $n+4$, where $n = 0,\dots,N_{max}-1$ and N_{max} denotes the number of the unit cells. As an example, two consecutive unit cells are presented in Fig. 4(a). Furthermore, each part of the unit cell is modelled with K_{max} line conductors carrying current I/K_{max}, where I denotes the current in the strip. Model of two consecutive unit cells for $K_{max} = 5$ is shown in Fig. 4(b). Since each part of the unit cell is modelled with K_{max} line conductors, it follows that each unit cell is modelled with $4K_{max}$ line conductors.

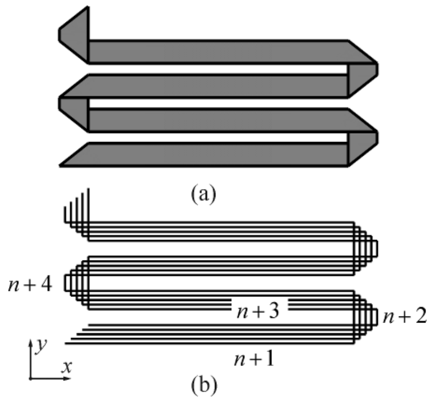

Figure 4. *Two unit cells of (a) aluminium strip and (b) model with K_{max} = 5 line conductors*

Parts numbered with $n+1$ and $n+3$ are horizontal parts starting from the left hand side and the right hand side, respectively. Parts numbered with $n+2$ and $n+4$ are vertical parts, which are placed on the right hand side and the left hand side, respectively. Moreover, the $(n+2)$nd part starts where the $(n+1)$st part ends, $(n+3)$rd part starts where the $(n+2)$nd part ends, and so forth.

Let a denote the width of the aluminium strip and s the separation between the adjacent edges of horizontal parts of the strip. Here we provide the description of the coordinates of the starting and ending points of the line conductors used to model one unit cell. For $(n+1)$st unit cell modelled with $4K_{max}$ line conductors, the x and y coordinates of the starting points can be expressed as

$$
\begin{aligned}
&x(4n+1,k) = D_x + (2k-1)d,\\
&y(4n+1,k) = D_y + (2k-1)d + 2n(s+a),\\
&x(4n+2,k) = D_x + (2k-1)d + L_x,\\
&y(4n+2,k) = D_y + (2k-1)d + 2n(s+a),\\
&x(4n+3,k) = D_x + (2k-1)d + L_x,\\
&y(4n+3,k) = D_y - (2k-1)d - s + (2n+2)(s+a),\\
&x(4n+4,k) = D_x + (2k-1)d,\\
&y(4n+4,k) = D_y - (2k-1)d - s + (2n+2)(s+a),
\end{aligned} \tag{1}
$$

where $n = 0,\ldots,N_{\max}-1,\ k = 1,\ldots,K_{\max}$ and $d = a/(2K_{\max})$. The end points of each line conductor can be obtained from

$$
\begin{aligned}
&x_e(m,k) = x_b(m+1,k)\\
&y_e(m,k) = y_b(m+1,k),
\end{aligned} \tag{2}
$$

for $m = 1,\ldots,4N_{\max}-1$ and

$$
\begin{aligned}
&x_e(4N_{\max},k) = D_x + (2k-1)d,\\
&y_e(4N_{\max},k) = D_y + (2k-1)d + 2N_{\max}(s+a).
\end{aligned} \tag{3}
$$

