Effect of Water Content on Thermal Decomposition and Gasification of Waste with Water-Absorbent Polymer

Yasuo Yamamoto1, Masahiro Saito1, Tomohiko Furuhatat and Masataka Arai1

1. Department of Mechanical System Engineering, Graduated School of Engineering, Gunma University, 1-5-1 Tenjin-cho, Kiryu-shi, Gunma, 376-8515, Japan

Abstract: The effect of water content on thermal decomposition characteristics of watery waste material were studied experimentally. In order to clarify the effect of water content on thermal decomposition process of disposal paper diaper with water-absorbent polymer, a piece of water-contained diaper was decomposed in an image furnace. It was found that the initiation time of thermal decomposition was delayed with increasing the water content, and thermal decomposition period became long compared with that of the dry sample. In the O2=0% condition, mass reduction was slower than that in the case of O2=21% and slow mass reduction occurred in the high temperature condition. Furthermore, the peak emission of HC in the decomposition process increased slightly with increasing the water content. In the case of the dry sample under the O2=21% condition, HC and CO were emitted simultaneously in the decomposition process. On the contrary, in the water-containing cases and O2=0% condition, the peak emission of HC appeared after the CO emission regardless of water content.

Keywords: Thermal Decomposition, Gasification, Waste Material, Water-Absorbent Polymer, Cellulose, Moisture Ratio

1. INTRODUCTION

Incineration treatment is useful to reduce the volume of waste, and it is effective for thermal recycling of waste materials [1]. However, the water-containing waste may damage a furnace with the steam emitted by combustion, and it has possibility to generate the harmful substances such as dioxin by lowering combustion temperature when it contains chlorine. In order to dispose these waste safely and pollution-free, it is necessary to clarify the thermal decomposition and gasification characteristics of watery waste, and to find the suitable disposal method. However, the effect of water content on thermal decomposition characteristics has not been clarified quantitively [2].

In this study, the effect of water content on thermal decomposition process of disposal paper diaper with water-absorbent polymer was investigated. Small diaper piece (0.2g) containing water up to 30 times of initial mass of dry sample was used for thermal decomposition test. Mass reduction, ambient temperature, and gas components were measured, and the relations between water content and mass reduction, generation of gas components were analyzed. The objective of this study was to identify the effect of water content on thermal decomposition and gasification processes of watery material quantitatively.

2. EXPERIMENTAL SETUP AND METHOD

2.1. Sample material

In this study, disposal paper diaper with water-absorbent polymer was prepared as the test material. As for the water-absorbent polymer, sodium polyacrylate grains are enveloped in the layer of pulp sheets. However, we have no more detailed data of the polymer. Cellulose is the basis of pulp which consisted of 40% of diaper piece. The physical properties of cellulose are shown in Table 1 [3]. Decomposition temperature of cellulose is 523K.

Initial mass of sample was set to 0.2g (15mm × 15mm). Tap water was added to obtain a water-containing sample. The moisture ratio, Cw, was defined as follow.

\[ C_w = \frac{M_{\text{water}}}{M_{\text{diaper}}} \]  

\[ \text{(1)} \]

\( M_{\text{diaper}} \) is the initial mass of dry sample, and \( M_{\text{water}} \) is the mass of water added to the sample. In this experiment, the moisture ratio was changed from 0 to 30. The dry sample (\( C_w=0 \)) contained a little water because water-absorbent polymer absorbed humidity. The sample diaper was swelled with the absorbed water. The apparent surface area of the sample with \( C_w=30 \) was about 4 times of the dry sample.

<table>
<thead>
<tr>
<th>Physical properties of cellulose</th>
<th>17430 kJ/kg</th>
<th>673 K</th>
<th>523 K</th>
<th>1545-1585 kg/m³</th>
<th>1.22 kJ/(kg K)</th>
<th>0.071 W/(m K)</th>
</tr>
</thead>
</table>

