Experimental Study on the Heating Effects of Microwave Discharge Caused by Metals

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The heating effects of discharge triggered at the appearance of metals are important under microwave irradiation but special studies have rarely been carried out. In our experiments, the heat generation was successfully isolated by embedding metal in quartz sand and measured through an indirect calorimetric method. All the experiments and analyses indicate that the discharge triggered by metals under microwave irradiation has remarkable heating effects. The microwave power, irradiation time, metal amount, and atmosphere are all important factors to influence the discharge intensity and then the heating effects. The understanding of the effects of metal discharge will help us to further research on the treatment of solid waste, such as the microwave pyrolysis of electrical waste. It may also be a good idea to use the discharge phenomena and their heating effects by embedding some metals to the microwave field in some certain applications. © 2012 American Institute of Chemical Engineers *AIChE J,* 58: 3852–3857, 2012
Keywords: microwave, discharge, heating effect, indirect calorimetric method

Introduction

Microwave heating is fundamentally different from the conventional heating. It can be considered as an internal heating way because electric energy is directly delivered to the microwave-absorbing media through their molecular interaction with the electromagnetic field. Microwave can penetrate the heated objects and different materials may show diverse microwave-absorbing properties, resulting in volumetric and selective heating. The featured heating way evokes a lot of concerns from scientists and engineers. So far, applications of microwave processing have been widely developed in physical and chemical fields, such as processing of solution and suspension, drying, organic material burnout, clinkering, sintering of ceramics and ceramic composites, preparation of specialty ceramics, plasma processing, processing of polymers and polymer composites, fabrication of functionally graded materials, joining, fiber drawing, melting, reaction synthesis of ceramics, and so on.[1–16] The various applications have revealed different advantages of microwave heating from conventional heating methods.

In recent years, the microwave processing has been used to treat different solid wastes, including waste scrap tire, plastic wastes, biomass, municipal solid wastes, electronic wastes, and so forth and shows great application potentials.[10,17–20] Our working group is just carrying out research on the recycling of electronic wastes through microwave processing and find that microwave-induced pyrolysis combined with a featured mechanical processing is a very efficient way to recycle these wastes.[21–24] In our studies, the organic compositions in electronic wastes can be recycled in the form of energy and the metals can be effectively recovered.

Because electronic wastes usually contain a big fraction of metals, intense discharge phenomena are observed during microwave-induced pyrolysis. According to the common knowledge, metal cannot be put into microwave oven to avoid any possible discharge or microwave reflection. However, the appearance of metal is unavoidable in our treatment of electronic waste, and therefore, its effects cannot be neglected. Besides the sparkling, we also notice some special phenomena in our experiments. For instance, the existence of metals can lead to pyrolysis enhancement, formation of local hot points as well as local melting. Similar to our observations, Pert et al.[25] also noticed that the insertion of a thermocouple could lead to field enhancement, local dielectric breakdown, or ohmic losses in the thermocouple sheath. These all findings indicate that the heating effects of metals in microwave field have to be paid enough attention to.

Some literatures have involved the metal–microwave interaction in microwave heating to some extent.[26–28] For instance, some theoretical investigations of microwave heating with/without metallic support or plate were done and it was found that various shapes of metallic support played important roles in optimizing heating effects.[26,29–31] Hussain found that the interaction of microwaves with iron produced heat and the temperature rose to the range of 1100–1200°C and even up to the melting point of iron.[27] Mishra et al.[32] and Rybakov et al.[33] theoretically analyzed the behavior of microwave heating in metal powder and concluded that electric field E could be induced on metal powder surface and subsequently surface current might be generated to release Joule heat. However, there is no special concern and rare

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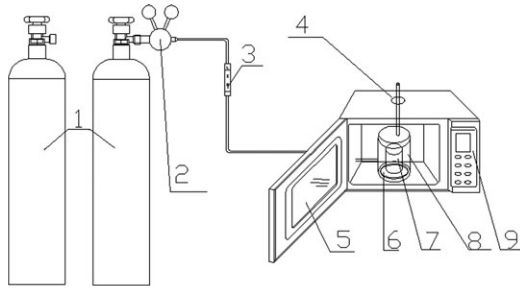

