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Development of Microwave Heating Process for Feedstock for Iron Production

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Abstract

Microwave heating efficiency was studied using FEM analysis of electromagnetic fields. Regarding heating of agglomerates of fine iron oxide and carbon powder on a metal conveyer of a band dryer by inserting a slot antenna into the agglomerate bed to irradiate microwaves selectively to the lower layer of the bed, the optimum position and shape of the antenna slots were studied. As a result, due to the interaction between the antenna and the metal conveyer, the adequate slot width changed depending on the position of the antenna relative to the conveyer floor. Through an analysis of microwave absorption by agglomerates of different micro mixing structures, the microwave absorption is improved when the agglomerates consist of double structure micro particles.

1. Introduction

Microwaves have a wavelength roughly 10000 times that of infrared and penetrate into the inside of matter. Because their energy is directly absorbed by the object matter according to their electromagnetic properties, microwaves can heat matter from inside rapidly with high energy efficiency. And they are widely used to heat various materials; examples of their application include kitchen ovens, and industrially, defrosting of frozen food, sterilizing, vulcanizing of rubber, etc.[1)]

Nippon Steel & Sumitomo Metal Corporation has long focused attention on the excellent characteristics of microwaves, developed a microwave heating system for drying monolithic refractories, and used such equipment in many works,[2)] whereby high-power oscillators exceeding 100 kW power are used for quickly drying monolithic refractories applied to ladle walls, etc. We realized an energy-saving process to realize short-time drying of monolithic refractories and reduce the energy required for drying compared to conventional gas heating methods.. Nippon Steel & Sumikin Chemical Co., Ltd., a Nippon Steel & Sumitomo Metal group company, has also studied microwave heating for chemical processing to make bio oil, Ni nanoparticles, etc.[3, 4)]

With the progress of microwave research in recent years, metal materials, which are conductive and were considered non-heatable by microwaves, can be heated well in the particle state, and many researchers focus on the principle of the heating mechanism of metal particles[5)] and microwave processing of various advanced functional materials and fine ceramics.[6)]

In this paper, we studied the optimal structure of the microwave antenna for drying equipment of iron feedstock agglomerate, which consists of iron oxide dust and carbon powder, to realize the most efficient heating by using electromagnetic FEM calculation.

2. Study of Microwave Drying of Iron Ore Agglomerates

2.1 Study of microwave heating using slot antenna

Since powdery, low-grade iron ore has increased in recent years, iron-containing dust agglomerates are important as iron feedstock. However, the crushing strength of raw agglomerates is low, which decreases the yield owing to breakage. Therefore, they need to be dried using a "band dryer" to reduce the amount of excess water and improve their crushing strength.[7)] In a band dryer, hot air from above is blown onto the stacked agglomerates on the conveyer, so the drying of the bottom part of the agglomerate layer is delayed because the temperature of the hot air drops when flowing through the layer. We investigated a microwave-assisted drying method to improve the above problem of the dryer. Microwaves are well absorbed into water and are suitable for use in drying treatment. The microwave-assisted band dryer system is shown in **Fig. 1**.

Different from the case of the drying of monolithic refractories, refractory raw material does not absorb microwaves, the agglomerate is composed of iron oxide powder and carbon powder with both good microwave absorption as well as water. Therefore, if the mi-

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crowaves are irradiated from above, the microwaves would be absorbed in the upper part of the agglomerate layer and not reach the bottom part. In addition, because the conveyer is a metal mesh belt and shields microwaves, microwave irradiation from the under side would not work either.