2.2. Experimental setup

The outline of the experimental setup is shown in Fig.1. In order to clarify thermal decomposition and gasification characteristics of the test material, an image furnace was used. A quartz pipe was installed vertically in the center of image furnace, and gas (air or nitrogen) stream was introduced from the bottom of the quartz pipe. Average gas velocity (\( V_g \)) at the bottom was 0.88 m/s. Test mate-
rial put on a holding plate was inserted from the top of the quartz pipe. Details around the sample are shown in Fig.2. A Pt-PtRh13% thermocouple was set up at 7mm under the holding plate in order to control the temperature around the sample. A chromel-alumel thermocouple was set up at 25mm upper position of the sample to measure the surrounding gas temperature around the sample during the experiments. A radial temperature distribution in the pipe was checked using the chromel-alumel thermocouple at 25mm upper position during a heating up process. As the result, the radial temperature distribution was nearly flat [4]. It was inferred that the surrounding gas was heated uniformly by the image furnace. In this experiment, the temperature measured at 25mm upper the holding plate was used as the ambient temperature of the sample.

Mass reduction during thermal decomposition was measured by using an electric micro-balance (AND Ltd, HX-100). Analog outputs from the electric micro-balance and thermocouple were taken in a computer with A/D converter and analyzed. Also the gas components such as HC(C1-C6), CO and CO2 were sampled and analyzed with gas analyzer (Horiba Ltd, MEXA 4000 FT). In order to measure exactly gas concentrations during thermal decomposition, it was necessary to clarify the radial concentration distribution of gases in the quartz pipe. The sampling position was traversed to radial direction at the exit of quartz pipe and the concentrations of gas components were measured. As the result, all gas components on radial direction had nearly uniform distributions [4]. Therefore, sampling probe was fixed at the exit on the inner side of quartz pipe. The generation rate of each gas components was calculated from the measured concentration and total gas flow rate.

3. RESULTS AND DISCUSSION

3.1. Effect of moisture ratio on mass reduction
Thermal decomposition experiment under constant temperature condition was carried out. Figure 3 shows the results of mass reduction. $T_a$ is the ambient temperature. Time scale had changed with the variation of ambient temperature. In the case of (a) $T_a=373K$, the mass reduction proceeds with long period and then reached to the initial mass of diaper. It was considered that water evaporation was only occurred because ambient temperature was below the decomposition temperature of cellulose (523K). In the case of (b) $T_a=523K$, mass reduction of water evaporation and thermal decomposition were occurred. And mass reduction reached to the 30% of initial mass of diaper. In the case of (c) $T_a=873K$, mass reduction proceeded rapidly and stopped about 15% of initial mass of diaper. The ambient temperature was considerably high compared with decomposition temperature of cellulose.
Therefore, it was considered that thermal decomposition and water evaporation occurred simultaneously.

Figure 4 shows the relation between moisture ratio and maximum mass reduction rate under constant temperature condition. Maximum mass reduction rate was calculated from the inclination of mass reduction. In the case of $T_a=373K$, the evaporation of water was mainly occurred. The maximum mass reduction rate increased steeply in the region of $C_w=0-5$, but the rate increased slightly $C_w=5-30$. In the case of $T_a=523K$, water evaporation and thermal decomposition were occurred. The open symbol indicates the maximum mass reduction rate in the evaporation region and the solid symbol indicates the rate in the thermal decomposition region. Primary mass reduction region was defined as evaporation region, and secondary mass reduction region was defined as thermal decomposition region. The maximum mass reduction rate in evaporation region for $C_w=0$ was 10 times of that at $T_a=373K$. However, the moisture ratio hardly affected the maximum mass reduction rate in the thermal decomposition region. As for the $T_a=873K$, thermal decomposition and water evaporation could not be distinguished. The maximum mass reduction rate of $C_w=0$ was almost 10 times of the maximum mass reduction rate in evaporation region at $T_a=523K$. And it increased with increasing the moisture ratio. It seemed that the maximum mass reduction rate at $T_a=873K$ was mainly caused by the water evaporation.

From these results, it was considered that mass reduction rate in evaporation region increased with increasing the water content because surface area of sample increased with increasing the water content.

### 3.2. Effect of oxygen concentration on thermal decomposition

Thermal decomposition experiment was carried out under temperature raising condition. The rate of temperature rising was controlled 20K/min by heat-up program. Since this rate was lower than decomposition rate, a start of thermal decomposition could be defined. Thermal decomposition experiments of $C_w=0$ sample was performed in $O_2=21\%$ and 0% conditions. The results were shown in Fig.5. The solid line in the figure indicates the variation of ambient temperature.

