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Published in: NERG : Tijdschrift van het Nederlands Elektronica- en Radiogenootschap

Published: 01/01/2011

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

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Citation for published version (APA):

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Double Solenoid ELF Magnetic Field Exposure System for In-Vitro Studies

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Abstract — Concerning in-vitro biological studies, it is necessary that a well-characterized exposure system is used particularly to validate and replicate key findings. Therefore, we improved and characterized an ELF magnetic field exposure system with high dynamic exposure range (µT–mT) and reduced stray magnetic fields for a 50/60Hz sinusoidal signal. The basic design is based on a double solenoid setup. The outer solenoid is used for the reduction of the stray B-flux densities. The system itself is modular to adapt to different biological experiments. To be able to apply a high dynamic exposure range a controlled air cooling system is added. The exposure system is using a control algorithm and associated Graphical User Interface. Temperature is measured and controlled inside the exposure area. The exposure characteristics along with temperature variation are monitored and recorded during the experiments. In conclusion, the ELF exposure system is well suited to conduct a wide range of real and sham ELF magnetic field cell-exposure studies.

Keywords—ELF magnetic field; In-vitro; Stray field reduction; Sham and real exposure; controlled air cooling system.

INTRODUCTION

Concern on possible health hazards due to exposure to ELF-MFs has led to the development of various exposure setups to support biological investigations, both for in-vitro and in-vivo studies, to examine possible effects and mechanisms of the ELF-MFs on biological systems ([1]-[8]). However, the causality of ELF-MF exposure effects is still an open issue. Replication of key findings by different laboratories is also very difficult due to incomplete characterization of the used exposure setups. Hence, the design and characterization of the exposure setup is, to our opinion, paramount within any research program involved in this field.

The most widely used exposure systems for magnetic field generation are exposure systems with simple geometrical shapes; systems with circular, square and rectangular coils of two or more windings with various spacing between the windings. For an overview of the generally used exposure systems we may refer to Gottardi et al. [1]. In recent years, more advanced systems have been designed allowing monitoring and recording of the exposure characteristics throughout the whole duration of the experiments [8].

The objective of this research was the development and characterization of an ELF-MF exposure setup with a high dynamic range (µT - mT) of uniform B-flux density exposure at 50 or 60Hz and low stray magnetic fields, to support in-vitro biological experiments. The system was designed to fit inside a commercial CO2 cell culture incubator. A controlled air cooling solution was developed to regulate and monitor temperature within the exposure area. In our research framework an important issue is the reproducibility of the biological experimental results. To support this a Graphical User Interface (GUI) for monitoring and recording the temperature and supplied electrical parameters during the experiments has been developed.

SYSTEM DESIGN

A. Exposure Coil Design

The exposure system (see Fig. 5) is based on an existing configuration of a double solenoid with double windings that fits inside a commercial cell culture incubator. The outer solenoid consists of two concentric coils with an inverse direction with respect to the electric current supplied to the main solenoid. This approach is known as the active magnetic shielding method used to reduce stray magnetic fields [7]. The compensation coils are symmetrically oriented with respect to the center of the system, consisting of equal number of windings. As stated in [7], the concentric compensation configuration has the advantage of reducing the fields in all directions. This statement has been observed during our analysis also. However, the compensation coils do deteriorate the field intensity in the exposure volume. To compensate for this amplitude reduction, double windings are placed at the edges of the inner solenoid. To clarify the previous, a vector view of the resulting B-flux density in a vertical cut is shown in Figure 1.

Figure 1. Simulated values of our basic ELF exposure design and vector field view of B-flux density depicted by the green arrows. The cone end-points pertain to the orientation of the B-flux vector. The cone size represents the B-flux magnitude.
For design and analysis, a simulation model designed in SEMCAD X (Version 14.2.1, Schmid & Partner Engineering AG, Zürich, Switzerland) of the exposure coil has been used.

B. Cooling System Design

According to biological conditions inside the exposure environment the temperature should remain with a maximum fluctuation interval. The allowable fluctuation depends on the type of biological experiments. The maximum achievable B-flux density is limited by the induced temperature-rise above its user defined limit.