Furthermore, magnetic flux density of the heating element can be calculated by superposition of the magnetic flux densities generated by the straight line conductors. Thus, for $N_{\max}$ unit cells containing four parts, where each part is modelled with $K_{\max}$ line conductors, the magnetic flux density vector generated by the heating element at point (x,y,z) can be calculated as

$$
\vec{B}(x,y,z) = \sum_{k=1}^{K_{\max}} \sum_{m=1}^{4N_{\max}} \vec{B}_{m,k}(x,y,z), \tag{4}
$$

where $\vec{B}_{m,k}(x,y,z)$ denotes the magnetic flux density of the line conductor starting at the point with coordinates $(x_b(m,k), y_b(m,k))$ and ending at the point $(x_e(m,k), y_e(m,k))$. In order to use (1)-(3) notice that $n = \lfloor (m-1)/4 \rfloor$, where $\lfloor (m-1)/4 \rfloor$ denotes the largest integer not greater than $(m-1)/4$. Thus, each m can be expressed as $m = 4n + n'$, where $n' \in \{1,2,3,4\}$. The reference direction of the current in each line segment is toward the end point. In the special case of the heating element realized with the single wire, the magnetic flux density can be calculated according to the procedure described above with $K_{\max} = 1$.

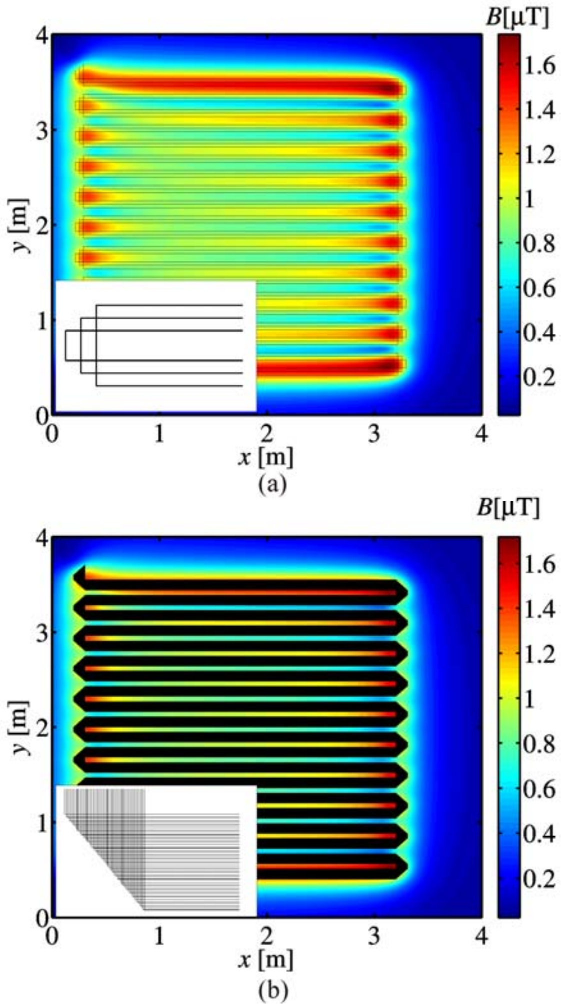

Figure 5. *Magnetic flux density at the plane 10 cm above the strip calculated with (a) $K_{\max}$ = 3 and (b) $K_{\max}$ = 52*

Here we consider the effect of the value of $K_{\max}$ on the accuracy of the magnetic flux density calculation. The magnetic flux density of the strip containing $N_{\max} = 10$ unit cells calculated with $K_{\max} = 3$ and $K_{\max} = 52$ are presented in Figs. 5(a) and 5(b), respectively. The strip width is $a = 11\,\text{cm}$, separation $s = 5\,\text{cm}$, current in the strip $I = 1\,\text{A}$, and the field is calculated at the plane $10\,\text{cm}$ above the strip. The positions of the line conductors used to model the strip are indicated by the solid lines. It is easy to see that the magnetic flux densities calculated for $K_{\max} = 3$ and $K_{\max} = 52$ are in very good agreement. Since, the result obtained with $K_{\max} = 52$ can be considered to be exact for the strip with uniform distribution of the current, it follows that the choice of $K_{\max} = 3$ provides sufficiently accurate calculation, which is considerably faster. Maximal magnetic flux density calculated for $K_{\max} = 3$ and $K_{\max} = 52$ is equal to $1.75\,\mu\text{T}$, and $1.73\,\mu\text{T}$, respectively.

