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Designing of Microwave Applicators by Electromagnetic Wave Analysis

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Abstract

Recent high productivity of steel making processes is forcing to achieve more rapid drying for refractories. Microwave heating has been required as the most powerful means to increase the speed of drying. Therefore, as a process-solution approach, the authors selected a new one to obtain the solution, the electromagnetic wave analysis, which may be expected to optimize the designing of a heating applicator. Trials succeeded quite well for a practical model for the applicator. In the trials, it was learned that the analysis has essential difficulties in designing applicators. This paper presents the difficulties and the techniques to eliminate them. It also describes the theory of the analysis in advance to provide a better understanding of their relationships.

1. Introduction

This paper presents an example of the designing of a microwave drying facility in steel making processes with electromagnetic wave analysis, which is a rather special variation of electromagnetic field analysis.

Nippon Steel has been applying microwaves to dry castable refractory materials used in a wide variety of steel making processes, and employing electromagnetic wave analysis techniques for the optimum design of the refractory drying facilities. Historically, electromagnetic wave analysis has been used in an overwhelmingly greater number of cases in the field of communication than in the production processes of manufacturing industries. Those cases have not required large-scale calculations. However, when the electromagnetic wave analysis is applied to a steel making process, it inevitably involves large-scale calculations as is described in detail below. Problems relating to the calculation encountered in its actual application to the steel making process are also dealt with in this paper.

Initially, an overview of the microwave application to industrial processes is addressed herein. Secondly, the electromagnetic wave analysis is described on its principle and modeling. Finally, applications to a specific steel making process are discussed in detail.

2. Overview of Microwave Application to Industrial Processes[1)]

What is commonly called a microwave is a kind of electromagnetic wave. Japanese radio regulation laws define an electromagnetic wave having a frequency of 3 THz or less as a radio wave. Radio waves that are within a frequency band from 300 MHz to 300 GHz are defined as microwaves. Most of the wide frequency range of microwaves is allotted to communication and radar uses under the radio regulation laws[2)], and only a few narrow frequency bands are open to manufacturing industry uses. The typical bands for industries are 915 ±25 and 2,450 ±50 MHz. The latter, in particular, is used more often. Conventional applications of microwaves include heating and sterilization of food, drying of ceramics, vulcanization of rubber, and woodworking, etc. Microwaves are employed mainly for heating because of their high frequency: when a microwave is irradiated to a dielectric (electrically insulating) material, the molecules of the material are excited, or given kinetic energy, as their orientational polarizations resonate at the frequency of the microwave as shown in **Fig. 1**. This excitation, and resulting friction, of the molecules causes the material to become hot.

Heating with a microwave has many well-known advantages: (1) shortened heating time; (2) an object material can be directly heated internally, regardless of its shape; (3) high heating efficiency (efficiency of 80% or higher can be achieved); (4) selective heating of an

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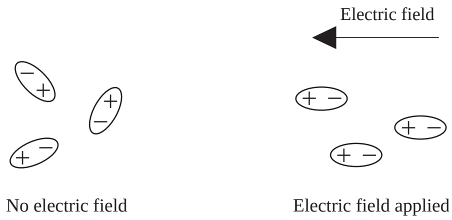


Fig. 1 Oriented polarization of molecules and microwave electric field

object material; (5) the heating process can be precisely controlled; and (6) microwave heating is silent and does not generate exhaust gas. It has also disadvantages such as: (1') the capacity of its power generator is limited to about 100 kW or less; (2') electrical discharge easily occurs with an object material containing solid or powder metal. Thus, the proper discharge-proof measures are necessary for the equipment and the work environment.

The facts that microwaves are mostly applied to heating and only a few frequency bands are allowed for use may give an impression that the future prospects for the application of microwaves are somewhat limited. However, the use of microwaves shows unexpected secondary advantages such as that sterilization by a microwave keeps foods remarkably better than by hot water, and that a microwave deactivates oxidative enzymes with short-time irradiation and maintains the quality of food for longer periods. Because microwave applications for these objectives have not been fully exploited, they may be described as yet immature. Thus, it would not be appropriate to determine based on the present status of microwave application that it is not very useful. Quite on the contrary, the authors believe that microwave technology still has many good prospects for development.

