Improvements in Pyrolysis of Wastes in an Externally Heated Rotary Kiln (Experimental Study on Heat Transfer Enhancement)*

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Abstract

The effects of rotating speed and internal structure on the performance of an externally heated rotary kiln for waste pyrolysis were investigated. A newly developed method was adopted to evaluate the overall heat transfer coefficient k_{m-w} from the inner wall to the wastes for this purpose. The experimental results revealed that k_{m-w} monotonically increased with the number of lifters and their height. When six lifters 200 mm in height were attached to the inner wall of the kiln, the mean value of k_{m-w} increased from 38.6 W/m²K to 45.3 W/m²K at 2.7 rpm. In addition, k_{m-w} increased to 50.1 W/m²K when the rotating speed was increased to 4.0 rpm. In the water vaporization phase during the course of the pyrolysis process, the height of the lifters had a significant influence on k_{m-w} . However, the number of lifters had a significant impact on k_{m-w} in the pyrolysis phase of the plastic-based wastes. According to measurements, a 10 % increase in k_{m-w} could be obtained when installing lifters to attain a ratio of lifter height H_l to the thickness of the waste layer H_w larger than 0.45 or when arc length between two lifters L_l to the arc length of the interface between the wastes and the kiln wall L_w was larger than 1.

Key words: Recycling, Gasification, Heat Transfer Enhancement, Pyrolysis, Rotary Kiln

1. Introduction

Externally heated rotary kilns are often used for gasification systems to melt generated municipal wastes because they are easy to operate, subsidiary materials for gasification such as coke, limestone, and oxygen are unnecessary, and pyrolysis gas and char with high calorific value are produced. However, it is necessary to improve heat transfer when the required heat value increases due to the changed quantities and properties of wastes because wastes are externally heated through the kiln wall.

The overall heat transfer coefficient k_{m-w} from a kiln to the wastes is a fundamental characteristic value for evaluating heat transfer in the kiln. We established a method of measuring overall heat transfer coefficient k_{m-w} through an experiment using a batch-type kiln in a previous study ⁽¹⁾. On the other hand, numerous studies have been made on the

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rotating speed and internal structure of rotary kilns since these parameters are generally known to influence the mixing behavior and residence time of the material that pass through a kiln ⁽²⁾⁻⁽⁶⁾. However, few studies have been done on enhancing heat transfer from the kiln wall to the material layer, although radial heat conduction in there has been investigated ⁽⁷⁾⁻⁽⁹⁾.

In this study, we clarify the influence that the internal structure and rotating speed have on overall heat transfer coefficient k_{m-w} from the kiln wall to the wastes and on the required time for pyrolysis, in order to obtain design principles that enhance the heat transfer.

Nomenclature

- D : inner diameter of cylinder, m
 F : feed rate of material, kg/min
 k : overall heat transfer coefficient, W/m²K
 H : depth or height, m
 l : length of cylinder, m
 L : length of arc, m
 n : number of lifters, -
 N : rotating speed, rpm
 β : angle of repose of material, degree
 ρ : bulk density of material, kg/m³

Subscripts

- c : char
 l : lifter
 m : inner cylinder
 $m-w$: from inner cylinder to wastes
 w : wastes

2. Experimental Method

2.1 Experimental Apparatus and Structure of Pyrolysis Reactor

The experimental apparatus and the structure of the pyrolysis reactor have been described previously ⁽¹⁾.

2.2 Measurement Method for Overall Heat Transfer Coefficient

There is no established method for direct measurement of the overall heat transfer coefficient k_{m-w} . In this study, we measured it using the previously reported method ⁽¹⁾. The heat balance of the experimental system was evaluated in all experiments to check the reliability of the measured values.

2.3 Experimental Conditions

The lifters shown in Fig. 1 were installed in the inner cylinder to improve mixing of wastes. Experimental conditions are listed in Table 1. Case No. 1 was the basic condition, and No.2 was the case where the inner wall temperature of

Table 1 Experimental conditions

Case No.	Kiln wall temperature (°C)	Rotating speed (rpm)	Lifter	
			Number (-)	Height (mm)
1	555	2.7	0	-
2	630	2.7	0	-
3	555	2.7	6	50
4	555	2.7	6	100
5	555	2.7	6	200
6	555	2.7	3	100
7	555	4	0	-
8	555	4	6	200

the kiln was 630 °C. In cases 3 to 6, the height of the lifters was changed from 50 to 200 mm, and their number was either 3 or 6. Cases 7 and 8 had a kiln rotating speed of 4.0 rpm.

2.4 Method of Fixing Lifters

In the experiments where lifters were installed, boards 25 mm thick and 1,500 mm long were fixed radially on the inner wall of the kiln. Figure 1 is a photograph of the inner cylinder of a kiln. Six lifters 100 mm in height were spot-welded to the inner wall surface so as to prevent them from being heated by heat conduction.

2.5 Composition of Simulated Wastes

We used the same raw materials as in our previous paper ⁽¹⁾. By using simulated wastes we could objectively compare the results between experiments. The dry-basis composition is listed in Table 2. Before all experiments, water was added to get 10 % moisture content for the wastes. This value was based on the mean value measured between the dryer exit and the pyrolytic kiln inlet in an actual plant.