The basic ELF exposure configuration is capable to support a natural airflow for keeping the temperature stable within its limits. However, our preliminary experiments revealed that this airflow is not sufficiently enough to support the whole dynamic range up to \(1 \text{mT}\). Hence an additional temperature-controlled cooling system that will not influence the actual experiments is needed. We decided to design this cooling system based on forced airflow [8]. Our design is presented in Figure 2 where the three mechanical parts (II, III, V) necessary to appropriately distribute the airflow through the system are separately indicated. A 48V DC fan (San Ace 120L) is used to minimize the presence of the parasitic B-flux density introduced by the coil inside the fan motor. The maximum airflow is 180 CFM.

The cooling system is controlled by adapting the fan rotations using Pulse Width Modulation (PWM) and basic EMC-measures are taken into account. The actual temperatures present at several locations in the exposure area are measured using a LabJack U6 Pro Data Acquisition (DAQ) system. The temperature sensors we use are Type-K thermocouples with an accuracy of 0.12°C. The thermocouples are placed on the Petri Dish Carrier (PDC, see Fig. 2 part IV). This PDC consists of four plates which could be taken out of the system. Each plate is able to carry one Petri Dish of 88mm diameter or three Petri Dishes of 54mm diameter and each plate has its own temperature sensor that is mounted in the middle of the plate indicated with the dots marked T1 to T4 (see Fig. 2 part I). T3 is used for controlling the fan where the other sensors are used for monitoring and recording the temperature difference within the exposure area. The fan is mounted on the “inlet adapter” (II) where through the “fan adapter” (III) the air is distributed with equally spaced velocity to enable a circulating airflow – like a vortex - through the system. In Figure 2 the forced airflow is depicted with the red arrows. It is noted that forced air only moves within the inner and outer cylinder where the heated copper wires are. At the top the heated air is distributed through the “outlet adapter” (Fig. 2, part V) thereby preventing the heated air to flow into the inner cylinder area. This approach avoids interaction with biological materials. To ensure that the air composition (i.e. the possibility to add CO\(_2\)) in the inner cylinder area is the same as in the rest of the incubator we created four channels (Fig. 2 part III) to support the natural airflow. This natural airflow is depicted with the yellow arrows.

The cooling capacity of our forced air cooling concept when placed in the incubator is limited since in general an incubator is not equipped with air-conditioning but with heating elements only. To be able to adapt this system to different kind of biological experiments and incubators, we created two different cooling setups, the so called “Intra-incubator” and “Inter-incubator” setup (See Fig. 3).

The “Intra-incubator” cooling setup is based on a closed air circuit which means that there is no air drawn from outside the incubator to circulate inside. The heated air is distributed by the cooling system to a larger volume away from the exposure area. This results in a delay in the warming up of the complete system until it reaches temperature equilibrium.

The “Inter-incubator” cooling setup mainly circulates the air inside the incubator and partially draws air from outside as depicted in Figure 3 (right picture). Through the blue pipe the much cooler external air (\(\Delta T > 12^\circ\text{C}\)) – with a maximum of 5 CFM – is mixed with the heated air within the system. In this case the amount of air that could be drawn from outside the incubator is limited by the diameter of the access port at the rear wall of the incubator. The access port diameter differs per incubator type. In order to avoid over- or underpressure it is important to ensure that the same amount of heated air is blown externally via the green pipe and equals the amount of air that is extracted from the outer environment.
C. Graphical User Interface

The GUI shown in Figure 4 is used to set and control the fan speed (PWM) – which influences the airflow - based on the actual temperature measured. The software has an algorithm which could be adjusted to defined temperature thresholds. The GUI visualizes the temperature history in a graph and the values of the air flow (CFM), electric current (A) and associated B-flux density (mT). There is also the possibility to store all these values and to be informed by e-mail when the measurement has finished.

D. Exposure Apparatus

In Figure 5, the total exposure design as described in chapter II A consisting of the attached “fan adapter”, the Petri Dish Carrier, a personal system depicting the GUI and the housing of the DAQ and control system is presented. The PDC is carrying two Petri Dishes of 54mm diameter filled with saline solution.