3. Characteristics of Electromagnetic Wave Analysis

In the 1980s, the capacity of computer memory was rapidly expanded, and the processing speed of computers was dramatically enhanced. Numerical analysis since the 80's, which has been applied to industry on a large scale, has developed in various fields of application incorporating unique new techniques. Along with the developments, the object of "electromagnetic field analysis" has also expanded quite smoothly from simple electrostatic and magnetostatic fields to complicated electromagnetic fields of real transient phenomena. On the other hand, "electromagnetic wave analysis" has treated the radiation and scattering of electromagnetic waves in the field of communication from the early stages of its development. Two of the analyses appear to be similar to each other now, but their origins are different and they have developed almost independently[3]. A good part of the difference comes from the characteristics of the equations used for the analyses. Below, a careful look is taken into the characteristics of the equations employed in electromagnetic wave analysis.

3.1 Difference in characteristics of equations

An electromagnetic wave is physically regarded as a form of electromagnetic field, therefore, it is theoretically presumed that electromagnetic wave analysis is classified as a variation of electromagnetic field analysis. In terms of numerical calculation, however, they are altogether different. The difference lies in the equations used therein.

All electromagnetic fields can be precisely expressed by the following Maxwell equations (the definitions of the symbols representing physical values are given at the end of this paper):

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t} \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \tag{2}$$

$$\nabla \cdot \boldsymbol{B} = 0,\ \nabla \cdot \boldsymbol{D} = \rho \tag{3}$$

$$\boldsymbol{B} = \mu \boldsymbol{H},\ \boldsymbol{D} = \varepsilon \boldsymbol{E} \tag{4}$$

Generally, at low frequencies, the term called the displacement current, the second term of the right-hand side of equation (1), is negligibly smaller than the other, and the approximated equations hence are obtained by omitting the term. That is to say, using equations (5) shown below, Maxwell equations (1) and (2) without the displacement current term are transformed into equations (6) and (7) through several steps of mathematical operations[4, 5].

$$\boldsymbol{B} = \nabla \times \boldsymbol{A},\ \boldsymbol{E} = -\frac{\partial \boldsymbol{A}}{\partial t} - \nabla\phi \tag{5}$$

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \boldsymbol{A}\right) + \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla\phi\right) = \boldsymbol{J}_0 \tag{6}$$

$$\nabla \cdot \boldsymbol{J} = \nabla \cdot \left[\boldsymbol{J}_0 - \sigma\left(\frac{\partial \boldsymbol{A}}{\partial t} + \nabla\phi\right)\right] = 0 \tag{7}$$

In equations (6) and (7), while the differentials to space are in the second order, those to time are in the first order, that is to say, their orders of differentials become asymmetric between to space and to time, changed from those in equations (1) and (2). As a result, the original nature of Maxwell equations to formulate wave propagation to infinite distance is lost in a low frequency range, and an electromagnetic wave represented by equations (6) and (7) damps rapidly as the distance from an electromagnetic source, such as a coil, increases. Whether or not the employed equations describe correctly the true nature of the propagation of electromagnetic waves directly influences the solution of electromagnetic wave analysis.

3.2 Discretization of equations

In order to express Maxwell equations numerically, it is necessary to discretize them with respect to space and time. It is also necessary to set conditions of boundaries, materials and power sources, e.g. electric currents on coils, so as to virtually form an electric field numerically. For the discretization with respect to space, the finite element method (FEM) is most commonly used in electromagnetic field analysis. As for the discretization with respect to time, either of the following two methods is used in electromagnetic field analysis: the finite difference method (FDM) and, for an alternating current electromagnetic field, the jω method, which is the substitution the time differential with a complex number jω where j is the imaginary unit[3, 4]. In electromagnetic wave analysis, on the other hand, FDM is mainly used for the discretization with respect to time, and FDM or the boundary element method (BEM) with respect to space.

These discretization methods are also strongly coupled with another factor to electromagnetic wave analysis: a balance between the analysis data and the capacity of a computer. In electromagnetic wave analysis, as a rule, all the portions of space to which an electromagnetic wave possibly propagates, except for the propagation to infinite distance, have to be taken into consideration. On the contrary, the length scale of an electromagnetic wave requires a resolution in the order of centimeter to realize its wave motion accurately. Suppose the propagation of a microwave in a 3-dimensional space that has a size in the order of meter is to be analyzed, then each dimension of the space must be divided into 100 or more, which means that the whole space will be divided into several millions of cells (in the example shown later, the number of cells is a little short of 90 million). The practicable method to carry out this for the present is FDM only, which needs a smaller number of data; by this method, the analysis calculation can be executed with a computer capacity only about several percents of that FEM requires. With respect to time, since the motion of a microwave is essentially a kind of wave propagation and its transitional change is conspicuously large, use of the FDM is appropriate.