Figure 1. The experiment setup for microwave discharge: (1) compressed air (nitrogen) cylinder, (2) cylinder valve, (3) glass rotameter, (4) exhaust gas tube, (5) inspection window, (6) asbestos plate, (7) reaction vessel, (8) pressure vessel, and (9) touch control microwave oven.

experimental studies have been conducted until now to investigate the heating effects of microwave discharge caused by the appearance of metals under microwave irradiation.

This work isolates the role of metals in microwave field and specially studies the heating effects of discharge caused by the appearance of metal through a series of experiments. The results will help us further understand the process of microwave discharge and the effects of metal. If the microwave discharge can be sufficiently used, the treatment of solid wastes such as electronic waste may be better organized.

Experiments

Experimental setup

A commercial household microwave oven (Galanz Model P70D20TP-C6) was reconstructed and used in the experiments. It had an input power of 1300 W and a frequency of 2450 MHz. The output power of the microwave oven can be changed from 0 to 800 W at the interval of 10% of the total power, and the irradiation time can be set freely. A visible window on the oven door enables the observation of the discharge phenomena. A self-made transparent quartz glass crucible was used as the reaction vessel, which could withstand the temperature up to 1450°C. The internal diameter of the crucible was 50 mm and the height was 80 mm. Under the crucible, an asbestos plate was fastened on the microwave oven chassis to insulate the vessel and reduce the direct heat conduction. During the experiments, to investigate the influence of atmosphere, air or nitrogen was released from the cylinders and entered a pressure vessel (see Figure 1), in which the crucible was placed, and therefore, the different atmosphere conditions could be obtained. A schematic diagram of the experimental setup is shown in Figure 1.

Table 1. The Physical and Chemical Properties of the Quartz Sand

Physical Properties			Chemical Properties		
Items	Units	Data	Items	Units	Data
True density	g/L	2660	Boiling point	°C	2550
Breakage rate	%	0.53	SiO_2	%	>99
Wear rate	%	0.38	Ca	%	0.02
Porosity	%	43–47	Dielectric constant		4.20
Thermal conductivity	W/m K	1.22	Fusing point	°C	1480

Experimental methods

The goal of our experiments is to reveal the heating effects of microwave discharge caused by metals. Then, the function of metals must be isolated. Our design is to eliminate any absorption of microwave by other materials and measure the heat generated only by interaction between microwave and metals.

The reaction crucible was filled with high-purity quartz sand, which had the average diameter of 1–2 mm and acted as the heat accumulating medium. The physical and chemical properties of the quartz sand are shown in Table 1. Because quartz has very low dielectric constant, it can be considered that microwave can penetrate it with little energy loss. Its low-thermal conductivity enables the maximum capture of heat generated by the microwave discharge.

Stainless-steel strips from a drilling machine were selected as the representative metals to excite discharge in microwave field. The shapes and appearances of the strips are shown in Figure 2. From Maxwell's equation, the metal conductor has the universal ‘‘skin effect’’ in the electromagnetic field, and the penetration depth of electromagnetic energy in bulk metal samples is micron sized. Microwave does not effectively couple with bulk metal as they reflect microwaves.[34] Steinberg et al.[35] found that the factor of the metal strip that affects the microwave inductance most strongly is the length l, whereas the width w has a much weaker influence and the strip thickness t can be neglected completely at $t \ll w$. Moreover, intense discharge phenomena could always be observed when long, thin metal strips were used in our previous experiments. Therefore, in this experiments, some thin, spiral stainless-steel strips, which had the same shapes (see Figure 2) with the thickness of 0.2–0.3 mm, the length of 6–6.5 cm, and the width of 3 mm, were used for discharge stimulation. During experiments, the strips were entirely buried in the quartz sand without terminals exposed to the air.

