Combustion of Carbon Black collected on an ESP by Microwaves Irradiation using Slit Plate

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Abstract. In order to apply the electrostatic precipitator to a ship, it is necessary to reduce the size of the cleaning system. In search for a solution, the effect of microwaves on combustion of the carbon black was investigated in the previous study. In order to put this microwave method to practical use, this study examined a new system in which carbon black located at 6 places was burned by microwaves passing through a slit plate. Furthermore, two types of plate were used. One had slits shaped apertures with the same width (Equal slit). The other had apertures with different width so that the microwave affect carbon black at each position in a uniform way (Stair slit). Although the combustion rates with the equal slit were between 23% and 45% at the location between 1 and 3, the rates at the locations between 4 and 6 were extremely low, which were less than 6%. The cause is that the absorption of the microwaves at the location near the irradiation port was greater than that at far location. When the stair slit was used, combustion rates were between 4% and 36%. Compared with the result with the equal slit type, the rates at the locations between 4 and 6 were higher, whereas the rates at the locations between 1 and 3 were lower. This is attributed to the decrease of the microwave power passing through the slit near the irradiation port, and the increase the power at the location far from the port. This results shows that the carbon black in the combustion part can be burned uniformly using the stair slit in a practical use. It will be investigated in the future how to increase the combustion rate.

Keywords: Microwaves, Carbon black, Combustion, Electrostatic precipitator.,

1. Introduction

Suspended particulate matters, which include black carbon, emitted from ships are regulated by the MARPOL treaty. In order to eliminate pollution, an electrostatic precipitator (ESP) has been developed. This highly efficient device should be periodically cleaned by removing dust accumulated on its electrodes by way of water washing or air suction. However, the problem is that these methods require too large space on a ship to be utilized.

In search for a solution, the effect of microwaves on combustion of the carbon black was investigated in the previous study [1]. Microwaves are characterized by rapid, direct, and selective heating, and the microwave absorption in carbon materials is high. So, there are the researches of microwave heating with carbon materials such as the activated carbon [2], the coal [2,3], the graphite [2,4], and the diesel dust [5].

In order to put this microwave method to practical use, this study examined a new system which has capacity for the dust exhausted from ships. Carbon black located at 6 places were burned by microwaves passing through a slit plate in the system. Two types of slit plates were used. The combustion effects at each position and the effects of the two different shaped slit plates were investigated by simulating microwave losses and experiments.

2. Simulation

The schematic diagram of the analysis model is shown in Fig 1. The model consisted of an outer case, a waveguide, insulations, a slit plate, alumina vessels and simulated dusts. Materials of the parts are shown in table 1. The outer case, the waveguide and the slit plate were modelled by the perfect conductor. The insulation and the alumina vessel were modeled by dielectric materials. Two types of slit plates were modeled. One had slits shaped apertures with the same width (Equal slit). The other had apertures with different width so that the microwave affect carbon black at each position in a uniform way (Stair slit). Simulated dusts were placed in 6 places. The permittivity and dielectric loss factor (tan δ), which determine the microwave absorption performance, of the dust were set to 112 and 0.73 [6], respectively. The microwave, whose frequency was 2.45 GHz, was irradiated, and the absorption amount of the microwave energy for the dust was analyzed. After the analysis, the microwave absorption rate η_x was calculated from Eq. (1)

$$\eta_x = \frac{W_x}{W_{all}} \times 100\% \tag{1}$$

where W_x was absorption amount of each simulated dust and W_{all} was the total absorption amount of all simulated dusts. CST Studio Suite 2021 (Dassault Systems Simulia) was used for the analysis.