Although various discretizing methods can be applied, in theory, to electromagnetic wave analysis from the above discussion, in consideration of computers' capacity presently available in the market, it is practical to use FDM for the discretization with respect to both space and time, called FDTD method. Equations (1) and (2) are discretized and expanded by the FDTD method using the central difference (8) to a certain physical value $\boldsymbol{F}$[6, 7].

$$\frac{\partial \boldsymbol{F}}{\partial x} \approx \frac{\boldsymbol{F}\left(x+\frac{\Delta x}{2}, y, z, t\right)-\boldsymbol{F}\left(x-\frac{\Delta x}{2}, y, z, t\right)}{\Delta x} \qquad (8)$$

where Δx is the division width in the x-axis direction.

The numerical preparation, descretization and expansion, of the fundamental electromagnetic wave equations are completed by the above procedures, the details of which are omitted here.

3.3 Physical values to evaluate in electromagnetic wave analysis

Another aspect in which electromagnetic wave analysis differs from electromagnetic field analysis is the difference of physical values to evaluate. In electromagnetic field analysis, in most cases, magnetic flux density, eddy current loss and electromagnetic force (Lorentz force and Maxwell stress) are extracted and used as indicators in equipment design. In electromagnetic wave analysis, in contrast, equations (1) and (2) are directly dealt with and (i) magnetic field intensity, (ii) electric field intensity and (iii) dielectric loss are employed as design indicators.

Here again, inasmuch as the motion of a microwave is essentially a kind of wave propagation, it is necessary to look at it in terms of transient change, and it is often inappropriate to judge a solution based on the field distribution at a certain point of time. In the case especially of irradiating an electromagnetic wave in a large closed space, it takes much time for reflection to repeat to form a standing wave and for this reason, if only a short analysis time is allowed so as to obtain a solution quickly, various physical values may be estimated incorrectly. It is hence very important for obtaining a correct solution to previously estimate how many calculation steps will be required.

The dielectric loss used as the direct indicator of heating is calculated by the following term using the vacuum dielectric constant ε_0 :

$$\frac{\omega\, \varepsilon_0\, \varepsilon''}{d}\, |\, \boldsymbol{E}\,|^2 \qquad (9)$$

4. Essential Points of Modeling in Electromagnetic Wave Analysis

In actually applying electromagnetic wave analysis to use of a microwave for an industrial process, an appropriate solution is not obtained unless the process is modeled accurately with its real conditions. Important factors among many to be taken into consideration in the modeling are explained below.

4.1 Definition of object material portions to heat (skin depth)[8]

As stated in section 2, there are in effect only two frequency bands of electromagnetic waves open to industrial use. In a heating process such as induction heating, an index called skin depth is used as an important indicator for judging how efficiently an object material is heated; it is an index to estimate how deep from the surface an electromagnetic field can penetrate into an object material. There is an equivalent index for electromagnetic waves and it is calculated by the following formula:

$$L = \frac{\lambda}{4\pi}\sqrt{\frac{2}{\varepsilon'\,(\sqrt{1+\tan^2\delta}\ -1)}}\ \ [\mathrm{cm}] \qquad (10)$$

where ε' is the real part of the dielectric constant ε of the object material considered. The skin depth L is proportionate to only the wavelength when heating objects consist of the same material. Therefore, when typical dimension of an object material is given, it is necessary for heating the object efficiently to select an adequate frequency based on the formula. To heat an object to the center, the lower frequency (915 MHz) is suitable, and to heat only the portion near its surface, then the higher frequency (2,450 MHz) should be selected.

4.2 Modeling of waveguide (forming of effective wave)

Modeling of a waveguide is also important. Since the wavelength of a microwave is in the order of 10 cm, the dimensional accuracy and thickness of a waveguide sometimes influence its propagation and diffusion. Therefore, when the spaces of a waveguide and the chamber where a microwave is irradiated are divided coarsely or the shape of an object material is modeled roughly, the propagation and reflection of a microwave inside an object space are not calculated correctly.