Fig. 1 Lifters fixed on the kiln inner wall

Table 2 Composition of simulated wastes

Raw material	Unit	Composition (dry weight basis)
Paper	wt%	30
Wood		25
Polyethylene (PE)		15
Polypropylene (PP)		15
Polystyrene (PS)		5
Grain		10

3. Experimental Results and Discussion

3.1 Influence on Pyrolysis Characteristics

The relationships between the elapsed time after feeding and the volume of pyrolysis gas are plotted in Figs. 2 (a)-(d). Three peaks appear in all cases. The first is the peak for the evaporation of moisture, the second is that for the pyrolysis of grain, paper, and wood, and the third is that for the pyrolysis of plastics as reported before ⁽¹⁾. We considered that pyrolysis had ended when the production of pyrolysis gas was finished. The results for the basic conditions without lifters, i.e. case No. 1 and case No. 2, are shown in Fig. 2 (a). The time required for pyrolysis was 42 min in case No. 1, but only 30 min in case No. 2. This meant pyrolysis was promoted by the increased heating temperature. The effect of lifter height on the behavior of pyrolysis is shown in Fig. 2 (b). Six lifters were installed in these cases. Increasing the height of the lifters from 50 to 200 mm reduced the time for pyrolysis from 40 to 33 min. In particular, the first and the second peaks appeared within a short time, and the evaporation of moisture and the pyrolysis of grain and paper were thought to be enhanced. The effects of the number of lifters for the 100 mm lifter height are plotted in Fig. 2 (c). The pyrolysis time was shortened from 42 to 37 min by installing three lifters and was shortened to 35 min with six lifters. The first peak was not be influenced by the number of lifters while the second and third peaks appeared within a short time by increasing the number of lifters. The effect of rotating speed is shown in Fig. 2 (d). Increasing rotating speed from 2.7 to 4.3 rpm reduced the time for pyrolysis from 42 to 38 min. Furthermore, in case No. 8 with six 200 mm lifters installed in the kiln and rotating speed increased to 4.0 rpm, the pyrolysis time was shortened to 31 min, which was almost the same as for case No. 2 where the inner wall temperature was the higher temperature, 630 °C.

Fig. 2 (a) Effect of reactor temperature on pyrolysis behavior

Fig. 2 (b) Effect of height of lifters on pyrolysis behavior

Fig. 2 (c) Effect of number of lifters on pyrolysis behavior

Fig. 2 (d) Effect of rotating speed on pyrolysis behavior

One reason why pyrolysis is promoted with the increase in rotating speed of the drum may be that solids are mixed more thoroughly in the transverse direction. The rotating speed and the material filling ratio of the drum in a commercial kiln are selected to make the material layer flow transversely in what is called “rolling” or “cascading”⁽¹⁰⁾. In the rolling state, solids continuously flow on the edge of the waste layer, while the core remains in the layer’s center. The heating speed in the core is slower than that on the edge because heat is only transferred by conduction⁽⁷⁾. By contrast, radiation and convection are the main paths of heat transfer in the cascading state because the whole layer is flowing constantly due to the high rotating speed. We considered that pyrolysis was accelerated due to the mixing of the core materials by the lifters attached to the drum as much as when the rotating speed was increased. It is known that the transfer rate of the material that pass through a kiln increases and the residence time decreases with increasing rotating speed in a continuous-type kiln^(4,5). Therefore, there is the possibility that, when the rotating speed is increased too much, the wastes pass through the drum before they are pyrolyzed entirely. On the other hand, it has also been reported that the residence time of the material in a kiln with lifters is much longer than that in a kiln without lifters⁽⁵⁾. From the above, we can see that the combination of lifters and increased rotating speed effectively improves pyrolysis.

3.2 Influence on Overall Heat Transfer Coefficient

The relationship between the height of the lifters and k_{m-w} is plotted for the cases with six lifters in Fig. 3 (a). These are the average k_{m-w} values during pyrolysis of the model wastes. The overall heat transfer coefficient k_{m-w} increased linearly with the height of the lifters. With 200 mm lifters, k_{m-w} was 45.3 W/m²K while the value for the no-lifter case was 38.6 W/m²K. The relationship between the number of lifters and k_{m-w} is plotted for the case of 100 mm lifters in Fig. 3 (b). k_{m-w} also increased with the number of lifters. The

relationship between the rotating speed of the kiln and k_{m-w} is plotted in Fig. 3 (c). k_{m-w} increased from 38.6 W/m²K to 43.4 W/m²K by increasing the rotating speed from 2.7 rpm to 4.0 rpm. At 4.0 rpm, k_{m-w} increased to 50.1 W/m²K by installing six 200 mm lifters.