We investigated an irradiating method using a narrow-width slot antenna inserted into the layer of the agglomerates from above as shown in Fig. 1. In this method, the microwaves propagate through the slot antenna and are irradiated to the agglomerate in the lower layer part of the opening of the antenna tip. The optimum conditions for antenna aperture size and antenna insertion depth were examined by electromagnetic field analysis to realize the efficient provision of microwave energy to the agglomerates in a band dryer.[8)]

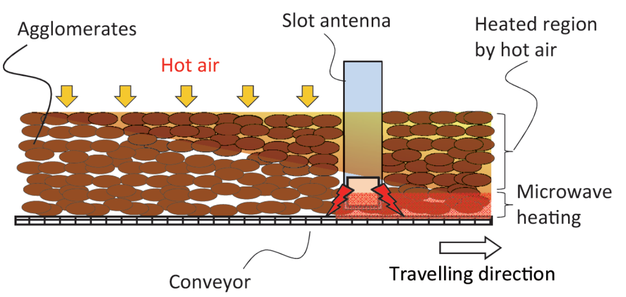


Fig. 1 Schematic diagram of microwave heating equipment for the band dryer

2.2 Structure of conventional slot antenna and microwave irradiation characteristics in free space

In industrial use, microwave power exceeding 1 kW is usually transmitted by rectangular waveguides. A slot antenna is an antenna designed to terminate a waveguide with a conductor and radiate electromagnetic waves to the outside through a slit opening provided on the side wall of the waveguide. The length of the long side (E plane) of the rectangular waveguide has a determined standard length to obtain high transmission efficiency dependent on the frequency of the transmitted microwave. For microwaves with a frequency of 2.45 GHz used for industrial heating, waveguides of EIA standard WR 430 with a long side of 109.22 mm are used. On the other hand, the length of the short side (H plane) of the waveguide does not affect the transmission efficiency of microwave power. We can use a narrow waveguide with short side length for microwave transmission under the condition that the transmitted power density does not exceed the discharge threshold.[9)]

Based on the above consideration, in order to irradiate the microwave to the agglomerates of the lower layer part, we investigated a method of inserting a narrow slot antenna into the agglomerates layer to transmit microwave power. In this method, the slot antenna was inserted so that the long side direction of the slot antenna is parallel to the conveying direction so as not to prevent the conveyance of the agglomerates.

Figure 2 shows the mechanism of microwave irradiation from a conventional slot antenna. To efficiently irradiate microwaves from the antenna, it is necessary that the slot is at the position where the magnetic field of the standing wave in the antenna is maximum. According to Ampere's theory, electric currents J are induced in the sidewalls by the field formed inside the antenna, but since the currents are interrupted by the opening of the slot, positive and negative charges accumulate at the slot edges to form an electric field E in the slot, and microwaves are irradiated to outside with the field E serving as the radiation source. According to above theory, the slot has to be at a position where the magnetic field in the waveguide is maximum as is the current in the side panel.[10)]

The antenna tip is terminated with a conductive metal plate, so the electric field is zero at the antenna tip, and the magnetic field is maximum. When a conventional slot antenna is placed in a free space, the maxima of the magnetic field occur at distances S integer times $\lambda_g/2$ above the terminal metal plate, where λ_g is the guided wavelength. **Figure 3** shows the magnetic field distribution in a waveguide when the tip is shorted with a conductive metal plate. As shown in Fig. 3, the irradiation efficiency of the antenna is maximized when a slot is opened at a position distant from the end plate by λ_g or its multiple.

2.3 Study of optimum structure of the slot antenna inserted into agglomerate layer

Next, microwave irradiation from a slot antenna inserted into the agglomerate bed was examined using electromagnetic field analysis.