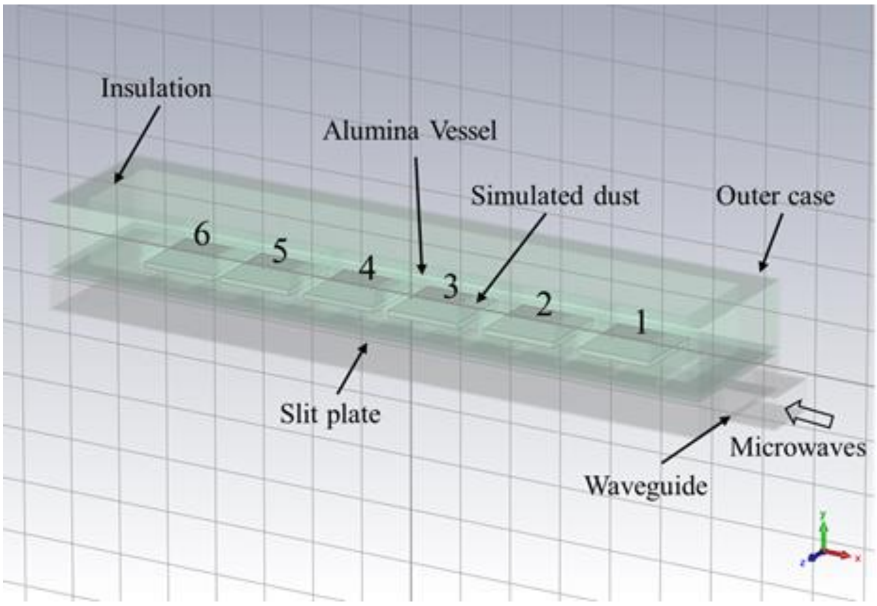

Fig.1. Schematic diagram of the analysis model.

Table.1. Schematic diagram of the analysis model.

Part	Material	Relative permittivity ε	tan δ
Outer case	Perfect conductor	—	—
Waveguide			
Slit plate			
Insulation	Dielectric	1.61	0.017
Alumina vessel	Dielectric	9.5	0.0005

3. Experiment

The schematic diagram of the experimental system is shown in Figure 2. The system consisted of a microwave power source system (IDX Co., Ltd. / IMH-20A259), an isolator (AET Co., Ltd.), a bidirectional coupler (AET Co., Ltd.), a quartz window (AET Co., Ltd.) and a combustion part. The combustion part was constructed with outer case, spacers (NICHIAS Corporation / TOMBO No. 5615), a slit plate, and insulations (NICHIAS Corporation / TOMBO No. 5625), and there were two rooms which were a waveguide room and a reactor. Two types of plates were used (Equal slit and Stair slit). The carbon black (47 g) in Alumina vessels was placed at six locations in the reactor. A number between 1 and 6 was added to a vessel located in the reactor. The vessel No.1 was near the microwave irradiation port, and the No. 6 was the farthest. The air at the temperature of 200 °C was flowed (90 L/min) from a hot air generator. The frequency of microwaves was 2.45 GHz, and the input power was 750 W or 1000 W. The microwaves were irradiated until the end of combustion or 480 min have passed. While irradiation, the reflected power, the temperature of carbon black surface and the concentration of carbon monoxide were measured with a universal power meter (Giga-Tronics / 8541C), an infrared thermometer (Sato Keiryo MGF. Co., Ltd. / C 6802) and a portable gas analyser (HORIBA / PG-300). Then, the microwave absorption rate η_W was calculated by equation (2).

$$\eta_W = \left(1 - \frac{W_{ref}}{W_{in}}\right) \times 100\% \tag{2}$$

where W_{ref} is the reflected power, and W_{in} is the input power. After irradiation, the combustion rate of the carbon black was calculated by equation (3).

$$\eta_M = \left(1 - \frac{M}{M_0}\right) \times 100\% \tag{3}$$

where M_0 is the mass of carbon black before irradiation, and M is the mass after irradiation.

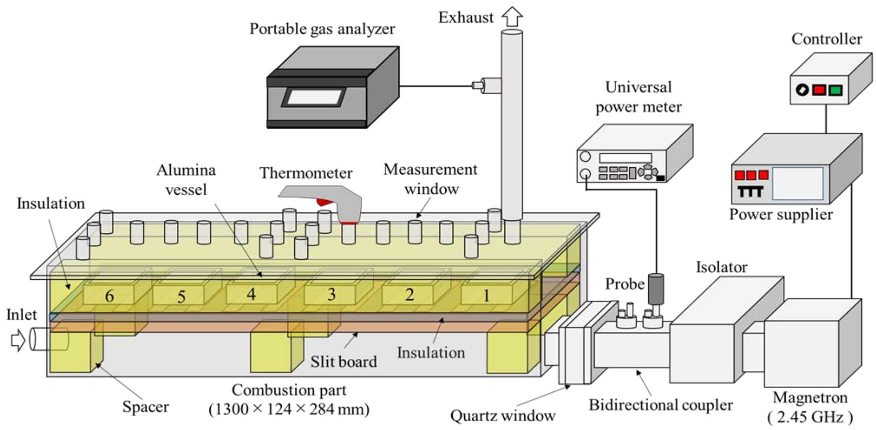

Fig.2. Schematic diagram of experimental system.