Meanwhile, a Tongfang wireless KWH meter, which has a resolution capacity of 0.0001 kWh, was used in the experiments to record the electrical energy that was inputted into the microwave oven. At the end of each experiment, the temperature of outer wall of the quartz crucible was measured by a noncontact infrared thermometer immediately. Because the temperature of quartz sand was not uniform after microwave discharge, it was not suitable to obtain the heating effect through direct measuring of temperature rise

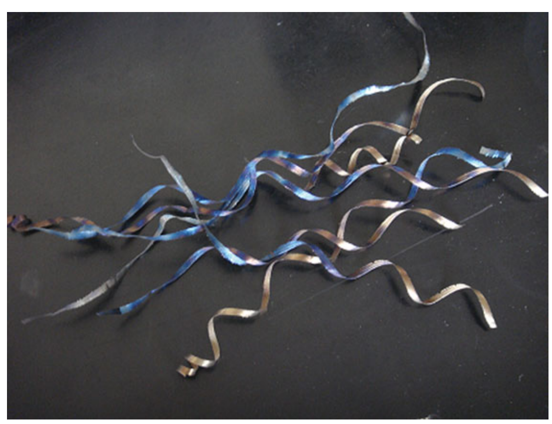

Figure 2. The metal materials used in the test.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

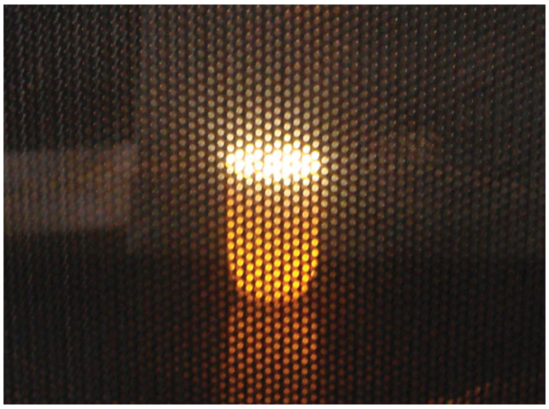

Figure 3. The discharge phenomenon in microwave oven.

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of the sand. Accordingly, an indirect calorimetric method was adopted, which is introduced in detail in ''Indirect calorimetric method'' section.

The effects of microwave power, irradiation time, numbers of iron strips, and atmosphere types were all investigated in our experiments. Moreover, to minimize the errors, any group of experiments was repeated at least five times and the average results were reported.

Indirect calorimetric method

The heat generated by the microwave discharge will cause the rise of temperature of the quartz crucible, the sand, and the iron strips. Then, to study the heating effects, the heat accumulated by all the media should be counted. The convenient indirect method might be to put the whole reaction vessel into some water and measure the temperature rise of the water. However, to avoid the breakage of the glass crucible, we only poured the hot metal strips and quartz sand into water but calculated the heat accumulation of the crucible according to its temperature rise.

The whole process was as follows: 0.5 L DO water was taken in a 1-L vacuum cup, which could be regarded adiabatic; the initial temperature of water was recorded as t_1; after each discharge experiment, the temperature of outer wall of the crucible was recorded as t_3, and the hot metal strips and quartz sand were poured into the water quickly and the final stable water temperature t_2 was measured by a mercury thermometer. The masses of crucible, quartz sand, and metal strips were obtained before microwave irradiation, and the final temperatures of quartz sand and metal strip were considered accordant with that of water in the cup after sufficient mixing. Finally, the heat generated by the microwave discharge could be obtained using the following formula

$$Q = \frac{4.187V(t_2 - t_1) + 0.55M_c(t_3 - t_0) + 0.756M_s(t_2 - t_0) + C_iM_i(t_2 - t_0)}{1000} \quad (1)$$

The above method also has some limitations. In fact, the temperature rise of crucible is not entirely uniform, so the adoption of single value t_3 may bring about some errors for its calculation of heat. However, the calorimetric accumulation of the crucible only takes up a small fraction, 8% at the most, of the totally generated heat; therefore, the above approximation is acceptable.

