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Estimation of the influence of the plane wave angle on the values of the electric field intensity in structures with a wall made of solid bricks and hollow bricks

Abstract. *The aim of the article is to analyse the influence of the wall positioning in relation to the incidence of a plane wave on the values of the electric field intensity. The subject of the analysis was an isolated system with a brick wall. Two commonly used types of bricks were considered: solid brick as a homogeneous material and hollow brick (clinker) considered as a heterogeneous material. The performed analysis also took into account various values of the electrical parameters of the ceramic material (permittivity and conductivity), which are used in the calculations. The distribution of the electric field strength generated by a wireless communication system operating at a frequency of 5 GHz is presented. The numerical finite difference time domain (FDTD) method was used. The influence of the drilling on the field intensity values in the area behind the wall is discussed. The obtained results may be useful when estimating the value of the damping coefficient for non-homogeneous materials, taking into account the angle of incidence of the plane wave.*

Streszczenie. *Celem artykułu jest analiza wpływu ustawienia ściany względem kąta padania fali płaskiej na wartości natężenia pola elektrycznego. Przedmiotem analizy był odosobniony układ zawierający ścianę wykonaną z cegieł. Rozpatrzono dwa powszechnie stosowane rodzaje cegieł: cegłę pełną, jako materiał jednorodny oraz cegłę z drążeniami (klinkierową) rozpatrywaną jako materiał niejednorodny. Dokonana analiza uwzględniała także różne wartości parametrów elektrycznych materiału ceramicznego (przenikalności elektrycznej i konduktywności), które są stosowane w obliczeniach. Zaprezentowany został rozkład natężenia pola elektrycznego generowanego przez system komunikacji bezprzewodowej pracujący przy częstotliwości 5 GHz. Zastosowano numeryczną metodę różnic skończonych w dziedzinie czasu (FDTD). Omówiono wpływ drążeń na wartości natężenia pola w obszarze za ścianą. Uzyskane wyniki mogą być przydatne przy szacowaniu wartości współczynnika tłumienia dla materiałów niejednorodnych przy uwzględnieniu kąta padania fali płaskiej. (**Ocena wpływu kąta padania fali płaskiej na wartości natężenia pola elektrycznego w konstrukcjach ze ścianą wykonaną z cegieł pełnych i cegieł drążonych**).*

Keywords: electromagnetic waves propagation, finite difference time domain method (FDTD), wireless communication, building materials.
Słowa kluczowe: propagacja fal elektromagnetycznych, metoda różnic skończonych w dziedzinie czasu (FDTD), komunikacja bezprzewodowa, materiały budowlane.

Introduction

Smart construction based on wireless networks and a permanent connection to the Internet is becoming a standard in the west and is also gaining popularity in Poland [1, 2]. When it comes to wireless communication, one should take into account not only the demand reported by constructors of new facilities, but also the modernization of the infrastructure that has existed for many years. The assessment of the reliability of a wireless link inside buildings becomes a problem. Both former and presently used materials for walls and ceilings have a great influence on the intensity of the electromagnetic field. The attenuation of the wave by the material from which the wall is made, for example, may even make communication impossible. The propagation of electromagnetic waves is strongly dependent on the geometry of the material (e.g. hollowing in clinker bricks, admixtures, metal inserts), as well as on its electrical properties [3].

The analytical solution of the problem related to the incidence of a plane wave and propagation in a homogeneous or multi-layer homogeneous plate with a given thickness is presented in the available literature [4, 5]. The coefficients determined in this way are used in selected cases when calculating the field distribution in large-scale systems. The analytical method [4] of calculating field phenomena has, however, limited application in the case of local material heterogeneities, e.g. when considering hollow bricks. According to the presented in [5, 6], in the frequency range of wireless communication, hollow bricks show features of heterogeneous materials, porous due to the electromagnetic wavelength, because they are composed of ceramics and air. For this reason, the article considers electromagnetic phenomena in systems with a homogeneous and heterogeneous material, with oblique incidence of a plane wave.

The aim of this study is to analyse the effect of the wall structure made of commonly used building materials (i.e. solid brick and clinker brick containing hollows) on the distribution of the electric field, taking into account the frequency used in wireless communication f =5 GHz.

The available literature presents various values of the electrical parameters of bricks (permittivity ε_r=3.7÷19 [7], ε_r=4.11÷4.62 [5], or conductivity (σ =0.00278÷0.244 S/m) [6, 5, 8]). For this reason, the study also analysed the impact of the variability of the electrical parameters of the ceramic material (i.e. electrical permittivity and conductivity) on the values of the electric field intensity. The analysis of the impact of the angle of wave incidence on e.g. a wall, or the adopted values of electrical parameters, will certainly facilitate the understanding of wave phenomena or even help in determining the attenuation of a given material.

