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Development of a novel hybrid microwave–heater reactor for paper-based waste treatment

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Abstract It is necessary to develop a medical waste management system featuring nonburning treatment and safety functions for small medical institutions. In this article, the development of a waste management system without oxygen injection was achieved by means of hybrid heating using microwave energy and an electric heater. The shape of the microwave reactor was a rectangular parallelepiped with a volume of about 0.1 m^3. In the experimental setup, microwave energy (2.45 GHz, about 800 W) was injected from the top of the reactor, while the heater (about 1 kW) was located at the bottom. Heat insulators were set into all the walls of the reactor. The gases generated in the system were vented through water and activated carbon. Five paper-based diapers with absorbed water were used as the waste sample. For the evaluation of performance, the reduction rate was defined as the ratio (in percent) of the weight before and after treatment. The reduction rate as a function of treatment time and the effect of the position of the waste in the reactor on the reduction rate and the uniformity of treatment were examined for about 3 kg of waste. It was found that the reduction rate reached as low as 4.2% at 3 h and then 3% after 8 h. The treated profile strongly depended on the position of the waste in the reactor. In particular, it was clarified that a metal cylindrical enclosure and a needle electrode played an important role in attaining uniform treatment of the waste.

Key words Hybrid heating · Microwaves and heater · Paper-based waste · Disposable diapers · Treatment

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Introduction

Traditionally, most paper-based waste has been landfilled or incinerated and only a small proportion has been recycled, although recycling efforts are increasing. One reason is that technologically it is very hard to obtain new paper products from recycled paper in which the pulp fiber content is high. This can be explained by the degradation of the pulp fiber during the recycling process, especially in the stages of impurity removal and dissociation of paper fiber.[1] Another reason is that severely contaminated paper is impossible to recycle. A special case of paper-based waste is that of disposable diapers. Such diapers usually have a core consisting of fluff wood pulp (ca. 43% of a diaper's mass) and a superabsorbent gel polymer (27%). This core is covered by a sheet of polypropylene (10%) to protect the skin, and by a sheet of polyethylene (13%) to protect clothes. The remaining components (7%) consist of tapes, adhesive materials, and elastics.[2] Despite sustained efforts for their recycling (see EDANA[2]), disposable diapers are still landfilled in huge quantities as part of regular municipal solid waste. This current state of affairs can be explained by the yearly increase in diaper use – by children, as well as by elderly people – and the reduced number of locations where diapers are collected separately from other waste categories in order to be treated by other methods. However, landfilling of such paper-based waste is not the best option for several reasons. First, these so-called disposable diapers are practically nonbiodegradable (their decomposition time is up to 500 years). Second, due to their containing untreated human waste, disposable diapers can represent a threat to the environment. Consequently, alternative treatment methods other than landfilling must be adopted. One of the methods commonly used today, which is also used for treating municipal solid waste in general,[2] is incineration. Even if incineration eliminates the possible infectious microorganisms and substantially reduces the weight and the volume of the waste, it has many drawbacks, e.g., gas emission, smoke and ash production (ash which modifies the soil texture at the disposal site[3]), and last but not least –

increasing public opposition.[4] Although incineration as a waste treatment method has the theoretical advantage of heat recovery, this is not possible in the case of disposable diapers. It is well known that waste processing in order to produce energy is an option only if the heat released on combustion is greater than 11 MJ/kg. In the case of paper-based disposable diapers, this heat value is about 7.5 MJ/kg,[5] so the only alternative for this kind of waste is definitive treatment (i.e., sanitation and destruction with no energy yield). For waste treatment, one positive alternative approach to incineration is microwaving.[6] This clean method has already been used in waste management for two decades and its advantages, including costs, energy savings, ease of control, and improved safety over incineration are evident.[7,8] Proof of the effectiveness of microwave heating is given by its successful use for the pyrolysis of various materials and residues, with superior net results than those obtained using the conventional approach, i.e., an electrically heated furnace.[9–12]

In medical facilities, large amounts of medical waste such as paper-based diapers, plastic syringes, and needles are generated every day. The treatment of such wastes is done by specially managed facilities because the waste is hazardous. The cost of this treatment is increasing annually. In small institutions for elderly people and in clinics, the problem of the safe storage of hazardous waste has occurred because not enough is generated for daily collection, so it is collected every few days.

In hazardous waste management facilities, incineration is mainly used for the treatment of waste. In principle, it is difficult to decrease the generation of CO and CO_2 during burning. In order to attain a reduction in CO and CO_2 production, it is very important to develop waste management systems with nonburning treatment and safety functions for small institutions. One such candidate for waste management is pyrolysis. In general, pyrolysis is achieved by electric heating or by heating due to burning and requires a long treatment time such as a few tens of hours or a few days, depending on the target treated. It is well known that the microwave has an excellent heating efficiency for polar molecules such as those in water. Thus, it would be expected that the heating of the water in a used diaper would be accelerated by microwave dielectric heating. However, it takes time to heat the water even using microwave dielectric heating. A hybrid approach to heating for pyrolysis by microwave energy and an electric heater should effectively enhance the treatment of diapers. In this article, the development of a waste management system without oxygen injection was achieved by means of hybrid heating by microwave energy and an electric heater.