Results and Discussion

When stainless-steel strips were inserted in the quartz sand, intense discharge phenomena were observed under microwave irradiation in all the experiments. The photograph in Figure 3 partially shows the typical discharge view although the visible window weakens the photographing to some extent. Figure 4 is the common appearance of the stainless-steel strips after experiments. The partial melting of the strips and their bonding with the sand reveal that the local temperature should be very high during discharging.

Through our indirect calorimetric method, some regular rules were found for the heating effects of microwave discharge caused by the appearance of metals. The effects of microwave irradiation time, amounts of metal trips, microwave output power, and atmosphere are introduced, respectively, as follows.

The effect of microwave irradiation time

To investigate the effect of microwave irradiation time, the microwave output power was fixed at 720 W and the irradiation time was changed within 1–5 min. In each batch of experiments, the same numbers of stainless-steel strips, which almost had the same shapes, were placed at the

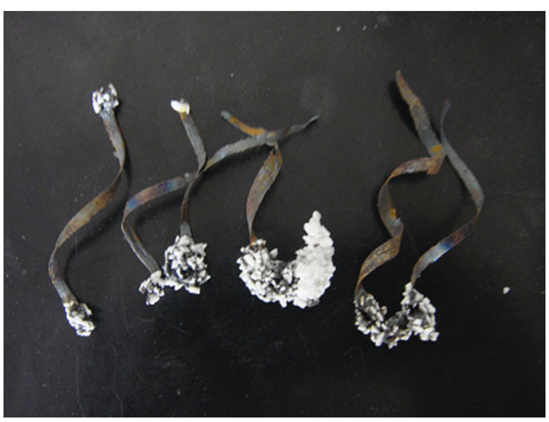

Figure 4. The appearances of the stainless-steel strips after microwave discharge.

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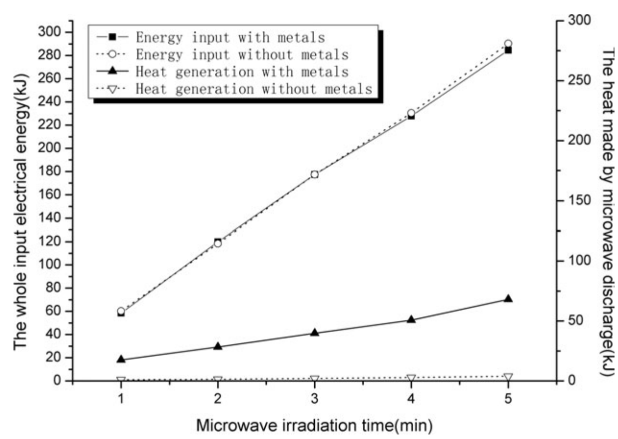

Figure 5. The changes of heat accumulation and input electric power to irradiation time.

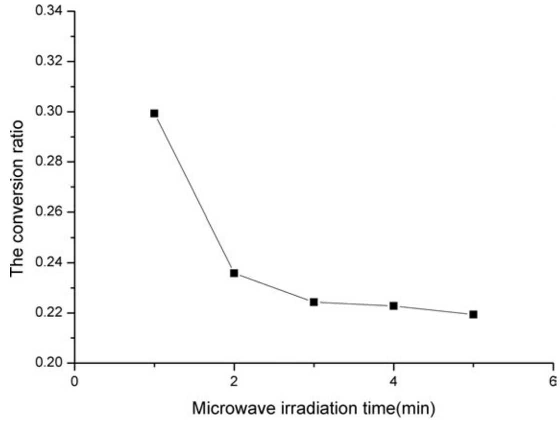

Figure 6. The changes of conversion ratio from electrical energy input to heat of microwave discharge.