Model construction and numerical conditions

The subject of the analysis is the influence of the angle of incidence of the electromagnetic wave on the field intensity values in the area behind the wall made of commonly used ceramic materials (solid bricks and hollow bricks). Walls of this type are classified as single-layer walls, often partition walls, which separate living or office spaces.

Due to the structure of the walls and the structure of materials, the phenomena occurring during the propagation of the electromagnetic wave in the systems with:

- homogeneous material in macroscopic terms, i.e. solid brick;
- heterogeneous material, the construction of which requires taking into account the system of components with different electrical properties (hollow brick).

Including the analytical solution of the problem in the model with hollow bricks is not possible due to the complex internal structure, which consists of a specific, repeatable arrangement of materials with different electrical properties. The evaluation of the phenomena occurring in this type of cases can only be performed with the use of numerical methods (e.g. FDTD [9, 10], FDFD, FEM [11, 19]).

The considered models of walls were created on the basis of data on commonly used solid and vertically hollow bricks, whose geometrical dimensions maintain the proportions 1: 2: 4 [12], i.e. 250×120×65 mm (Fig. 1). Included in the construction of the model:

- solid bricks (C);
- bricks with 30 holes (C30).

Fig.1. Two models of analysed bricks: a) solid brick; b) brick with 30 holes

For the purposes of further numerical analysis, the dimensions given in Fig. 1 were determined as averaged values based on the performed measurements. The method of determining the test parameters is specified in the standard [13, 14]. The guidelines of the standard specify the number of samples required to test each property of a masonry element for 3 or 10 pieces. In order to perform the analysis, it was decided to make one's own measurement on a randomly selected sample of 50 bricks. The main reason was the lack of regulations concerning the dimensions of the hollows inside the bricks. The standards describe the permissible deviations of the external dimensions of bricks, resulting from the processes of forming, drying or firing ceramic materials [13, 14]. Estimation of the relative share of drilling of masonry elements is determined by, inter alia, hydrostatic weighing. Such defined samples constitute the basis for accepting a given batch of material. Due to the assessment of the electrical properties, it is necessary to take into account the distribution and size of the hollows.

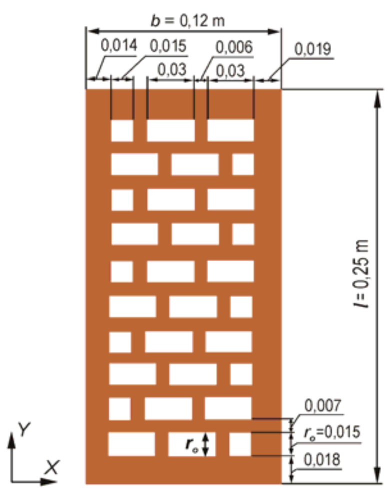


Fig.2. Geometrical sizes of brick with hollows (B30)

Due to different values of electric parameters of bricks [7-8, 15, 16] and their structure, four variants were considered (Tab. 1).

Table 1. Designations of wall models and description of their properties

Designation	Building material	Relative permittivity ε_r'	Conductivity σ [S/m]
C_01	full brick	4.44	0.01
C_002	full brick	4.14	0.002
C30_01	clinker brick with 30 holes	4.44	0.01
C30_002	clinker brick with 30 holes	4.14	0.002

Wall models with a thickness of 0.12 m were used to analyze the influence of the wave incidence angle (α_p) on the values of the field intensity (Fig. 2). The dimensions and geometry of the model are shown in Fig. 3. This arrangement allowed for the observation of the electric field distribution in front of and behind the wall.