In general, plastic syringes and needles should be included in medical waste. In this experiment, however, since the treatment of exhaust gas from plastic materials is unresolved, the paper-based diaper was chosen as the medical waste to be handled. In particular, paper-based diapers containing human waste must be managed as hazardous medical waste.

Experimental procedure

The experimental device is basically a microwave cavity reactor operating at atmospheric pressure. Figure 1 shows a schematic of the experimental setup including some construction characteristics. The reactor is fed with 2.45-GHz microwave (MW) radiation arriving in the processing chamber through four waveguides from one microwave generator. The MW maximum effective input power is about 1 kW. In order to avoid excessive heating of the microwave generator, the waveguides are separated from the cavity reactor by dielectric windows (quartz plates). To achieve minimum power reflection, a good impedance match was ensured by appropriate adjustment of the tuning stubs mounted in the input waveguides (i.e., adjustment via the stubs offers a good method for controlling the intensity of the injected microwaves into the processing chamber). The shape of the reactor is a rectangular parallelepiped with a volume of about 0.1 m^3, as shown in Fig. 2. Two heaters with a combined input power of 1 kW were located under-

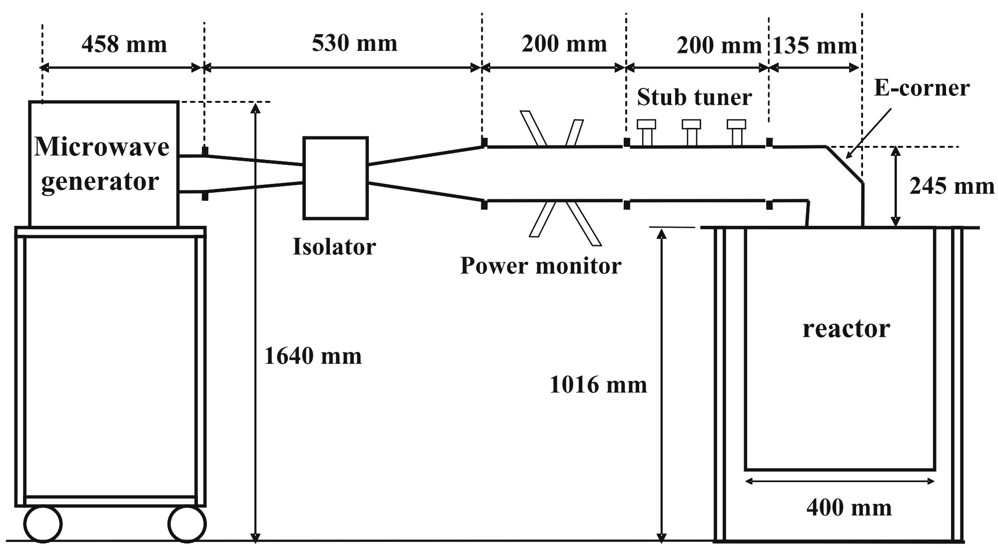

Fig. 1. Schematic of the experimental setup, including some construction features

neath the reactor. The MW power and the heaters were switched on at the same time. Heat insulation layers covered the outsides of all the walls of the reactor, as illustrated in Fig. 2. A carbon-based gasket was inserted between the flange for knockout and the inlet of the reactor to suppress the leakage of harmful gases and evaporated water. Two physical setups for the location of waste in the reactor were used, as illustrated in Fig. 3. In one setup, the waste was uniformly located at the bottom of the rectangular reactor (setup A). In the other setup, the waste was placed in a copper cylinder which was placed in the reactor (setup B). The role of the copper cylinder is to enhance the injection of MW power into the waste.

Five paper-based diapers were used for the waste. The cotton and polymer absorbents were separated from the five diapers and only these parts were used in the experiments to avoid the generation of harmful gases from the outer resin of the diaper. In general, the weight of the waste added to the reactor, including water, was about 3 kg; the weights of the absorbents and the water were 0.4 and 2.6 kg, respectively.

In the evaluation of the treatment, the reduction rate is defined as the ratio (in percent) between the weight before and after the treatment. Here, the weight of the waste includes water. The inner temperature in the reactor was also monitored with a thermocouple.