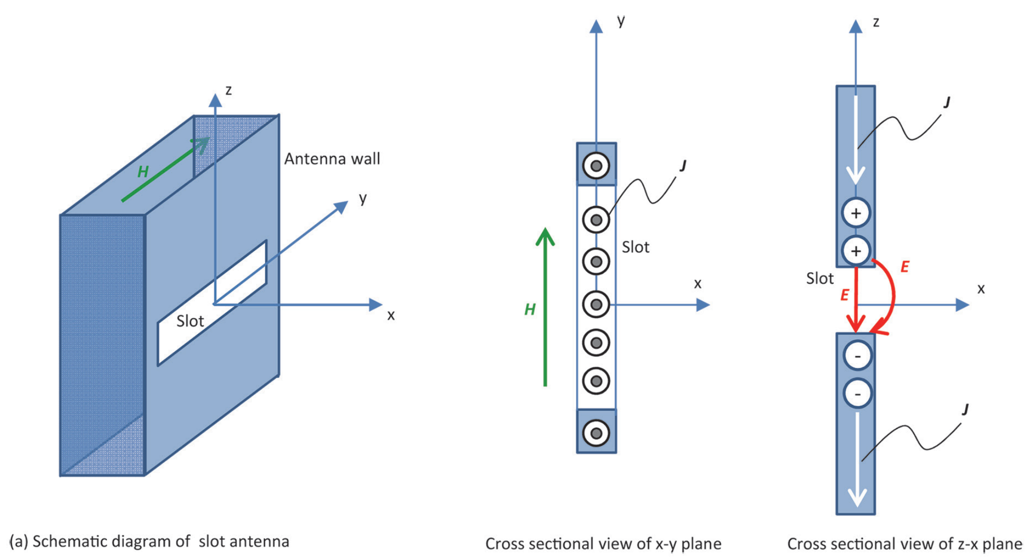


Fig. 2 Microwave radiation from a slot antenna

Figure 4 shows the simulation model used for the analysis.

In the model, rectangular blocks of the agglomerates ② were arranged along and in contact with the lower part of the long sides of the antenna ① in five tiers (see Fig. 4 (A)). The appearance of the slot antenna without the blocks is given in Fig. 4 (B): the antenna is positioned at a distance L above the metal conveyer ③ of the band dryer, and there are two slots ④, h in width, at the lower end of each side wall of the antenna. By this simulation model, the relationship between the distance L from the antenna tip to the metal conveyer belt of the band dryer, the width h of the slots at the lower end, and the efficiency of microwave irradiation were analyzed using ANSYS HFSS for electromagnetic field analysis FEM.

2.3.1 Microwave irradiation characteristics of slot antenna inserted into agglomerate bed

Using the FEM calculation, when the slot antenna was inserted deep into the agglomerate bed, the electromagnetic field distribution in the waveguide was changed compared to that of the slot antenna in a free space because of the interaction of the magnetic field between that in the antenna and that of the near-by conveyer surface. As an example of the analysis results, the intensity distribution of the magnetic field in an x-y section parallel to the H plane of the antenna when L=25 mm and h=30 mm is shown in **Fig. 5**. A local maximum of the magnetic field occurred at the maximum at the position where S=L symmetrical to the conveyor surface across the antenna tip of the metal plate. On the other hand, the magnetic field at the position of $S=\lambda_g/2$, which was the maximum of the magnetic field when the antenna was placed in free space (see Fig. 3), became small. The cause of the change of the magnetic field distribution is assumed as follows. The magnetic field formed by the eddy current in the metal conveyer belt creates the secondary eddy current in the antenna tip metal plate, and as a result, the mode of the standing wave in the antenna changes and the local maximum of the magnetic field appears at the position L from the antenna tip (see Fig. 5 (c)).

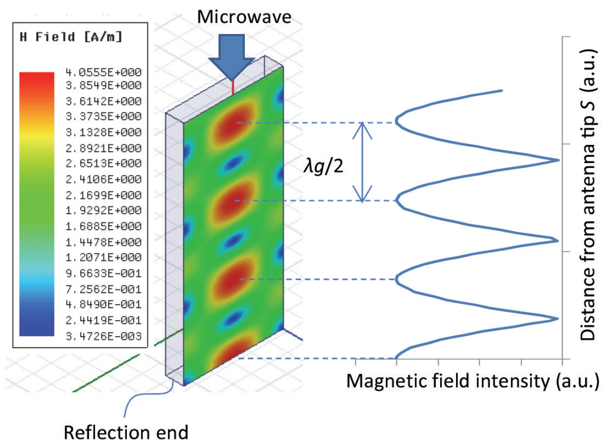


Fig. 3 Magnetic field distribution of E-plane inside a slot antenna

As a result of electromagnetic calculation, when the slot antenna is inserted into an agglomerates bed to dry the agglomerates on a metal conveyer, the position of a local maximum of the magnetic field changes depending on the antenna-conveyer distance L, and it is necessary to set the slot width h to satisfy $h>L$ so that the slot window includes the position of a local maximum of the magnetic field.