In the case of $O_2=21\%$, slow mass reduction started with rising the temperature. This slow mass reduction was due to the evaporation of a little water which contained in dry sample. The rapid mass reduction appeared around 600s with the temperature of 520K. The initiation temperature of rapid mass reduction was almost equal to the decomposition temperature of cellulose (shown in Table 1). Therefore, it seemed that the mass reduction of sample was started from the part of cellulose. The mass of remains was 13% of the initial mass of diaper.

In the $O_2=0\%$ condition, the rapid mass reduction also appeared around 600s with the temperature of 520K. However, the mass reduction rate of rapid mass reduction region became slow compared with that of $O_2=21\%$ because no exothermic reaction by oxidation between ambient gas and sample was existed. It seemed that thermal decomposition proceeded from surface toward inside of sample. Since the carbon layer which formed on the surface of sample prevented the heat transfer, mass reduction stopped once after the rapid mass reduction. And then, the gradual mass reduction was occurred in the high temperature condition. The un-reacted substances were existed in the sample, since thermal decomposition became slow. Therefore, it was considered that the gradual mass reduction corresponded to the secondary decomposition of un-reacted substances in high temperature condition. The mass of remains was almost equal to that of $O_2=21\%$. It seemed that un-reacted substances were almost decomposed because they were exposed to high temperature ambient for a long period.

Figure 6 shows the photograph of remains after thermal decomposition. In the case of $O_2=21\%$, many white ashes remained after thermal decomposition finished. From this result, it was found that the sample was oxidized by surrounding air. On the other hand, in the $O_2=0\%$ condition, gray ashes were remained after thermal decomposition.
decomposition. As mentioned before, it was considered that slight carbon was contained in the remains, since thermal decomposition became slow compared with $O_2=21\%$.

### 3.3. Effect of moisture ratio on thermal decomposition

Figure 7 shows the effect of moisture ratio on mass reduction in the thermal decomposition experiments under $O_2=21\%$ condition. Fig. 7 (a) is the global view of mass reduction, and Fig. 7 (b) the enlargement of thermal decomposition region. Mass reduction rate during the rapid mass reduction increased with increasing the moisture ratio. It was considered that the rate of water evaporation increased with increasing the moisture ratio because the surface area of sample became large with increasing the water content. By observing the completion time of mass reduction, thermal decomposition period became long with increasing the moisture ratio. It was inferred that temperature rise of sample was prevented by the latent heat of water evaporation. The mass of remains was 13-18\% of initial mass of diaper.

Figure 8 shows the result of $O_2=0\%$ condition. The effects of moisture ratio on mass reduction rate during rapid mass reduction were similar to $O_2=21\%$ condition. And first thermal decomposition period became long with increasing the moisture ratio. Moreover, initiation time of thermal decomposition of un-reacted substances delayed with increasing the moisture ratio. It was considered that the moisture remained in the sample increased with increasing the moisture ratio. The mass of remains was 12-19\% of initial mass of diaper.

Figure 9 shows the relation between moisture ratio and maximum mass reduction rate. Maximum mass reduction rate was calculated from the inclination of mass reduction, and evaporation region and thermal decomposition region were distinguished by gas components generated or not. In the case of $O_2=21\%$ condition, the maximum mass reduction rate of $C_w=0, 5, 10$ appeared during thermal decomposition region and the rate of $C_w=20, 30$ appeared during water evaporation region. The moisture ratio did not affect the maximum mass reduction rate in decomposition region. However, the maximum mass reduction rate in water evaporation region increased with increasing the moisture ratio.

In the $O_2=0\%$ condition, maximum mass reduction rate of thermal decomposition region was appeared only $C_w=0$ sample, and this mass reduction rate was about 20\% of $O_2=21\%$ condition. As mentioned before, it was the reason that oxidization of the sample was not occurred in nitrogen atmosphere. Maximum mass reduction rate in...
water evaporation region increased with increasing the moisture ratio, and it was similar to that of O₂=21%. Therefore, it seemed that oxygen concentration did not affect maximum mass reduction rate in water evaporation region.