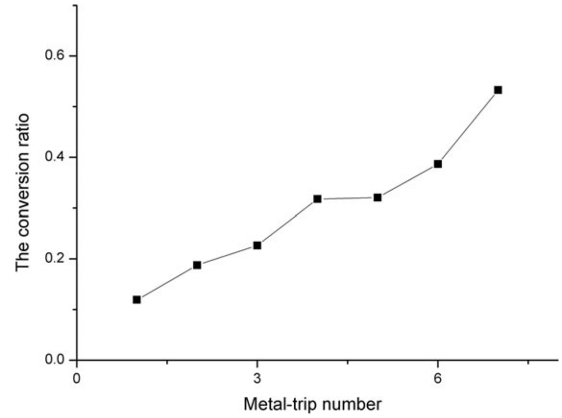

Figure 8. The change of energy conversion ratio with the increase of metal strips.

possibly same positions in the quartz sand and the generated heat was recorded.

Figure 5 shows the effect of irradiation time on the microwave discharge in terms of heat accumulation. The upper two lines are the electrical energy consumptions recorded by the KWH meter. Both lines are linear, which means the energy input was very stable during the experiments. In view that the two lines nearly overlap, it can be inferred that whether metal embedded in the sands or not has little effect on the electrical energy input. The lower two lines are the changes of heat accumulation, which were generated by the microwave discharge and recorded by our indirect calorimetric method. It can be seen that, when no metal is embedded, the heat accumulation of quartz sand is almost negligible and changes little with the extending of irradiation time. It indicates that the quartz sand performs very well to let microwave penetrate and that our isolation of the metal discharge is successful. Then, in this case the inputted electrical energy should have mostly dissipated without any effective absorption or utilization. However, in the case of metal embedded, obvious heat accumulation can be seen in Figure 5. In the direct experimental recording, the maximum temperature rise of water could amount to about 20 K and some local points of the quartz sand rose more than 100 K. All the observation verifies that the heating effect of metal discharge cannot be ignored. The line of heat accumulation rises steadily indicates that the metal discharge should be continuous with the irradiation time elapsing.

Figure 6 gives the changes of conversion ratio from electrical energy input to heat of microwave discharge. The energy conversion ratio varies from 30 to 22%. The decline of the line with time can be attributed to the weakening of discharge. Although the discharge phenomena were continuous during the experiments, much more intense sparkling view was observed in the initial 1 min than that during the following period. The partial melting of the steel strips should be the main reason of weaker discharge and less heat generation.

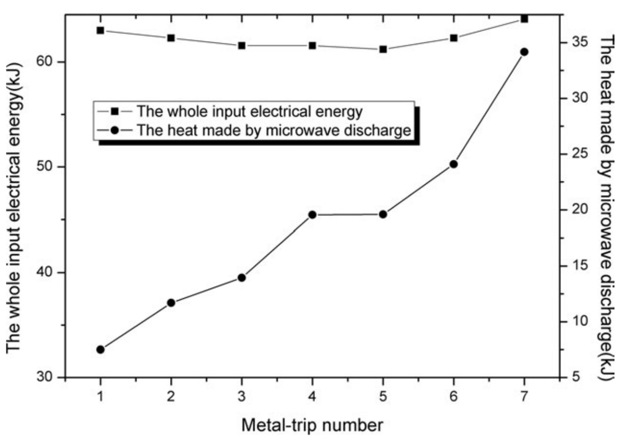

Figure 7. The effect of the number of stainless-steel strips.

The effect of the number of stainless-steel strips

The number of stainless-steel strips inserted in the quartz sand was found to be another factor that affects the heat accumulation. In the experiments to study its effect, the input microwave power was fixed at 720 W and the irradiation time at 1 min. Figure 7 illustrates the results. It can be seen that the heat accumulation rises significantly when the number of metal strips increase from 1 to 7. However, the electrical energy input is almost unchanged, indicating that it is not influenced by more insertion of metal strips. In Figure 7, when seven stainless-steel strips are inserted, nearly 40 kJ heat is generated by the microwave discharge according to our indirect measuring. Because the temperature of metal and quart sand was already very high, no more metals had been added to avoid the breakage of the glass crucible. With the increase of number of metal strips, more intense discharge phenomena were observed during the experiments.