2.3.2 Experiments of microwave heating of ore agglomerates using a slot antenna

The microwave heating experiments of ore agglomerate were conducted. A slot antenna was inserted into an agglomerates layer packed in a metal box. as shown in **Fig. 6**. The temperature of the agglomerates was measured with thermocouples inserted into representative agglomerates.

The agglomerates were heated by microwave irradiation under four different conditions of the slot width h (mm) and the distance L (mm) between the antenna tip and the bottom of the metal box sim-

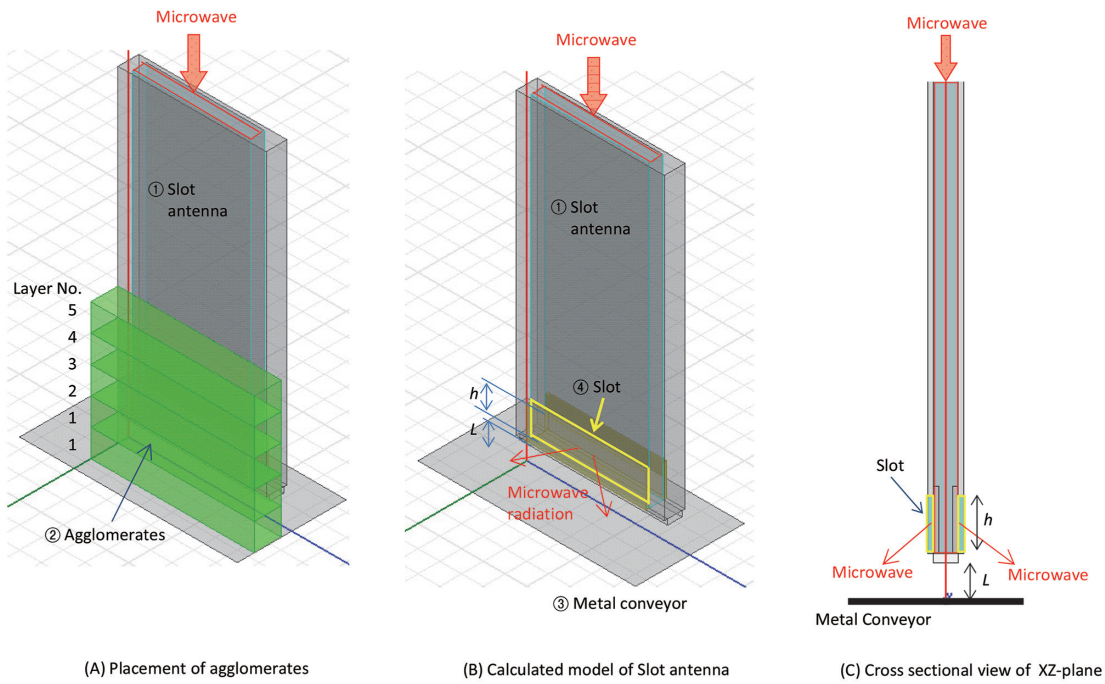


Fig. 4 Geometry of the numerical simulation model

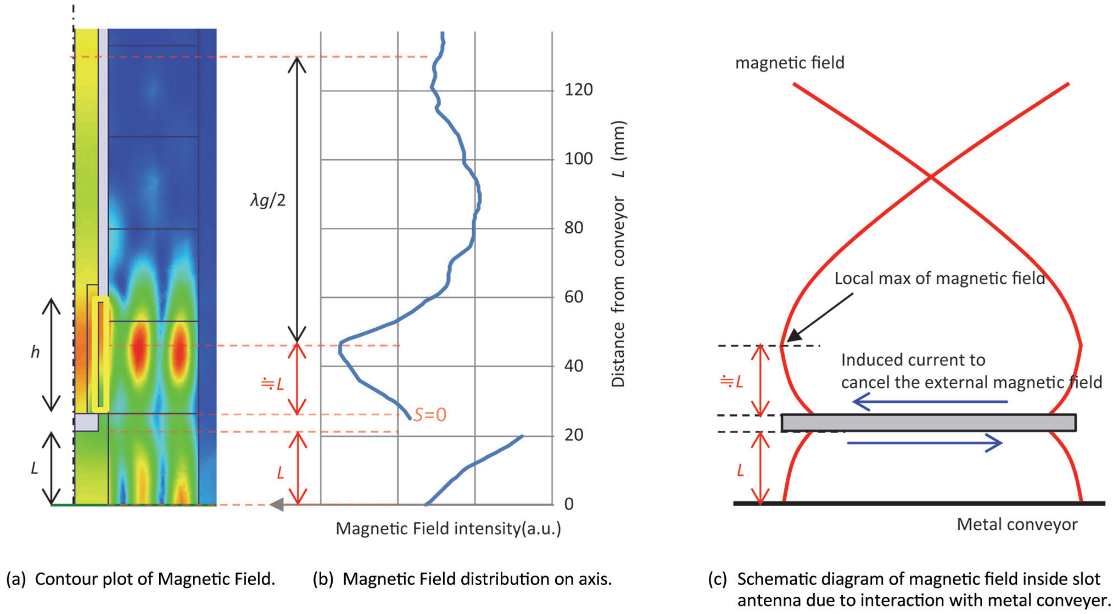


Fig. 5 Calculated magnetic field distribution inside slot antenna inserted into agglomerate layer

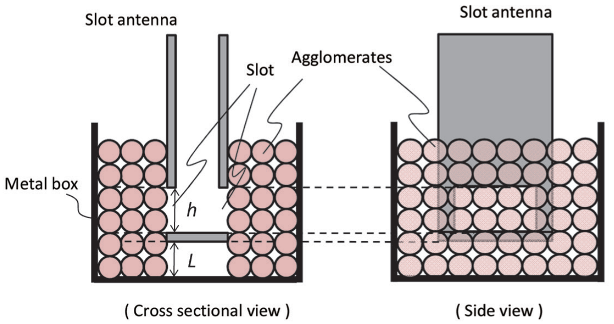


Fig. 6 Experimental setup of microwave heating of agglomerates using slot antenna

ulating the conveyer belt. **Table 1** represents the values of h and L in the heating experiments, and the reflectance R of microwave power during the heating, and **Fig. 7** is the graph of the calculated absorptance of microwave power of the agglomerates placed at different positions in the metal box.

In Cases A and C, in which slot size $h > L$ (distance between the antenna tip and metal box), the reflectance of microwaves was low. In these cases, the position of the local maximum of the magnetic field in the slot antenna would be present within the slot opening according to the electromagnetic calculation. On the other hand, in Case D in which $h < L$ and the position of the local maximum of the magnetic field in the antenna was outside of the slot opening, the reflectance of microwave power was high.

In Case B, in which $h > L$, but h was so large that $h \fallingdotseq L + \lambda_g/4$ and the position of a local minimum of the magnetic field was present near the upper edge of the slot opening, irradiation efficiency of microwaves was significantly low and the reflectance was high. In Case C, in which the distance L of the antenna tip from the bottom of the metal box was close, agglomerates in the bottom layer were heated better than in upper regions, and in Case A, in which the distance L was large, the agglomerates at higher regions were well heated. These results indicate that the heating pattern of the agglomerates can be controlled by changing the insertion depth of the slot antenna into the agglomerate bed. We also conducted the heating experiments in a commercially operated band dryer, the slot antenna was inserted into an ore agglomerate bed and agglomerates near the bottom conveyer floor were ascertained to have been heated, which confirmed the effectiveness of the present heating method.