Moreover, from Fig. 5(a) and 5(b) it can be observed that the magnetic flux densities generated by the inner horizontal parts partially cancel each other. On the other hand, this is not the case with the magnetic flux density generated by the outer parts. Thus, at least in the first approximation, magnetic flux density generated by this type of the heating element can be estimated by calculating the magnetic flux density of the single loop which overlaps with the outer parts of the heating element.

MEASUREMENTS

The magnetic flux density of an ERHS sample, whose layout is shown in Fig. 6(a), is measured along *z* – axis at three different heights (20 cm, 40 cm, and 60 cm) above the middle part of the sample, as illustrated in Fig. 6(b). The ERHS sample is made of folded 5.5 cm wide aluminium strip, with separation of 2 cm between the adjacent edges. For themeasurements,EFA-300 field analyser (Fig. 6(c)) is used. The magnetic flux density is measured at 50 Hz with isotropic magnetic field probe with 10 cm^2 cross-sectional area [7]. During the measurements, the rms value of the current in ERHS sample was 42 A.

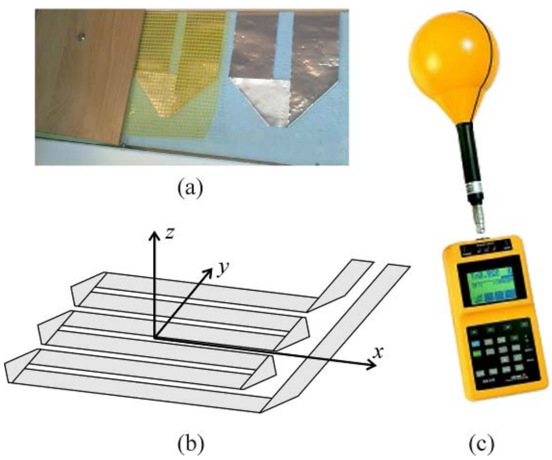

Figure 6. (a) *Photo of the ERHS sample,(b) layout of the sample and (c) EFA-300 with magnetic field probe*

The results of the measurements (B_{meas}) and calculations (B_{calc}), based on the model described in the previous Section, are compared in Table I. The relative difference between measured and calculated values (fifth column in Table I) are obtained from the following formulae

$$\varepsilon[\%] = \left|1 - \frac{B_{calc}}{B_{meas}}\right| \cdot 100. \qquad (5)$$

According to Table I, the measured and calculated results are in good agreement. These results provide another verification of the model proposed in this paper.

Table 1. *Measured and calculated values of the magnetic flux density at three different heights above the EHRS sample.*

Point No.	Heigh [cm]	B_{meas} [μT]	B_{calc} [μT]	ε [%]
1	20	20.9	19.5	6.69
2	40	9.97	9.07	9.03
3	60	5.08	4.41	13.18

The calculated values of the magnetic flux density distributions above the sample at tree planes parallel to the sample are presented in Fig. 7.