4. Results and discussion

4.1. Simulation result

Simulated microwave absorption rate is shown in Fig 3. The absorption rate at the location No. 1 on the equal slit was 28%. The rate decreased as the location number increases, and it was 3% at the location of No. 6. It is due to the fact that the slit width was the same, whereby the microwaves entered from the slit near the irradiation port into the reactor. On the other hand, when the stair slit plate was used, the absorption rates at the location of No. 1 was 18%, and slightly increased with increasing the location number. The rate at the location No. 6 was 8%. Compared with the result the equal slit typed one, the difference of absorption rate between locations was small. This is due to the effect of stair slit plate which had apertures with different width so that the microwave affect carbon black at each position in a uniform way. This result shows that the carbon black can be burned more uniformly with the stair slit plate.

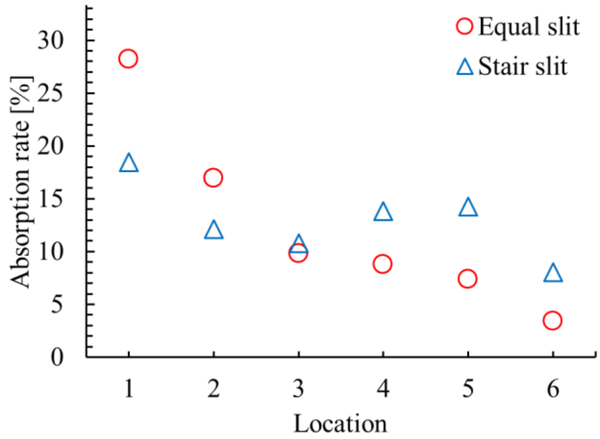

Fig.3. Microwave absorption rate at 6 locations.

4.2. Microwave absorption

The experimental result of the elapsed time dependent microwave absorption rate and input power is shown in Fig. 4. The input power was gradually increased to 750 W every 20 minutes. The microwave absorption rate was always almost 100% in both cases of the equal slit and the stair slit. Thus, the energy of microwaves is absorbed completely in the combustion part, whereby it is expected that the carbon black is heated by the microwaves.

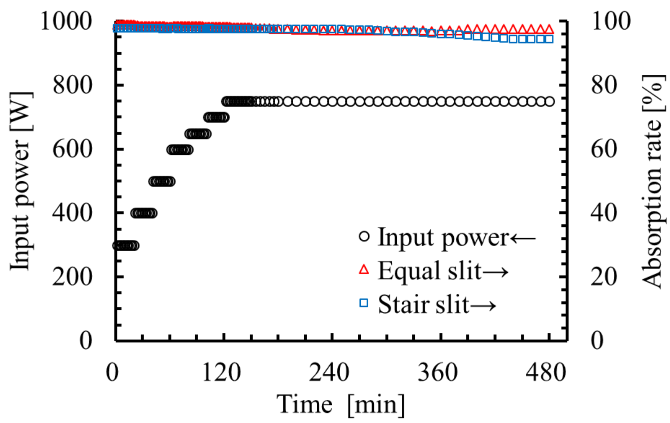

Fig.4. Time dependent input power and microwave absorption rate (750 W).

4.3. Effect on temperature of dust

The temperature of carbon black surface under microwave irradiation with the equal slit is shown in Fig 5. As expected, the surface temperature increased over time, and saturated at any locations. The saturated temperature decreased with distance from the irradiation port. The ignition temperature of carbon black is approximately 290 °C. The measured temperature exceeds it, and that inside the dust should be higher. Therefore, it is possible that carbon black is burned at all locations. However, the difference in peak temperatures between location 1 and 6 was approximately 200 °C. On the other hand, the temperature with the stair slit is shown in Fig. 6. The tendency was similar to that in the result with the equal slit as shown in Fig. 5, whereas the difference in the temperatures between location 1 and 6 is approximately 100 °C. From this result, it was found that the stair slit can heat the dust more uniformly than the equal slit, and expected that combustion is also uniform.

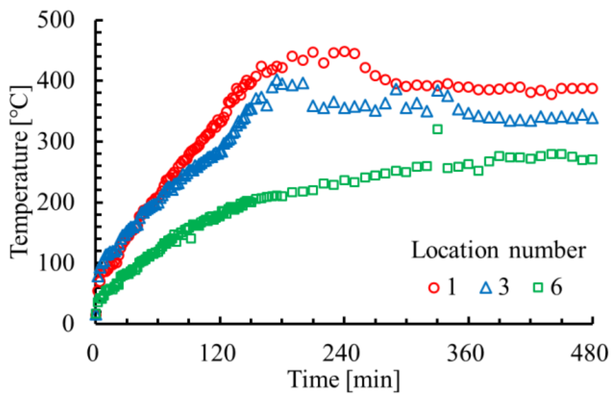

Fig.5. Temperature of carbon black surface while microwave irradiation with the equal slit.