Table 1 Reflection coefficient R with respect to antenna installation height L and slot size h in the experiments

Case	A	B	C	D
L (mm)	20	20	10	10
h (mm)	30	60	15	5
R (%)	8.3	75	19	71

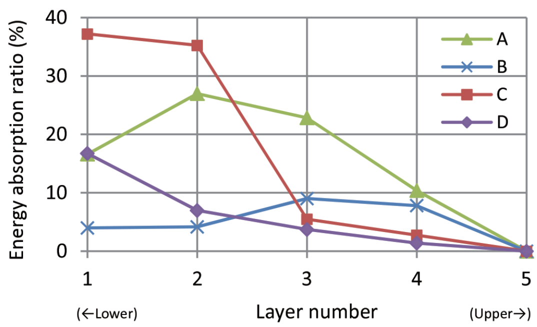


Fig. 7 Energy absorption ratio at different layers

3. Effects of Microstructure of Ore Agglomerates on Microwave Absorption

Next, to enhance the efficiency of microwave heating of iron ore agglomerates, we examined the effect of the microstructure of the agglomerates of mixed iron oxide and carbon on microwave energy absorption to clarify the suitable agglomerate structure for microwave heating.

3.1 Analysis models

The change in microwave absorption depending on the mixing condition of fines of iron oxide and carbon was investigated using electromagnetic FEM calculation. **Figure 8** schematically shows the composition of the models, wherein it was assumed as follows: a model agglomerate was composed of 64 cubic particles, each having sides 100 μm in length, arranged in 4×4×4 with a 20-μm gap between every two; and microwave was irradiated along the Y axis. The microwave beam was assumed to be in plane wave having an electric field along the Z axis and a magnetic field along the Y axis. The upper and lower end faces of the model parallel to the X-Y plane were defined as the symmetrical boundaries with respect to the electric field, and the two side faces parallel to the Y-Z plane as those with respect to the magnetic field. Like the analysis in subsection 2.3 above, HFSS of ANSYS was also used for this analysis.

The model agglomerate was assumed to consist of two types of materials, those of iron oxide Fe_2O_3 and others of carbon black, the volume ratio of the two was fixed at 1 to 1, and the microwave energy absorbed by the particles composing a model agglomerate was calculated regarding the following Models (A) to (E). **Figure 9** shows the particle arrangements of the model agglomerates.

Models (A) and (B): In consideration of the case where the iron oxide and carbon black are segregated and form comparatively large clusters, all the component particles were Fe_2O_3 in Model (A), and