As described earlier, a huge computer capacity is needed for an effective application of electromagnetic wave analysis to an actual industrial process and the situation being such, there is practically no other choice than to use FDM. However, the use of FDM inevitably leads to the following problem in the modeling: the method permits space division only in lattices, and division into tetrahedrons, triangular prisms and the like, which are allowed in FEM, is not accepted. Thus, when an object material has curved surfaces or a rectangular object is placed obliquely to a dividing lattice, the only acceptable means is to approximate its surfaces as if they are composed of small steps cut by the dividing lattice.

An electromagnetic wave is generated from a dipole point source placed inside a waveguide. Here, the length of the waveguide and the position of the point source are also significant. With respect to the position of the point source, however, it is usually set at $\lambda/4$ from the end of a waveguide so as to diminish the affection of reflected waves, which are little formed inside a waveguide actually, since they are mostly absorbed by a dummy load absorber built in the power supply. By this positioning, the electromagnetic waves that go from the source to the end of the waveguide reflect and offset each other, as a result, the reflected components of the waves are not emitted from the waveguide to space.

4.3 Modeling of boundaries (elaboration of analysis object)

Below, the setting of boundary conditions is examined. In electromagnetic wave analysis, boundaries are classified generally according to the two of criteria: one is reflection and absorption at boundaries; the other is whether the system in question is closed or open. When an electromagnetic wave is radiated in a space surrounded by metal walls, the system is a reflective and closed. In a little more complicated case where an electromagnetic wave is emitted in a space surrounded by thin walls of dielectric materials that absorb electromagnetic waves, it is possible to set a boundary condition such that a part of the electromagnetic wave passes through the walls and diffuses to infinite space. Moreover, another set of metal walls may be provided outside the dielectric walls. An analyzer has to decide about the setting of boundary conditions in consideration of what extent of accuracy is required of the numerical modeling.

As described above, like in ordinary electromagnetic field analysis, in each of analysis cases there are many factors that require consideration for obtaining an accurate result; the factors to consider include the properties of an object material, the size of space, the frequency of the microwave and the shapes of the object material and surrounding walls. In addition, owing to the characteristics of wave propagation, one of these factors often exerts an influence over the whole system. For this reason, it is difficult to work out a generally applicable design philosophy that can instruct what to do to obtain a satisfactory solution under a wide variety of conditions.

5. Analysis Example (Drying Facility of Refractory for Steel Making Processes)

The items outlined in the previous section are explained here more specifically based on an example of heating refractory structures to dry them.

Fig. 2 is a schematic illustration of a large chamber surrounded by steel plates and refractory bricks (the ceiling is composed only of a steel plate) in which microwaves are irradiated (the ceiling and two front walls are not shown). Three refractory structures to dry are placed on the floor. Three rectangular waveguides are arranged in an angle of 120˚ to each other to reduce mutual interference. The waveguide in the left-hand side front position is aligned to the division lattice and the other two are not. In order to minimize the influence of the non-alignment of the two waveguides, the space of the chamber was divided using as fine the lattice as possible and as a result, the number of division cells was 87,882,624. A microwave with a frequency of 915 MHz was irradiated at a power input of 18 kW, and an HPC-Alpha DP264/667F computer with main memory 4 GB and 600 MHz CPU was used for the calculation. It took about 1 day for the computer to carry out 5,000 calculation steps.

Fig. 3 shows the change in the microwave emission when the position of the point source of one of the waveguides is shifted. The