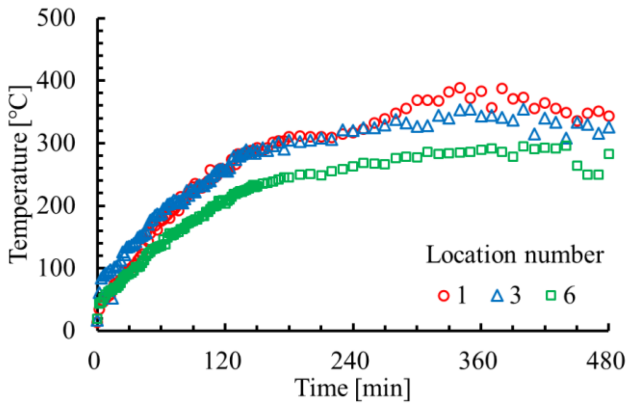

Fig.6. Temperature of carbon black surface while microwave irradiation with the stair slit.

4.4. Concentration of carbon monoxide

As carbon oxide is generated when the carbon black burns, the time dependent concentration of carbon monoxide in the gas emitted from the reactor was measured. The result is shown in Fig 7. The carbon black was irradiated by the microwaves from the time of 0 s. The carbon monoxide with the equal slit increased with time, and had the peak value of approximately 5000 ppm at the time of 180 min. And then, the concentration decreased with time. This is most likely caused by the heat dissipation which becomes greater than the heat generation due to the combustion of carbon black. The tendency with the stair slit was similar to that in the result with the equal slit. However, the peak concentration significantly decreased, and the time to reach the peak increased compared to those on the latter. The cause is that the temperature of carbon black at the location 1 near the irradiation port in the case of the stair slit increased slowly in comparison to the case of the equal slit as shown in Fig. 5 and 6.

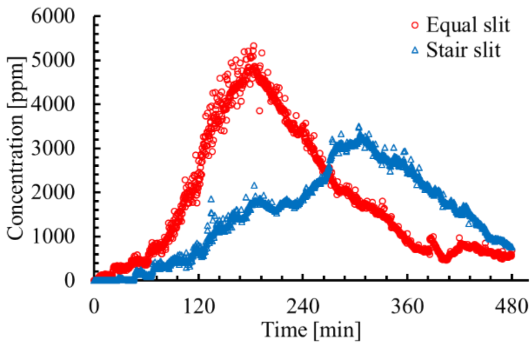

Fig.7. Time dependent concentration of carbon monoxide in the gas emitted from reactor.

4.5. Combustion rate

The relationship between the combustion rate of the carbon black and the location is shown in Fig. 8. Each numerical value is the average of those obtained in the two experiment, and the error bar indicates the maximum and the minimum values. The combustion rate at the location of No. 1 in the Equal slit was 55%. The rate decreased as the location number grows, and it was less than 2% at the location of No. 6. The rates at the locations from 4 to 6 were extremely low, less than 6%. This is caused by the absorption of the microwaves at the locations near the irradiation port which was greater than that at the far locations. When the stair slit plate was used, combustion rates were between 4% and 36%. Compared with the result with the equal slit, the rates at the locations from 4 to 6 were higher, whereas those at the locations from 1 to 3 were lower. Thus, the difference between the locations with the stair slit was smaller than that with the equal slit. This is attributed to the designed stair slit plate which decreased the microwave power passing near the irradiation port and increased it at the locations far from the port. This result shows that the carbon black in the combustion part can be burned uniformly when the stair slit in practical use. Further study is required to increase the combustion rate.

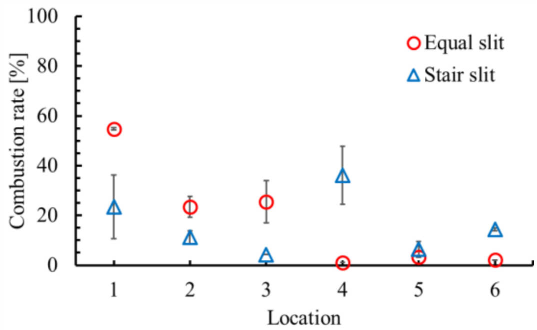

Fig.8. Relationship between combustion rate of carbon black and location (Input power: 750 W).