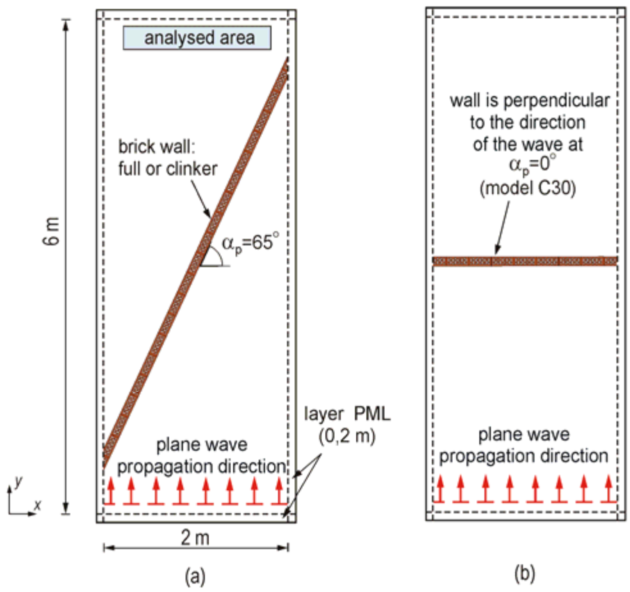


Fig.3. Model geometry for the angle of incidence of an electromagnetic wave: (a) maximum angle, i.e. 65°, (b) minimum angle, i.e. 0°

The source of the field was a plane wave propagating in the direction perpendicular to the wall when the angle of incidence of the wave α_p=0°. The field forcing in the system was a harmonic plane wave polarized linearly, propagating in the direction of the axis Oy ($\mathbf{k} = \mathbf{1}_y$)

(1) $$\mathbf{E}(x,y,t) = E_z \mathbf{1}_z = \sin(\omega t)\cdot 1(t)\cdot \mathbf{1}_z \,.$$

The analysis used the Finite Difference Time Domain (FDTD) method [9, 10], which is used to calculate electromagnetic fields that vary in time and for high frequencies and broadband signals [1]. The method is based on the transformations of Maxwell's equations into a differential form [9, 10]:

(2) $$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t},$$

(3) $$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t}.$$

The calculations were based on the frequency used in wireless communication (f = 5 GHz). The field distribution analysis as well as the quantitative evaluation of the wave attenuation were performed in the area behind the wall, based on the observation of the field component max(E_z) [9]. The field distribution in the analysed domain is calculated by direct integration method in time and space. Analyzed component of electric field (E_z) takes the form:

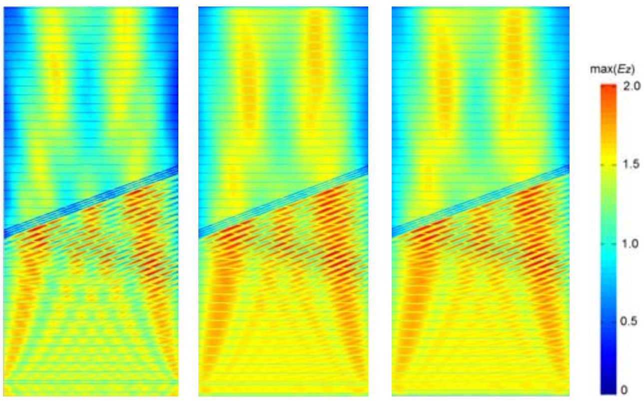
$$\frac{E_z\big|_{i,j,k}^{n+1} - E_z\big|_{i,j,k}^{n}}{\Delta t} = \tag{4}$$

$$= \frac{1}{\varepsilon}\left(\begin{aligned} &\frac{H_y\big|_{i+1/2,j,k}^{n+1/2} - H_y\big|_{i-1/2,j,k}^{n+1/2}}{\Delta x} - \\ &- \frac{H_x\big|_{i,j+1/2,k}^{n+1/2} - H_x\big|_{i,j-1/2,k}^{n+1/2}}{\Delta y} - \sigma E_z\Big|_{i,j,k}^{n+1/2} \end{aligned} \right),$$

which, after transformation allow the determination of the value of E_z component of the electric field intensity at observation point (i, j+1/2, k+1/2) in time (n+1/2) on the basis of the components of the magnetic field in the previous moment t at appropriate points space.

The area of the considered models was discretized by entering a uniform grid of Yee cells, the size of which in the considered models was $\Delta_x=\Delta_y=1$ mm. With the adoption of electrical parameters describing the material of the bricks (permittivity $\varepsilon_r'=4.44$ and conductivity $\sigma=0.01$ S/m) the minimum number of Yee cells per wavelength was 28. For this reason, the staircase effects in the construction of the model were also significantly reduced.

In the analysed problem, the Perfectly Matched Layer (PML) boundary conditions [9, 17, 18, 19] were used at the model edges. Figure 4 shows the instantaneous distribution of the electric field intensity in a system with a clinker brick, at a wall inclination angle of 30°, for three variants of the thickness of the PML layer. The presented results were obtained for the already steady state in the time step of 522.