Figure 8 gives the energy conversion ratio from energy input to heat accumulation. With the increase of strip numbers, higher-conversion ratio can be observed clearly. At the insertion of seven strips, as much as 53% of the inputted electrical energy can be converted to heat through metal discharge. The results also prove that more metal strips can trigger more discharge as well as more heat generation.

However, the weight of metal strips may not be a predominant factor that influences the discharge. Table 2 gives the

Table 2. The Relationship between the Numbers and the Weights of Metal Strips

Number of Strips	1	2	3	4	5	6	7
Weight of strips(g)	0.39	1.27	1.55	2.02	3.29	3.17	2.93
Heat energy(kJ)	7.51	11.69	13.95	18.56	19.60	24.09	34.15

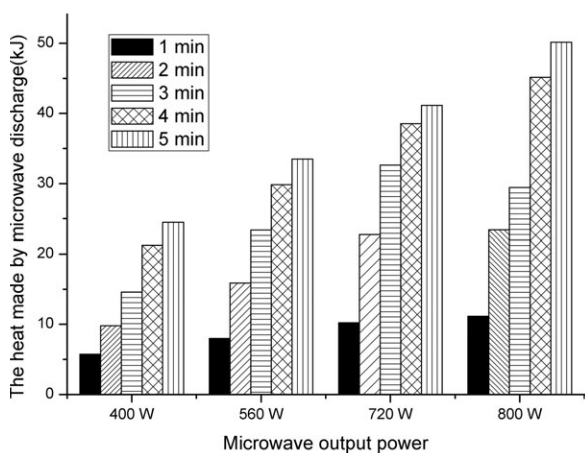

Figure 9. The heating effect of different microwave power.

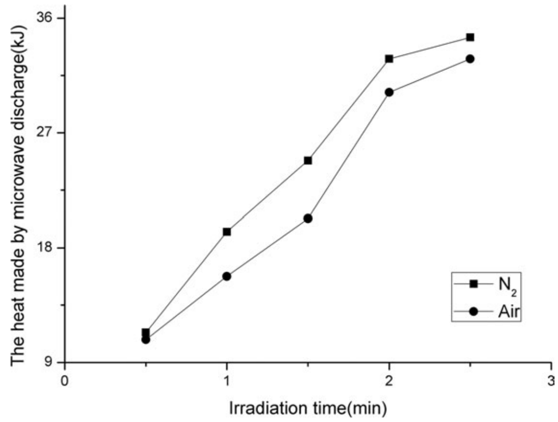

Figure 11. The change of heating effect in N_2/air atmosphere.

weight of the different numbers of strips used in the experiments. Because the sizes of the strips are not entirely uniform, more strips do not definitely show bigger weight values. No clear link between the heat accumulation and the weight of strips can be found by comparing the data.

The effect of microwave power

The influence of microwave power on the heating effects of microwave discharge was also investigated. Figure 9 shows the results. In this investigation, five stainless-steel strips were always inserted in the quartz sand and they were placed nearly at the same locations as shown in Figure 10. The output power of microwave oven was changed among 400, 560, 720, and 800 W, and the irradiation time was fixed at 1, 2, 3, 4, and 5 min, respectively.

The multiset bar chart shows a summary of the effects of microwave output power on the heat generation. It can be found that the heat accumulation rises with the increase of irradiation time at a certain output power, and that it also rises with the increase of output power at a certain irradiation time. When the microwave output power is 800 W, the heat accumulation measured can reach up to 50 kJ at the irradiation time of 5 min. Conclusively, bigger output power of the microwave oven may trigger more metal discharge too.