E. B-Flux Density

At first we simulated the whole coil setup. The numerical model consists of separate coils. The resulting B-flux density, is analyzed by using SEMCAD X. By using Biot-Savart’s law the total B-flux is computed as the superposition of the B-flux densities of the separate coils. To investigate the uniformity of the B-flux distribution, we define our reference point at the centre of our exposure system. The B-flux at the center is denoted by Bo. The Uniformity of B-flux density of the exposure system is defined as

\[ U = \frac{|B - B_0|}{B_0} \times 100\% \] [1].

The 1, 5 and 10% uniformity areas in vertical cuts are depicted in Figure 6. The red dashed lines indicate the “useful” exposure area. The term “useful” is introduced to characterize the area that can actually be used for ELF-exposure of the biological samples. The geometrical characteristic of the exposure system and the size of the “useful” exposure areas as computed through simulations are listed in Table I.

![Figure 4. Graphical User Interface. On the left is the control and on the right the temperature readout.](image)

![Figure 5. Basic exposure system with attached “fan adapter”. The GUI is depicted in the right and the housing of the DAQ and control system is depicted at the right back corner.](image)

![Figure 6. Uniform areas of 1, 5 and 10% of the exposure areas in vertical cuts (blue line). “Useful” area (red dashed line). Total exposure area (gray dashed line).](image)

<p>| TABLE I. ESSENTIAL CHARACTERISTICS OF THE EXPOSURE SYSTEM |</p>
<table>
<thead>
<tr>
<th>COIL SETUP</th>
<th>Inner Solenoid (mm)</th>
<th>Outer Solenoid (mm)</th>
<th>Single Windings (mm)</th>
<th>Double Windings (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil radius</td>
<td>92.5</td>
<td>200</td>
<td>68</td>
<td>18</td>
</tr>
<tr>
<td>Length of the solenoid</td>
<td>392</td>
<td>392</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of windings</td>
<td>8</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pitch of the windings</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The reduction of the stray magnetic fields outside the incubator is deemed necessary to minimize EM coupling with neighboring electronic devices and enable closer proximity of an additional ELF exposure system in the same or a second incubator. Computing the influence of the the compensation coil, we obtain 16 dB and 17dB reduction of stray B-flux...
densities, at 640mm and 520mm horizontal and vertical distance from the solenoid center, respectively. At approximately 320 mm and 260 mm in both planes the compensation coil doesn’t result in the decrease of the stray B-flux density.

To validate the simulation results we conducted several measurements where the B-flux density of the ELF-MF exposure system and the homogeneity of the exposure volume have been determined. We used a 3-channel Hall effect Gaussmeter (Model 460, Lake Shore Cryotronics, Inc.) with ± 0.1% accuracy of reading, equipped with a 3-axis temperature regulated magnetic field probe (High Sensitivity Probe, MMZ-2502-UH, Lake Shore Cryotronics, Inc.) of 4.6mm probe diameter and resolution of 0.1µT. The probe was handled by a positioner constructed of foam for the mapping and alignment of the probe. Foam has been used to avoid the perturbation of the measured B-flux density. The measurement setup was designed to perform measurements every 5mm. The 1% uniform region as determined through simulation and measurement data is compared in Figure 7. The measurement results deteriorate the “useful” exposure area by approximately 2mm compared with simulations. This discrepancy can be explained by the uncertainty of the probe position. However, we consider the results to be in excellent agreement.

![Figure 7. Comparison of 1% uniform region](image)

**F. Electric Fields**

At ELF frequencies, non-magnetic biological systems do not perturb the magnetic field and time varying ELF-MFs induce internal electric fields determined by Faraday’s law of induction which for a Petri Dish of radius $r$ and B-flux density of frequency $f$ is defined as

$$E_{rms} = \pi fr B_{rms} \ [2].$$

The induced electric field generates a current density in the conductive medium which according to Ohm’s law is directly proportional to the electric field strength but depends also on the conductivity of the medium.

The exposure of biological samples in a highly uniform magnetic fields results in highly non-uniform induced electric fields and current densities but low within the medium. For 1mT$_{rms}$ exposure, the order of magnitude for the electric field is 4mV/m (SAR values less than $10^{-10}$ W/Kg). The magnitude and spatial distribution of the induced electric fields are relatively low and highly dependent on the tissue container geometry.