(a) (b) (c)

Fig.4. Modelled PML layer tests: a) PML=0.1 m, b) PML=0.2 m, c) PML=0.3 m

As can be seen, with PML=0.2 m and PML=0.3 m, the electric field distribution is practically the same, which allows the adoption of a layer PML=0.2 m, which is sufficient for perform calculations. Also, this variant does not force the model size to be increased, as well as the number of degrees of freedom as a consequence by increasing the width of the PML layer to 0.3 m. However, based on the tests, it can be concluded that the layer PML=0.1 m is not sufficient to obtain correct results, because the effect of an excessively narrow PML layer is visible in the form of large differences at the edges of the regions after the EM wave passes through the wall. The absorption of the propagating wave was finally achieved by adopting a layer with a depth meeting the criteria for declaring such conditions [10, 19] (i.e. PML=0.2 m).

Tests performed in a model system (wave propagation in an open half-space with vacuum properties) confirmed the correctness of the adopted layer width, with the error of the results not exceeding 0.5%.

Results and discussion

Figure 5 shows the maximum values of the field strength obtained for wall models made of solid bricks (C) and hollow bricks (C30). The characteristics show the influence of the wave incidence angle on the value max(E_z) n the area behind the wall. Regardless of the value of the electric parameters of the bricks, the calculations showed that although the hollow bricks contain air, behind the wall made of solid bricks, the field strength values are higher, i.e. the quality of the transmitted signal is better. Drilling affects the local reduction of the field value, which is visible for $\alpha_p=40^\circ$. It can also be seen that with a conductivity σ =0.01 S/m and above $\alpha_p=30^\circ$ there is a clear increase in the value of the electric field for hollow brick. For both types of bricks, the greater value of the conductivity (σ =0.04 S/m) causes practically the values of the electric field to be lower than those calculated with σ =0.1 S/m.

In the case of hollow bricks, the characteristics have maxima and minima, which are very clearly visible for the C30_0.01 variant. In this case, the maximum is at $\alpha_p=40^\circ$ and is max(E_z)=0.95, while the lowest value is at $\alpha_p=5^\circ$ (max(E_z)=0.5). The difference between the maximum and minimum for the variant with a higher conductivity value (C30_0.04) is smaller, i.e. the maximum is at $\alpha_p=40^\circ$ and amounts to max(E_z)=0.7, while the lowest value is at $\alpha_p=0^\circ$ (max(E_z)=0.35). The indicated effect results from the small angle of incidence of the wave, which increases the length of the path that the electromagnetic wave propagates through the hollows in the bricks.

An additional reason is the fact that with the increase of the angle of incidence of the wave, the "real" path of the wave passing through the porous material, such as brick, lengthens. Thus, the effective damping in the ceramic material increases, while the number of ceramic-air interface is gradually increased. Therefore, the number of partial reflections inside the wall is also increased.

With a fourfold increase in conductivity, in the case of solid bricks, the characteristics follow a similar course and the values vary by 5% until the incidence angle does not exceed 35°. In the case of the C_0.01 model, along with the increase of the angle, the electric field values increase compared to the C_0.04 model, where the difference reaches even 30%. However, in the case of hollow bricks, a fourfold increase in the conductivity value causes that the characteristic is less variable than in the case of C_0.01.

From the physical point of view, such a phenomenon results from the field continuity conditions obtained from considering the Maxwell equations at the boundary of environments with different electrical and magnetic properties [4, 9, 10, 17]. The component normal to the surface of the material discontinuity, directed to the second area, is partially reflected depending on the electrical parameters of a given medium.

Physical phenomena occurring when the wave propagates through successive areas of air and ceramic mass are reflected in the maximum values of the E_z component. The indicated effect is particularly visible when assessing the phenomena occurring behind a wall made of hollow bricks. The effects of wave reflections from the wall cause the formation of instantaneous minimums and maximums, the number of which depends on the angle of wave incidence (Fig. 5-6).

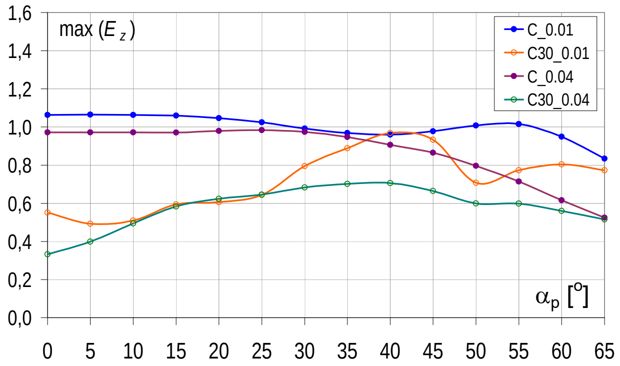


Fig.5. Characteristics of changes in the maximum value of the field intensity max(E_z) as a function of the angle of incidence of the electromagnetic wave

When considering a wall modelled with solid bricks (C_04), a decrease in the maximum field intensity values was noticed along with an increase in the wave incidence angle ($\alpha_p \geq 30^\circ$). The difference in values max(E_z) between the variant of the wall placed perpendicular to the direction of wave propagation and the case for $\alpha_p \geq 65^\circ$ is almost 50%.