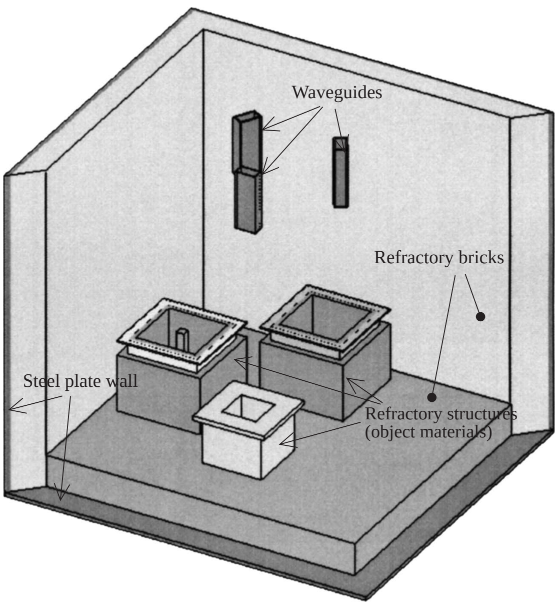


Fig. 2 Drying chamber model surrounded by steel plates and refractory bricks

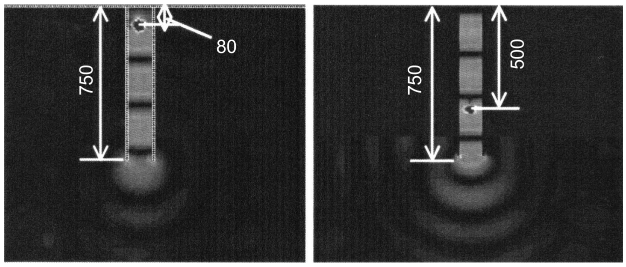


Fig. 3 Influence of point source position in waveguide (electric field intensity)

electric intensity of electromagnetic wave, which is shown here in grayscale pictures, changes depending on the position of the point source. The right-hand part of the figure shows an example where the electric field is intensified as a result of the superposing the waves reflected at the top of the waveguide. There are also some shifts of wave intervals demonstrating mixture of different wavelengths due to the reflection. The same thing occurs with the other two waveguides; with the division lattice used in this analysis, the non-alignment of the waveguides does not affect the solution much, but the position of the point source did.

Analyses were carried out changing the conditions further (see **Table 1**). When the height of the ceiling is lowered to examine the influence of the position of the waveguides, the heating energy delivered to the object refractory structures; i.e. the sum of the dielectric losses of the three structures, increases significantly as the waveguides is lowered. Next, reflectors, or stirrers, are put on at the exits of the waveguides to strongly diffuse the microwaves. This time, the energy input increases when the ceiling is high, but when the ceiling is low, the heating energy delivered to the object materials is markedly reduced owing to a strong effect of wave reflection. Furthermore, in order to improve wave reflection of the walls, the bricks on the chamber walls are removed to leave only the steel plates. This time, the heating energy hit the highest value of 15.8 kW when the ceiling is low.

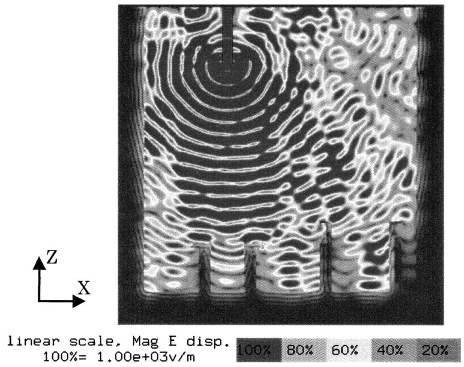
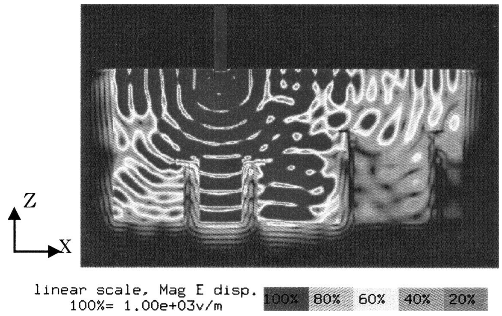
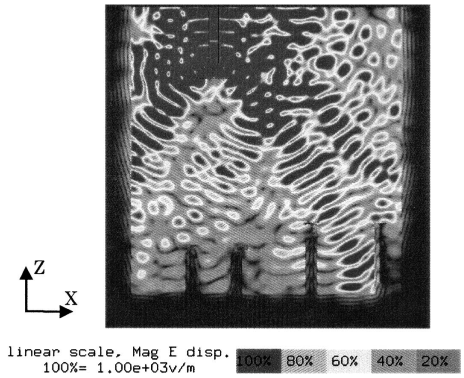
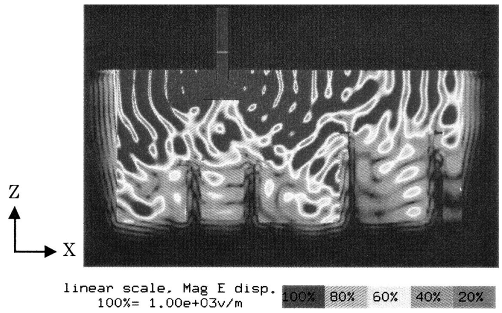
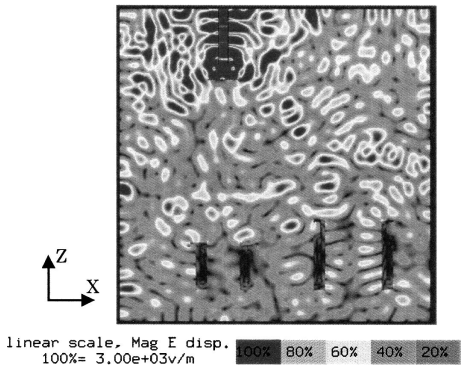
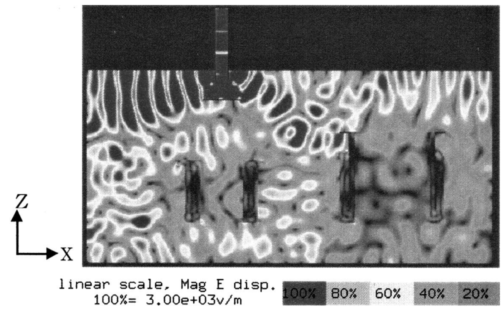
It is made clear from the above that the best heating efficiency is achieved with a low ceiling, reflectors at the exits of waveguides and the chamber walls composed only of steel plates. The most suitable equipment construction was thus identified. Just for reference, the software used for the analysis was XFDTD of Remcom, U.S.A.