**G. Temperature Development**

While characterizing this system we studied different quantities in relation to the applied B-field from 5µT$_{rms}$ up to 4mT$_{rms}$ as documented in Table II. It clearly shows that there is already a ΔT of 2.5°C for 1mT$_{rms}$ where 11.32 Watts have to be dissipated. As for the wire (diameter = 3mm) of the coils it should be capable to easily support the applied current but nevertheless resulted in an increase of temperature. This is mainly caused by the specific solenoid setup. The coils are partially embedded in the PMMA cylinders. This means that only half of the wire is exposed to the environmental air and thus limited to dissipate the heat through natural airflow which, as it turned out to be, is not sufficient enough for the entire dynamic range (See Table II).

**TABLE II. RELATION BETWEEN APPLIED B-FIELD AND TEMPERATURE**

<table>
<thead>
<tr>
<th>B-Field mT</th>
<th>Current A</th>
<th>Voltage V</th>
<th>Power W</th>
<th>Temperature °C ΔT</th>
</tr>
</thead>
<tbody>
<tr>
<td>~0.005</td>
<td>0.035</td>
<td>0.006</td>
<td>0.0002</td>
<td>-</td>
</tr>
<tr>
<td>~0.5</td>
<td>4.45</td>
<td>0.71</td>
<td>3.16</td>
<td>-</td>
</tr>
<tr>
<td>~1.0</td>
<td>8.45</td>
<td>1.34</td>
<td>11.32</td>
<td>~2.5</td>
</tr>
<tr>
<td>~2.0</td>
<td>16.55</td>
<td>2.61</td>
<td>43.20</td>
<td>~12.0</td>
</tr>
<tr>
<td>~4.0</td>
<td>33.34</td>
<td>5.30</td>
<td>176.70</td>
<td>~34.0</td>
</tr>
</tbody>
</table>

As described earlier we introduced two cooling systems which primarily differ by whether or not external air is used to obtain heat exchange with the outer environment. It is noted that the incubator access port limits the amount of air, in our case 5CFM maximal. Both system setups where tested inside an incubator and the outcome is presented in Figure 8.

![Figure 8. Comparison between "Intra-incubator" and "Inter-incubator" temperature measurements](image)
incubator” setup to run the fan constantly or with the highest speed. For that we introduced a fan controlled algorithm. This algorithm consists of controlling the speed of the fan by varying the duty cycle based on the actual temperature variation from the reference temperature (∆T). The higher the ∆T the higher the fan speed will be. Adapting this algorithm to the “Inter-Incubator” setup it resulted in an average duty cycle of approximately 80%.

To complete our research on this topic we monitored the three other temperature sensors placed on the PDC during the earlier described measurements. The maximum temperature difference between the top and bottom carrier plate temperature sensor is approximately 0.15°C.

**DISCUSSION**

In this paper we designed and determined the performance of a simple however advanced ELF-MF exposure system for in-vitro studies. We concentrated on the size of the exposure apparatus, on the reduction of the stray magnetic fields outside the incubator, and on the temperature regulation for high B-flux densities. To reduce the stray magnetic fields a concentric compensation coil configuration was chosen. The coils are connected in series avoiding amplitude differences in the current and phase shift between the inner and outer coil configuration. These are known difficulties at individually driven coils as described in literature [2, 8].

According to our design one system fits inside a commercial incubator. To house two systems, for real and a sham exposure, inside the same incubator two issues should be addressed namely; (1) the minimization of the exposure system and (2) the use of bifilar coils. Bifilar coils are double wound so we can ensure that real and sham exposure system [1, 2, 8] have similar heat production. When the windings are driven by currents of opposite direction the net B-flux density is zero for the sham exposure. To enable the proximity of the two systems the limitation of stray magnetic fields in shorter distance is an important feature. Three systems with double solenoids and different ratios of the outer and inner solenoid radius (r) but with the same volume (radius of outer solenoid and height are kept constant) are compared with a single solenoid system. Figure 9 depicts the horizontal B-flux distribution for four minimized exposure systems correspondingly.