Fig. 6 shows an example comparison of the distributions max(E_z) at $\alpha_p = 60^\circ$. As shown in the figure, the maximum values of the field strength between the C_01 and C30_01 models differ by 12%, where the higher value is for the hollow brick model. The indicated effect results from the complex structure of the brick causing the interference, which results in momentary minima and maxima in the area behind the wall.

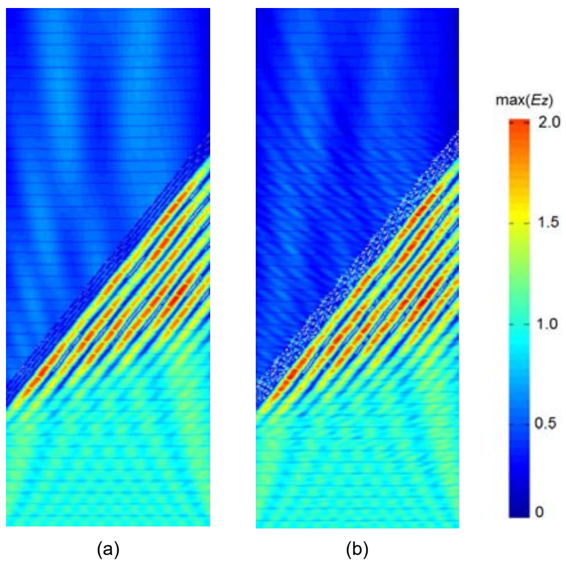


Fig.6. Envelopes of the maximum value of the E_z component in the area under consideration, at $\alpha_p = 60^\circ$ for models: (a) C_01, (b) C30_01

Regardless of the angle of incidence of the plane wave, it was found that the propagation of the electromagnetic wave inside the brick has a complex course. For this reason, there are multiple reflections on the air-ceramic interface. The number and size of the holes in the brick, as well as the value of the wave incidence angle, change the image of the electric field strength in the area behind the wall (Fig. 6).

Conclusions

The article presents an analysis of the influence of the plane wave angle on the values of the electric field intensity in a system with a wall made of a homogeneous and composite material. The dependence between the values of electrical parameters normally adopted for bricks and the field intensity distribution was also taken into account. The analysis of the considered models showed that:

- increasing the conductivity of the analysed materials causes only a decrease in the value of max(E_z) while maintaining a similar shape of the characteristics;
- the variability of the plane wave incidence angle results in numerous interferences on the air-ceramic mass interface, which changes the image of the field intensity, especially in the area behind the considered wall structures;
- in the case of a wall made of solid bricks, an increase in α_p causes a decrease in the field intensity by a maximum of 43% compared to the model with a perpendicular wall arrangement to the direction of EM wave propagation;
- at $\alpha_p = 25^\circ$, for both types of clinker bricks, the values of max(E_z) differ at most 2%, because at such an angle of incidence of a plane wave, the least reflections inside the hollows occur;
- In the case of a wall made of hollow bricks, the highest values of the field strength were obtained at $\alpha_p = 40^\circ$.

As the analysis shows, the angle of incidence of the plane wave and the structure of the wall made of non-homogeneous material have a large impact on the obtained values of the electric field intensity. This is an important aspect due to the correct interpretation of wave phenomena occurring in structures containing complex and heterogeneous building materials.

Each building material is characterized by the variability of electrical parameters resulting, among others, from atmospheric factors that are often ignored in the analysis of such issues. When considering large-scale systems, an additional difficulty is the accurate reproduction of all the hollows in the bricks that make up the building structure. For this reason, it is necessary to determine substitute parameters for this type of complex materials. The results presented in this article may help in determining such substitute parameters allowing for the replacement of heterogeneous material (hollow bricks) with a model made of a homogeneous layer.

The aim of subsequent works is a further detailed analysis of commonly used building materials taking into account the above-mentioned problem, especially for issues related to the water absorption of building materials.

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