3.4. Effect of moisture ratio on gasification

Gas analysis during mass reduction experiments for C₆=5 sample was performed in the case of O₂=21% and 0% condition. The results of gas analysis in the decomposition processes are shown in Fig.10. In the O₂=21% condition, CO, CO₂, and HC(C₁-C₆) were detected during the mass reduction. The generation rate of these gas components was highest in the rapid mass reduction period. The mass when the gas components generated exceeded the initial mass of diaper. It was conjectured that the thermal decomposition and oxidation of cellulose occurred before the complete water evaporation. Thus, the mixture of water vapor and gas components were evolved simultaneously.

As for the O₂=0% condition, slight amount of CO₂ was detected and generation rate of HC and CO were slower than that in the O₂=21% condition. Further, CO was generated again during the slow mass reduction region. The generation of CO and CO₂ in the O₂=0% condition was caused by the oxygen contained within the sample.

The results of O₂=21% and O₂=0% condition are shown in Fig.11. In the case of O₂=21%, and C₆=0, peak generation rate of HC and CO were investigated. The generation time of these gas components continued for a long period with low generation rate. Concerning the first emission of CO, it was thought that the moisture ratio did not affect the amount of CO. As for the secondary emission of CO, it was also inferred that the amount of CO which generated by the reaction between oxygen and carbon that were contained in un-reacted substances was not affected by the moisture ratio. On the other hand, peak generation rate of HC increased linearly in proportion to the increase of moisture ratio. It was considered that the generation of HC was promoted in the gas phase by the secondary thermal decomposition in high temperature ambient because more periods required evaporating the water content with increasing the moisture ratio.

3.5. Effect of moisture ratio on generation time of gas components

The effects of moisture ratio on the generation time of CO and HC were investigated. The generation time defined as elapsed time at peak emission of gas components. The results of O₂=21% and O₂=0% condition are shown in Fig.12. In the case of O₂=21%, and C₆=0, peak emission of CO and HC were appeared simultaneously. In the no-water condition, it was considered that CO and HC were emitted simultaneously, since sample temperature rose rapidly by the exothermic reaction of oxidation. However, in the water-containing conditions, the peak
emission of HC appeared after the CO emission. In the water-containing condition, CO was generated first by the partial oxidation at the surface of sample. However, inside of the sample, thermal decomposition was occurred under the low oxygen condition by the generation of steam. Therefore, it was thought that peak emission of HC appeared after CO emission.

In the case of O₂=0%, and C_w=0, peak emission of HC and CO (peak 1) appeared later than that in the case of O₂=21%. It was considered that thermal decomposition proceeded only radiant heat from image furnace because exothermic reaction by oxidation was not occurred. Concerning the moisture ratio, difference of generation time between HC and CO (peak 1) was smaller than that in the case of O₂=21%. When the ambient atmosphere was nitrogen, it was considered that generated HC was difficult to oxidize to CO. Furthermore, observing the generation time of CO (peak 2), it delayed slightly with increasing the moisture ratio. It was thought that the moisture remained in the sample increased with increasing the moisture ratio.

4. CONCLUSIONS

The effect of water content on thermal decomposition and gasification were experimentally investigated. Main results are summarized as follows.

(1) Mass reduction rate during evaporation region increased with increasing the water content. On the other hand, mass reduction rate during decomposition region was hardly influenced with water content.

(2) Thermal decomposition temperature of the dry sample was almost equal to that of cellulose.

(3) Initiation time of thermal decomposition delayed with increasing the water content, and thermal decomposition period became long with increasing the moisture ratio.

(4) In the case of O₂=0%, the mass reduction rate during rapid mass reduction was slower than that in the case of O₂=21%, and slow mass reduction occurred again in the high temperature condition.

(5) In the case of O₂=21%, peak generation rate of gas components became slow with increasing the water content. As for the dry sample, HC and CO were emitted simultaneously. However, water-containing condition, peak emission of HC appeared after the CO emission regardless of water content.

(6) Even in the case of O₂=0%, CO was generated during rapid mass reduction region and slow mass reduction region. And peak generation rate of HC increased slightly with increasing the water content.

(7) In the case of O₂=0%, peak emission of HC always appeared after the CO (peak 1) emission regardless of water content.

REFERENCES