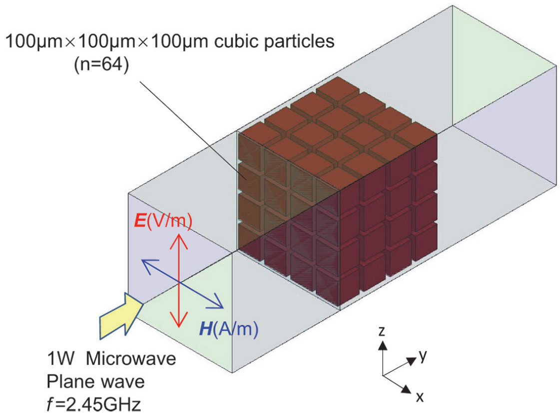


Fig. 8 Geometry of the numerical simulation model

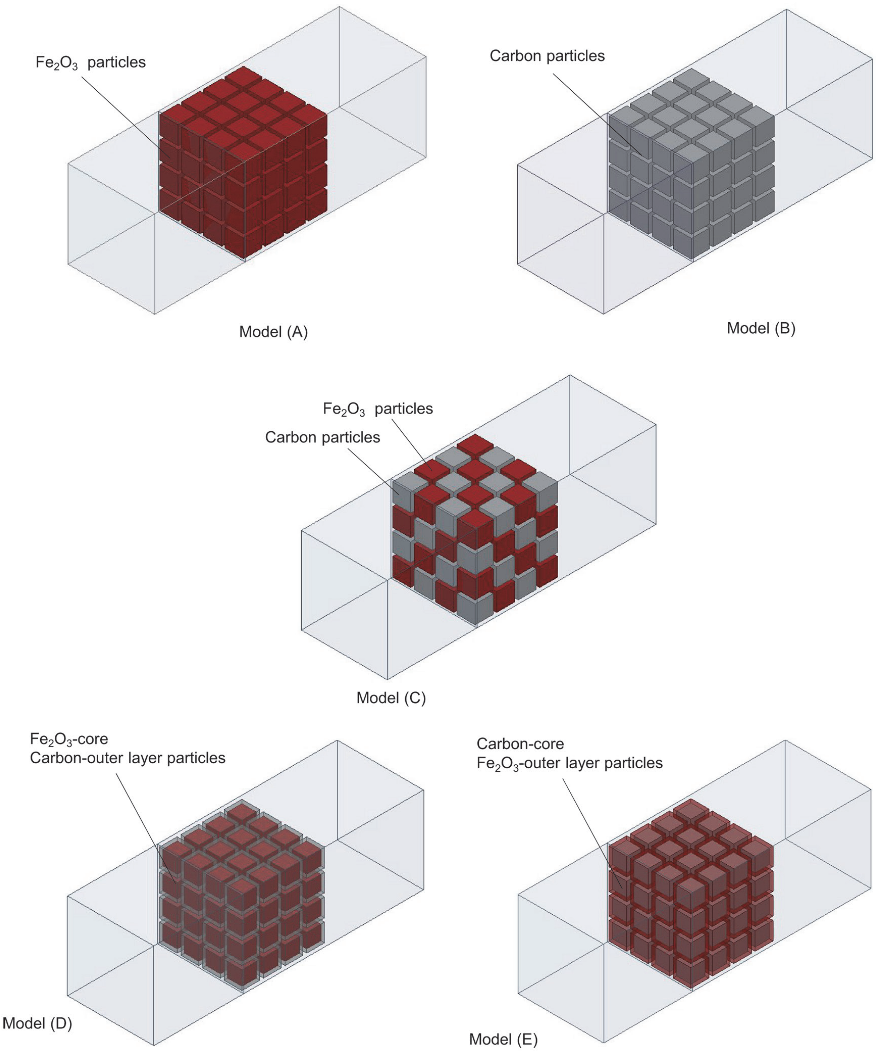


Fig. 9 Calculation models

all of them were carbon black in Model (B). The average microwave absorption of the two was used for evaluation of the mixtures of the two types of large clustered particles of iron oxide and carbon black.

Model (C): As a model in which fines of iron oxide and carbon are evenly mixed, a model agglomerate was assumed to consist of 100 μm cubes of Fe_2O_3 and those of carbon black alternately arranged to form, so to say, a three-dimensional checker.

As the models of more microscopic mixing of the two materials, the following two models were also examined.

Model (D): A core grain of carbon black is coated with Fe_2O_3 powder forming a dual-layer particle, and a model agglomerate is composed entirely of such particles.

Model (E): A core grain of Fe_2O_3 is coated with carbon black powder forming a dual-layer particle, and a model agglomerate is composed entirely of such particles.

In Models (D) and (E), the shape and size of the particles was assumed to be the same as in Models (A), (B) and (C), namely cubes all sides of which are 100 μm long, the core was supposed to be a cube all sides of which are 79.4 μm long, and the coating layer of the other material to be 10.3 μm thick, so that the volume ratio of the two materials was 1:1 in every particle.

3.2 Microwave energy absorption behavior of each model

Figure 10 shows a comparison of the microwave energy absorption behavior of the analyzed models. With regard to Models (A) and (B), the average energy absorption of the two is shown in the graph; this average value was considered to apply to the absorbed energy in the case where comparatively large agglomerates consisting only of iron oxide and those only of carbon are mixed.

There is no significant difference between the average energy absorption of Models (A) and (B) and the energy absorption of Model (C), where particles of the two materials are evenly mixed to form a model agglomerate. This seems to indicate that, when the two materials are locally segregated, there will be local difference in heating due to the difference in microwave absorption between the two materials (iron oxide and carbon black), but as long as the two are mixed at a ratio of 1:1 (correspond to the case of average of Model (A) and Model (B)), there is no significant difference in absorption efficiency in the entire system compared with the case where fine particles of the two materials are evenly mixed (Model (C)).

On the other hand, in either of Models (D) and (E), in which the component particles were supposed to have a dual-layer structure, there was a remarkable improvement in the energy absorption from Model (C) of simple mixing of particles of the two materials. These results point to the possibility of improving the microwave heating efficiency of agglomerates by adequately controlling the grain sizes of the materials to be mixed and thus forming dual-layer particles. **Figure 11** shows the result of the analysis of microwave absorption distribution of Models (D) and (E): the microwave absorption behavior is different at the core and at the outer layer of the dual-layer particles. It can be assumed that selective heating is realized for one or other of the materials by changing the particle structure.