The effect of atmosphere

Generally speaking, the discharge phenomena triggered by metals in microwave field are mainly due to gas breakdown. All the above experiments were carried out in the atmosphere of air, with air in the crucible at the normal atmospheric pressure. To investigate the effect of atmosphere, a flow of air or N_2 and a pressure vessel were used as shown in Figure 1. Still, five stainless-steel strips were inserted in the quartz sand according to the placement shown in Figure 10. The output power was fixed at 800 W and the irradiation time varied within 0.5–2.5 min at the interval of 0.5 min. The gas flow rate was both set at 1 L/min. As the gas flow was very small and the surface temperature of the crucible was not high, the heat taken away through convection could be considered equal and had not been taken into account in the calculation of heat accumulation.

Figure 11 shows the difference of heating effects of microwave discharge at N_2 and air atmospheres. It can be seen both the two curves rise rapidly with the increase of irradiation time. However, the heat accumulation in N_2 is always a bit higher than that in air. No across point emerge means the regularity can be assured. Figure 12 is the conversion ratio from inputted electrical energy to heat accumulation. Clearly, the microwave discharge in N_2 shows higher-energy conversion ratio than that in air. Thus, it can be concluded that, under the same experimental conditions, N_2 atmosphere can help to trigger more intense metal discharge compared to the air. The phenomena may be attributed to the ionization characteristics of different media but more work is needed to unveil the mechanism.

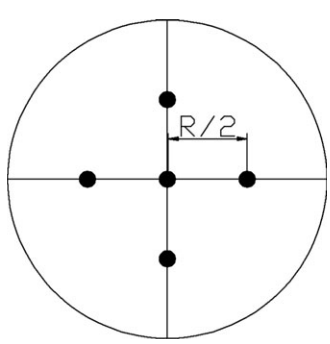

Figure 10. The placement of metal strips in the crucible.

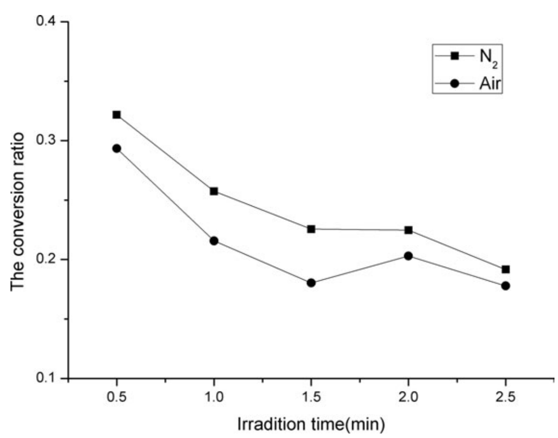

Figure 12. The conversion ratio change to time in N_2 and air atmosphere.

Conclusions

All the experiments and analyses indicate that the discharge triggered by metals under microwave irradiation has remarkable heating effects. The microwave power, irradiation time, metal amount, and atmosphere are all important factors to influence the discharge intensity and the consequent heating effects. To study the heating effects of microwave discharge, the successful isolation of heat generation in our experiments is important and the indirect calorimetric method is also proved to be an effective way to measure the heat. The whole process provides a valuable solution for the similar scientific problems.

In the experiments, the local temperatures of the metal strips were not obtained because of the complexity of the microwave discharge and the difficulty of direct measuring. However, it can be inferred that at some local hot points 1000°C has been exceeded according to the melting of iron. Therefore, the local temperature is fairly high and the heating effect is amazing. The understanding of the effect of metal discharge will help us to further research on microwave pyrolysis of electrical waste. Perhaps, it is also a good idea to use the discharge phenomena and its heating effects by embedding some metals to the microwave field in some certain applications. The application of some foreign metallic media may be useful to focus energy for a controlled microwave heating.

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Notation

C_i = the heat capacity of metal, kJ/kg·K
M_c = the mass of the quartz glass crucible, g
M_i = the mass of the metal strips, g
M_s = the mass of the quartz sand, g
Q = the heat made by microwave discharge, kJ
t_0 = the ambient temperature, K
t_1 = the initial temperature of tap water, K
t_2 = the average temperature of the mixture, K
t_3 = the outer wall temperature of beaker, K
V = the volume of water, cm^3

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