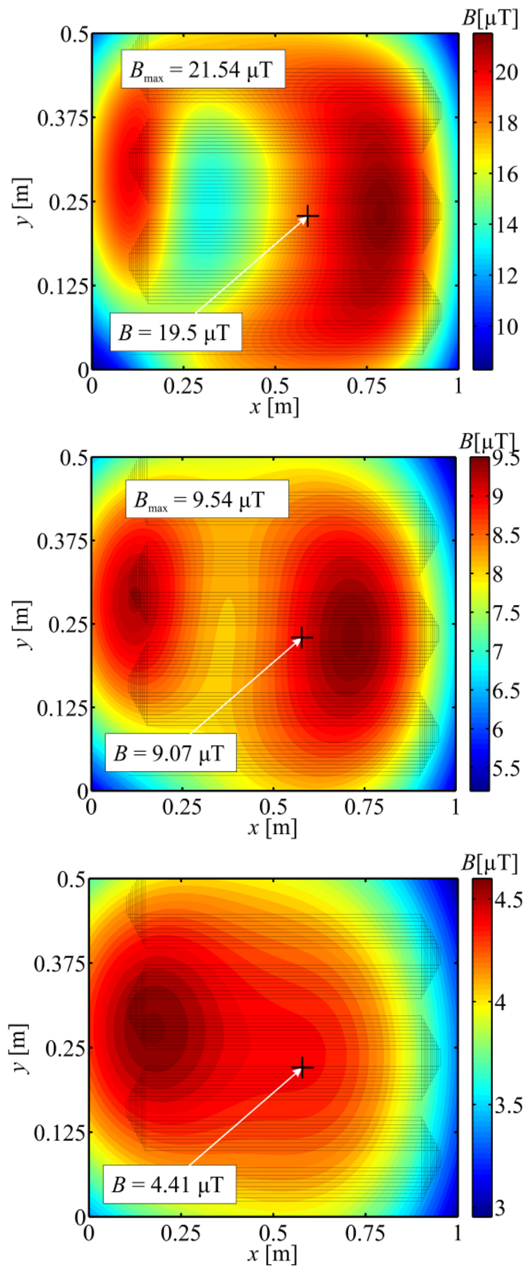

Figure 7. *Magnetic flux density at the planes 20, 40, and 60 cm above the EHRS sample calculated with* K_{max} *= 10*

CONCLUSION

In this paper, we consider in detail the calculations of the magnetic flux density above ERHS heating elements realized with single aluminium strip. The procedure can be easily applied for calculation of the magnetic flux density of a single wire heating element as well. Method of calculations based on Bio-Savart law is verified with the results obtained by FEM and through the comparison with the results of measurements.

Magnetic flux density generated by single wire ERHS heating element can be estimated, at least in the first approximation, by calculating the magnetic flux density of the single loop which overlaps with the outer parts of the heating element.

The magnetic flux density of ERHS is linearly proportional to the current in the system and depends on the layout of the conductors and distance from the system. We show that current in the heating element as low as 1 A generates up to $1.7\,\mu T$, $0.35\,\mu T$ and $0.2\,\mu T$ at heights of 10 cm,30 cm and 50 cm above the conductors, respectively. Since the current in the heating element can be significantly higher than 1 A, it follows that magnetic flux density above the single wire ERHS heating element can significantly increase the level of magnetic field in comparison to the typical ambient level at homes (which is up to $0.2\,\mu T$).

ACKNOWLEDGMENT

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BIOGRAPHY

Miodrag M. Milutinov was born in Serbia in 1976. He received his PhD degree in 2017 at the Faculty of Technical Sciences, University of Novi Sad, Serbia. Currently, he is a assistant professor of basic electrical engineering at the Faculty of Technical Sciences, University of Novi Sad. His research interests include electromagnetic computation, electromagnetic field measurements and material characterization.

MAGNETNO POLJE SISTEMA GREJANJA ELEKTRIČNOG RADIJENTA

Miodrag Milutinov, Anamarija Juhas, Neda Pekarić-Nađ

Rezime: *U ovom radu je razmatrano magnetsko polje koje generišu provodnici sa strujom kao deo sistema električnog grejanja. To su sistemi sačinjeni od kablova koji mogu biti postavljeni u podu, zidu ili plafonu prostorije. Magnetsko polje u okolini tih sistema pre svega zavisi od jačine struje, koja opet zavisi od veličine prostora koji treba zagrejati. Na osnovu rezultata prikazanih u radu, može se zaključiti da električno podno grejanje izvedeno sa jednožilnim kablovima može stvoriti značajno veliko magnetsko polje u odnosu na dozvoljene referentne granične vrednosti.*

Ključne reči: električno podno grejanje, magnetsko polje, izloženost.