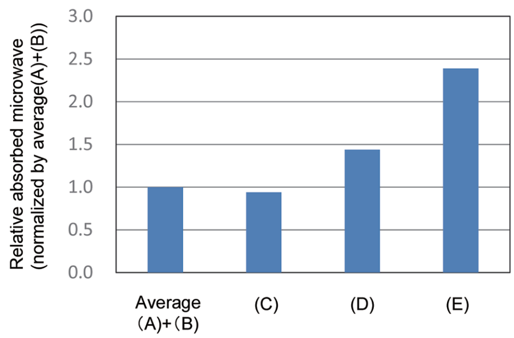
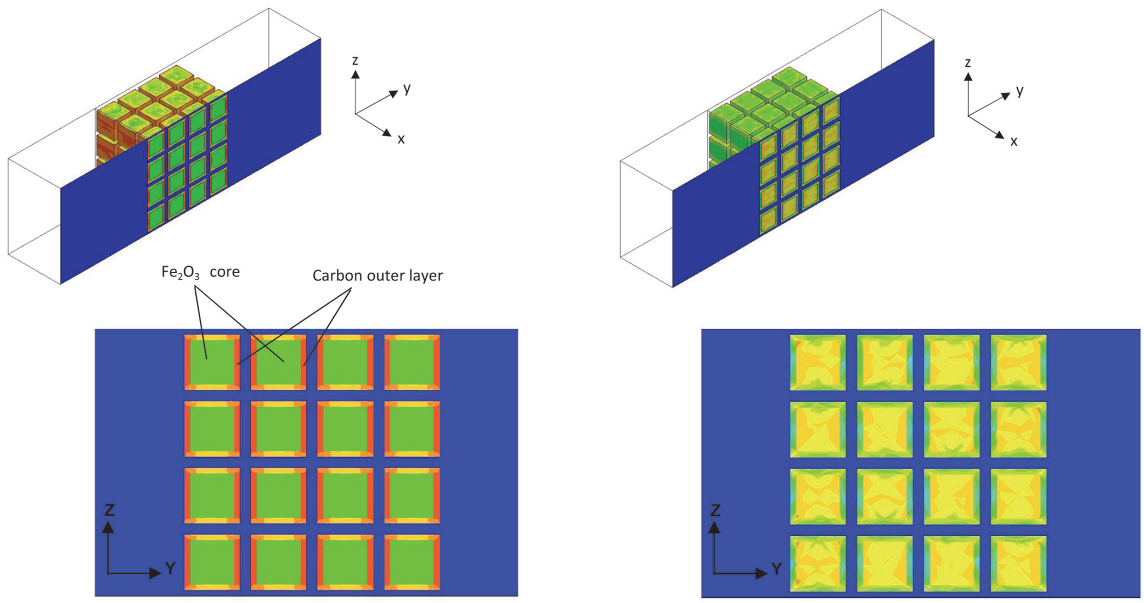


Fig. 10 Calculation results of the microwave absorption of the analyzed models



(a) Absorbed power density distribution of Model (D)

(b) Absorbed power density distribution of Model (E)

Fig. 11 Calculation results of absorbed microwave power distribution of Models (D) and (E)

4. Conclusion

Regarding microwave heating and drying of agglomerates of the feedstock for blast furnaces, this paper examined the heating efficiency change depending on the structure of the slot antenna used for irradiating microwaves, and based on the result of electromagnetic field analysis, demonstrated the possibility of significantly improving the microwave heating efficiency by optimally forming the microstructure of the agglomerates. Nippon Steel & Sumitomo Metal has applied 100 kW-class microwave oscillators to steel manufacturing, and commercially employed unique energy-saving heating methods. By combining equipment technology with the electromagnetic field analysis technique, it will be possible to develop new microwave processes to bring about greater energy saving in the steel making industry.

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