6. Closing

The above explains the characteristics and procedures of electromagnetic wave analysis, which has so far been little applied to steel making processes. An example of application of the analysis has also been presented herein. The authors have stated that, while electromagnetic wave analysis is classified physically as a kind of electromagnetic field analysis, because of its special characteristics, the calculation for the analysis requires complicated elaboration as well as a huge computer capacity as far as presently available computers are concerned. In the example of electromagnetic wave analysis application, which mainly relates to equipment design, it is described how equipment specifications are defined to obtain an optimum solution.

Some remarks are given here on the future prospect of electromagnetic wave analysis. As stated earlier, electromagnetic wave analysis has been applied far more in the field of communication than to the processes of manufacturing industries. The communication industry is expected to continue developing further, and electro-

Table 1 Distribution of electric field intensity (effects of position of waveguide, use of stirrers and structure of chamber walls)

	High ceiling	Low ceiling
Waveguides without stirrers	 Total heat energy of structures: 2.5 kW	 Total heat energy of structures: 6.2 kW
With stirrers	 Total heat energy of structures: 3.2 kW	 Total heat energy of structures: 1.5 kW
Steel plate walls (without bricks)	 Total heat energy of structures: 10.0 kW	 Total heat energy of structures: 15.8 kW

magnetic wave analysis is going to be applied to examine problems related to radio communication such as electromagnetic interference.

Besides the above, the secondary effects peculiar to the treatment of materials by microwaves have also been explained. Those effects are suspected to relate to the molecular structure of materials and in consideration of this, changes in material characteristics in a molecular structure level have been being studying worldwide. Thus, microwaves are attracting attention from the viewpoint of material development, and will find wider applications also in a variety of other fields.

On the other hand, owing largely to technical difficulties, high-power electromagnetic wave generators applicable to the processes of manufacturing industries are supplied only by a limited number of manufacturers, with only a limited number of models available, and this has been one of the reasons for the present limited application of electromagnetic waves. However, since this problem is being solved, equipment applying electromagnetic waves is likely to find wider industrial applications before long to an extent comparable to that of other forms of electromagnetic energy applications such as induction heating equipment, and melting and stirring equipment. At that time, equipment design based on numerical analysis as described herein will be a daily practice. The authors are confident that the electromagnetic wave analysis technologies presented in this paper are useful for whatever form of electromagnetic energy application that will appear in the future.

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Symbols of physical values

Bold letters represent vector quantities and others scalar quantities, basically.

$\boldsymbol{B}$: magnetic flux density (Wb/m^2)
$\boldsymbol{H}$: magnetic field intensity (A/m)
$\boldsymbol{E}$: electric field intensity (V/m)
$\boldsymbol{D}$: electric flux density (C/m^2)
$\boldsymbol{A}$: vector potential (Wb/m)
ϕ : scalar potential (V)
$\boldsymbol{J}_0$: forced current density (A/m^3)
t : time (s)
μ : magnetic permeability (H/m)
ε : dielectric constant (F/m)
ε'' : complex dielectric constant (F/m)
ρ : charge density (C/m^3)
σ : conductivity (S/m)
ω : angular frequency
λ : wavelength (m)
d : density of dielectric body (kg/m^3)
δ : loss coefficient of dielectric body