The system with inner and outer radius \(R_i=39.5\text{mm}\) and \(R_o=85.5\text{mm}\) respectively, maintains the ratio (r) of the original design. Figure 9 depicts also two exposure systems in vertical cuts separated by 140mm. Increasing the ratio (r) of the outer compensation solenoid radius over the inner solenoid radius, results in higher reduction of the stray magnetic fields. However, this leads to smaller inner solenoid radius thus deteriorating the “useful” exposure volume. Table III summarizes the geometrical and physical characteristics of the four (4) exposure systems, following the example of Gottardi [1].

**TABLE III. COMPARISON OF DIFFERENT SOLENOID CONFIGURATIONS**

<table>
<thead>
<tr>
<th>Solenoid</th>
<th>Single Solenoid</th>
<th>Double Solenoid r=1.29 (mm)</th>
<th>Double Solenoid r=1.62 (mm)</th>
<th>Double Solenoid r=2.16 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner radius ((R_i))</td>
<td>66</td>
<td>66</td>
<td>52.5</td>
<td>39.5</td>
</tr>
<tr>
<td>Outer radius ((R_o))</td>
<td>-</td>
<td>85.5</td>
<td>85.5</td>
<td>85.5</td>
</tr>
<tr>
<td>Overall Volume (V)</td>
<td>2.32d(^a)</td>
<td>2.32d(^a)</td>
<td>2.92d(^d)</td>
<td>3.89d(^d)</td>
</tr>
<tr>
<td>Uniformity region 1% ((U_1))</td>
<td>0.72d(^d)</td>
<td>0.77d(^d)</td>
<td>0.78d(^d)</td>
<td>0.78d(^d)</td>
</tr>
<tr>
<td>Uniformity region 5% ((U_5))</td>
<td>1.40d(^d)</td>
<td>1.38d(^d)</td>
<td>1.91d(^d)</td>
<td>2.20d(^d)</td>
</tr>
<tr>
<td>V/V(_i)</td>
<td>3.24d</td>
<td>3.01d</td>
<td>3.73d</td>
<td>4.99d</td>
</tr>
<tr>
<td>V/V(_5)</td>
<td>1.66d</td>
<td>1.69d</td>
<td>1.52d</td>
<td>1.77d</td>
</tr>
</tbody>
</table>

\(^a\) “d” is inner solenoid diameter (2R\(_i\))

**CONCLUSIONS**

According to simulations and experiments we conclude that the outer coils reduce the stray B-flux density significantly in comparison with a single solenoid. This prevents influencing the environment where possibly other experiments are conducted. The outcome of varying the diameter of the inner and outer cylinder and thus the diameter of the coil introduced the possibility to create a smaller design so a real and sham exposure system could fit in one incubator. Depending on the biological experiments a specific tolerance of the homogeneity can be chosen with a trade off for the “useful” area. The exposure dynamic range that can be chosen is somehow limited by the temperature rise but with the introduction of the air cooling solution it is possible to use this design up to 1mT for the “Intra-Incubator” setup. All values can be monitored and recorded so different experiments can be compared with accurate knowing of the circumstances.

The Petri Dish Carrier supports in many ways the experiments, by its specific design reproducibility for the two Petri Dishes is guaranteed. The temperature sensors are close to the samples so the temperature in that area is accurately determined. The PDC is placed on rubber blocks so heat conduction and vibrations have negligible values. The system is useful for a wide range of biological experiments with the advantage that every important quantity is recorded which makes it a well-characterized system.

![Figure 9. Comparison of horizontal B-flux distribution of three Double Solenoids with a Single Solenoid. Real (yellow dots) and sham (black dots) exposure systems are 140mm apart.](image-url)
ACKNOWLEDGMENT

The authors would like to thank dr. Jan Cuppen of Immunent for the concept of this exposure system that served as the basis for our research and for our discussions and his support. Special thanks are expressed to the biologists dr. B. Eppink from the Erasmus University of Rotterdam and dr. L. van Kemenade and dr. M. Bouwens form the University of Wageningen for their essential inputs. We are also thankful to M. Uyt De Willigen for his technical support and lending us his measurement equipment. Last but not least we would like to thank prof. dr. A. Tijhuis for his unconditional and enthusiastic support and the Netherlands Organization for Health Research and Development (ZonMw) for their enabling financial support.

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