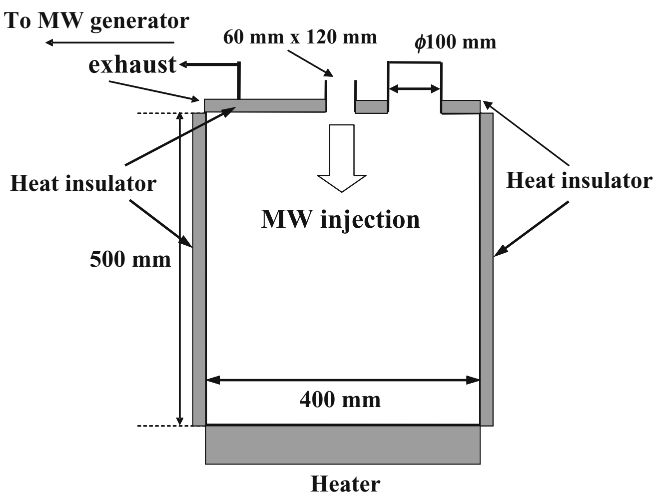

Fig. 2. Structure of the reactor. *MW*, microwave

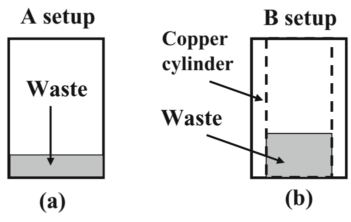

Fig. 3a,b. Two experimental setups were used for charging the waste in the reactor. **a** The waste is uniformly located on the bottom of the square reactor. **b** The waste is in a copper cylinder in the reactor

Results and discussion

In order to evaluate the performance of the proposed reactor, the treatment of waste was examined by changing the treatment time. After each experiment, tarry carbon was deposited on the inner wall of the reactor. Consequently, before each experiment, the contaminated walls were cleaned with ethanol and water. Figure 4 shows the temporal evolution of the reduction of waste. It was found that for setups A and B, the reduction rate decreases rapidly for the first 3 h and then decrease more gradually. For t > 6 h, the reduction rate barely changed. After 3 h, the reduction rates were less than 10%, and the reduction rate for setup B (4.2%) was also lower than that for setup A (8.6%). This indicates that the copper cylinder enhanced the reduction rate.

At t = 8 h, the reduction rates were about 6% and 3% for setups A and B, respectively. Before the treatment, the ratio of the absorbent weight (0.4 kg) to the total weight of waste including water (3 kg) was about 10%. For setup B, after t = 5 h, all the water had evaporated and 70% of the absorbents had been treated, whereas for setup A, only 40% of the absorbents had been treated. This finding shows that the copper cylinder is effective for the weight reduction of the waste. The inner temperature was also measured at the same time as the treatment.

Figure 5a,b shows the temperature profile inside the reactor for setups A and B, respectively. The MW power was applied for 6 h from time zero. In the case of setup A, the temperature became 100°C at about t = 20–30 min and then gradually increased with the treatment time and approached 500°C after 6 h.

In contrast, for setup B, the temperature became 100°C at 20–30 min and then slightly increases with the treatment time for t < 120 min. At around t = 120 min, the temperature increased markedly to about 480°C and then remained constant until the MW power was switched off. For setup B, the inner pressure began to increase beyond 1 atm at t > 20–30 min and reached a peak value at t = 70–80 min. After that, the pressure decreases and returned to atmospheric pressure. In setup A, it is considered that the water content of the waste was evaporated gradually with increasing time because of the time variation of the temperature. This indi-

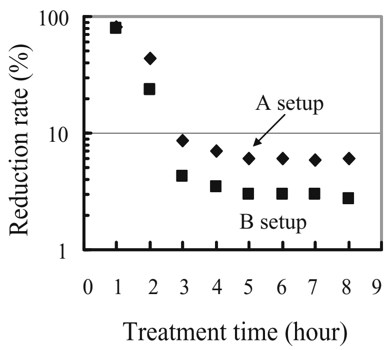

Fig. 4. Reduction rate of the waste for setups A and B

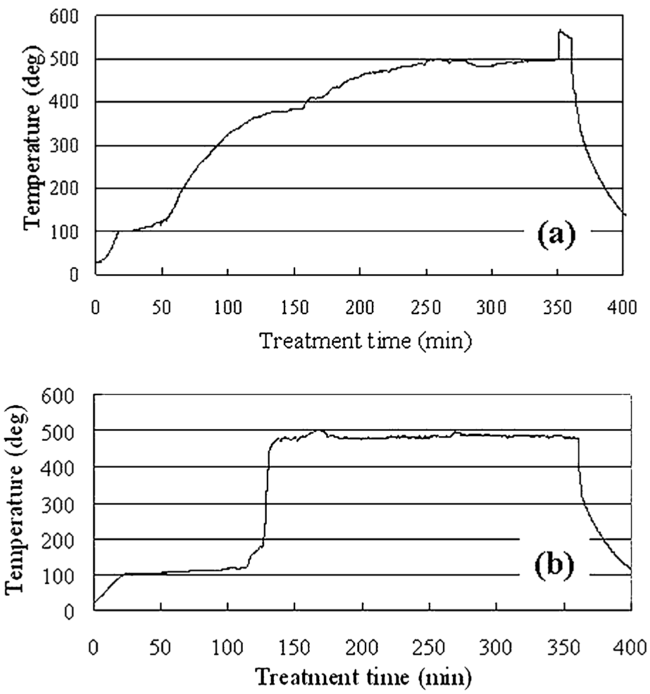

Fig. 5. Temperature profiles in the reactor for setup A (**a**) and setup B (**b**)