4.6. Effect of input power on the combustion rate

In order to improve the combustion rate, another experiment was carried out at the microwave input power of 1000 W. The input power and microwave absorption rate are shown in Fig. 9. The input power was gradually increased to 1000 W every 20 minutes. The microwave absorption rate gradually decreased with the elapsed time. It was found that the energy greater than 800 W was absorbed into the carbon black. The cause of the decrease in the absorption rate is that the mass of carbon black decreases due to combustion.

The relationship between combustion rate of the carbon black and location is shown in Fig. 10. The number of experiments was one time. The combustion rate at each location was between 51% and 69%, and it was found that the carbon black could be burned uniformly using the stair slit. The rate was improved 25 ~ 63% at all positions compared to the case of 750 W as shown in Fig. 8. From this, it was clear that the combustion rate can be improved by increasing the input power.

As the exhausted dust concentration and the exhaust gas flow rate of an auxiliary engine (1200 kW) of a ship is approximately 30 mg/Nm^3 and 6000 Nm^3/h, the amount of collected dust is 162 g/h if the collection efficiency of an ESP is 90%. In this experiment, the total carbon amount of 282 g (47 g/aluminum vessel * 6 pieces) could be burned in 8 hours. Improvement of the combustion rate and the combustion time will be investigated in the future.

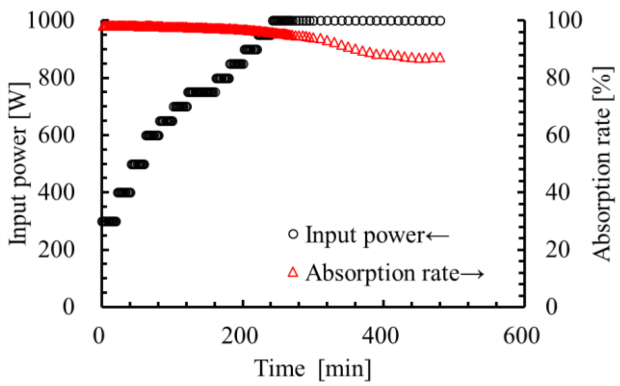

Fig.9. The input power and microwave absorption rate (1000 W max input power).

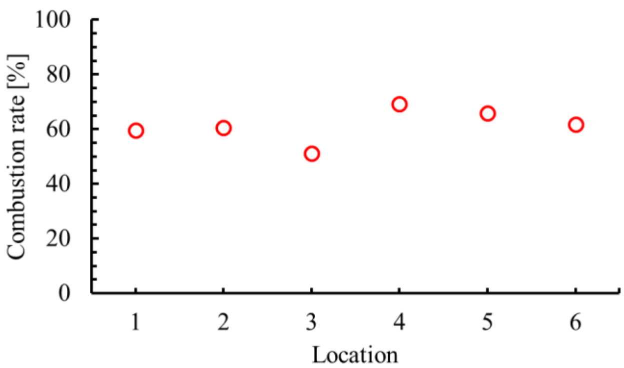

Fig.10. Relationship between combustion rate of carbon black and location (1000 W max input power).

4. Summary

For development of the electrostatic precipitator for ships, the combustion effects of microwaves on the carbon black and the effects of the two different shaped slit plates (Equal slit and Stair slit) were investigated by the computer analysis and the experiments. Results are follows;

1) The difference of calculated microwaves absorption rate between locations in the case of stair slit was smaller in the case of the equal slit.
2) The experimental microwave absorption rates were almost 100% in both cases of the equal slit and the stair slit.
3) The temperature of the dust surface decreased as the location of the dust separate farther from the irradiation port in the case of the equal slit. On the other hand, the temperatures at each location in the stair slit was almost the same.

4) The peak value of the CO concentration and the time to reach the peak with the stair slit were significantly decreased compared to the slit types.
5) The combustion rate at each location was between 4% and 36%. The difference of the combustion rates between the locations with the stair slit was smaller than that with the equal slit.
6) The combustion rate at each location was between 51% and 69% in the input power of 1000 W, and it was found that the carbon black could be burned uniformly using the stair slit.

The results indicated the effect of the stair slit. In order to obtain high combustion rate and high efficiency, it is necessary to put ingenuity into the slit plate shape such as the number and the size of slits, and adjust the input power in the future. In addition, it's expected that the dust in the combustion part will be evenly distributed, and the substances and densities are considered to be different from a practical use. Therefore the influence of them also have to be investigated.

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