cates that all water vapor was removed by t = 120 min and the process succeeded more efficiently than it did for setup A. The differences in the reduction rates of the waste between setups A and B might have been caused by this mechanism.

Figure 6a,b shows images of the waste after treatment for setups A and B, respectively. Here, the treatment time (i.e., the application of MW power and the heaters) was 8 h. For setup A, it is seen that the four-sided area in the reactor is not completely treated. On the other hand, for setup B, it was found that the waste was entirely and uniformly treated. The advantage for setup B might be ascribed as follows. The thermocouple, like a needle rod, is mounted in the center of the reactor. As the thermocouple is covered by a stainless steel rod, microwave energy can concentrate at the thermocouple. Heat energy obtained at the thermocouple is diffused to the wall. For the case of setup A, as the shape of the wall is square, the treatment of the waste positioned at the four corners was insufficient. In contrast, for setup B, uniform treatment of the waste was realized as a result of the effect of the copper cylinder, because the shape of the wall is curved. The ash produced after the treatment was fibriform carbide, including a charcoal component. In the future, a detailed analysis of the ash will be conducted.

Conclusions

The treatment of waste without the emission of CO and CO_2 is required from a viewpoint of environmental protection. A reactor for paper-based waste treatment was developed with hybrid heating using MW energy and an electric heater. A copper cylinder mounted in the reactor played an important role in processing the paper-based waste completely. The reduction rates for the reactor with and without the copper cylinder were found to be less 10% at t > 3 h. When a copper cylinder was used (setup B), the reduction rate of the waste weight reached about 3%. In the future, plastic syringes and needles will be managed by the addition of treatment facilities for the exhaust gas.

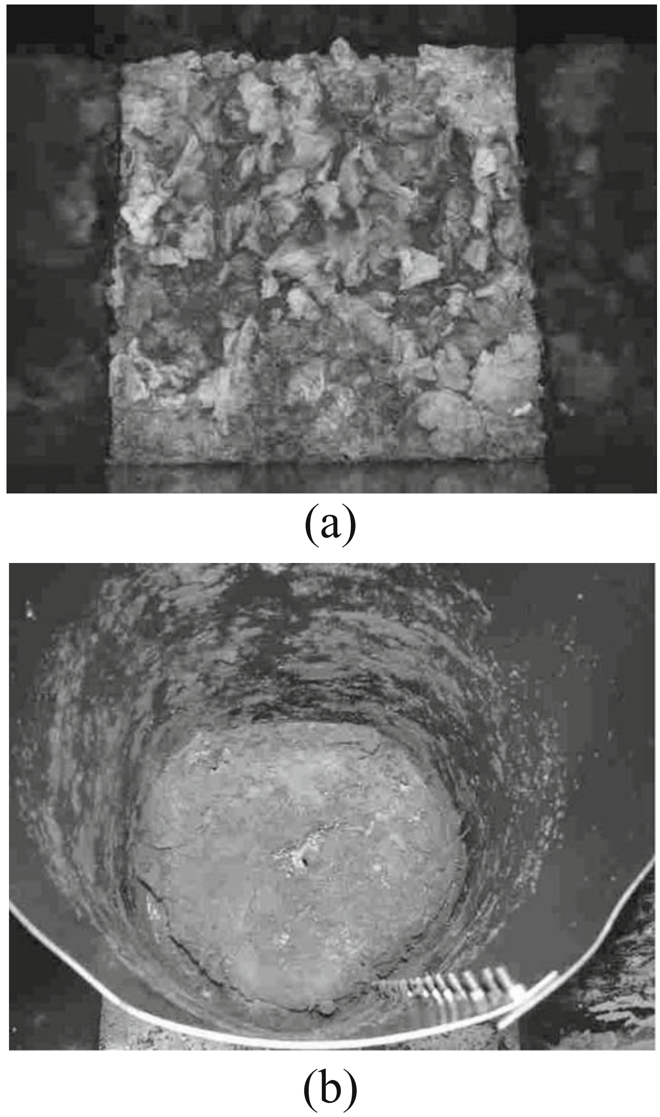

Fig. 6. Images of the treated wastes for setup A (**a**) and setup B (**b**)

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