Pyrolysis of waste proceeds through three successive phases ⁽¹⁾. First, moisture evaporates (phase 1), then celluloses such as grain, paper, and wood are pyrolyzed (phase 2), and finally plastics are pyrolyzed (phase 3). According to these reactions, three peaks appear in the pyrolysis gas volume. On the other hand, k_{m-w} is not constant during the pyrolysis, but it increases with wastes temperature. This suggests the possibility that the effect of lifters may be different in each phase. To confirm this, the process of pyrolysis was divided into three phases based on pyrolysis gas production, and the average value of k_{m-w} was calculated in each phase. In this experiment, a suitable height and number of lifters were selected to improve k_{m-w} 10 % or more from the basic case. The effect of lifter height on the overall heat transfer coefficient is plotted in Fig. 4 (a). The vertical axis shows the ratio of k_{m-w} in the improved cases to that in case 1 (the basic case). In phase 1, the 50 mm lifters had a slight effect, while the ratio of k_{m-w} increased by 18 % for the 200 mm lifters. However, in phase 3, this was improved by more than 10 % even with 50 mm lifters. The effect of the number of lifters on the overall heat transfer coefficients is plotted in Fig. 4 (b) for the case with 100 mm lifters. In phase 1, k_{m-w} was scarcely improved regardless of the number of lifters, while it was improved 6 % with three lifters and 17 % with six lifters in phase 3. We evaluated the geometric relationship between the waste layer and the lifters to clarify why the effect of lifters was different in the three phases. The geometric relationship between the waste layer and lifters is outlined in Fig. 5. The height of the waste layer H_w was about 430 mm and the arc length was 1420 mm just after feeding according to the experiment conducted at ambient temperature. We considered that the configuration of the layer in phase 1 was similar to this. On the other hand, the height of the char layer H_c was about 110 mm and the arc length after pyrolysis L_c was 680 mm, according to the measurement after the pyrolysis process. This configuration was considered to be similar to that in phase 3.

Fig. 3 (a) Relationship between height of lifters and overall heat transfer coefficient

Fig. 3 (b) Relationship between number of lifters and overall heat transfer coefficient

Fig. 3 (c) Relationship between rotating speed and overall heat transfer coefficient

Fig. 4 (a) Effect of lifter heights on overall heat transfer coefficient

Fig. 4 (b) Effect of number of lifters on overall heat transfer coefficient

The ratios of lifter height H_l to the depth of waste layer H_w and to the depth of char layer H_c are listed in Table 3. Using the 50 mm lifters, the ratio of lifter height to the waste height H_l/H_w was 0.12, and the ratio of lifter height to the char height H_l/H_c was 0.45. As shown in Fig. 4(a), only the 200 mm lifters showed a marked heat transfer enhancement in phase 1, while 10 % improvement of k_{m-w} was observed even with 50 mm lifters in phase 3. These results suggested that the heat transfer enhancement due to installation of lifters appeared only when the H_l/H_w or H_l/H_c exceeded a certain value. Under the conditions, the criterion was about 0.45. The ratios of arc length between two lifters L_l to the arc length of wastes in contact with the inner surface of kiln L_w and to that of the char layer L_c are listed in Table 4. As shown in Fig. 4(b), in phase 1, the number of lifters scarcely affected k_{m-w} . This was because the height of the lifters, 100 mm, was not enough as mentioned above. However, in phase 3, there was a 17 % enhancement of k_{m-w} in the case with six lifters, while there was a 6 % enhancement with three lifters. The ratio L_l/L_c in six lifter case is less than 1. Therefore, in order to enhance heat transfer efficiently by installing lifters, it is desirable to set the number of lifters so that the ratio L_l/L_w or L_l/L_c is less than 1.

Fig. 5 Geometric relationship between remaining wastes and lifters

Table 3 Height ratios of lifters to the wastes (char)

H_l (mm)	H_l/H_w	H_l/H_c
50	0.12	0.45
100	0.23	0.91
200	0.47	1.82

Table 4 Ratio of spacing between lifters to arc length of interface between wastes (char) and kiln wall

Number of lifters	L_l (m)	L_l/L_w	L_l/L_c
0	3.14	7.31	4.62
3	1.05	2.43	1.54
6	0.52	1.22	0.77

3.3 Design of Continuous Type Kiln

We applied the above results to design a continuous-type kiln. The kiln specifications are listed in Table 5. It is advantageous to design the kiln so that the ratio H_l/H_w (H_l/H_c) exceeds 0.45 and that the ratio L_l/L_w (L_l/L_c) is less than 1 to maximize the effect of lifters to increase k_{m-w} . However, it is impossible to predict the layer thickness of the wastes moving

in the kiln and the arc length of the contact surface with the kiln wall. Therefore, it is necessary to estimate these values first. Equation (1) for the layer thickness of powder H_f passing through a horizontal rotary kiln ⁽¹²⁾ was used to estimate the layer thickness and arc length.

$$F = 0.74 \left(\frac{H_f}{D} \right)^{2.05} \frac{D^4 \cdot N \cdot \cot \beta \cdot \rho}{l} \quad (1)$$

The concept of estimation is outlined in Fig. 6. First, a small section L_1 is divided from the outlet port of the kiln in the axial direction, and the layer height H_f is calculated by using Eq. (1). The distribution of the waste layer height in the rotating kiln is estimated by repeating this calculation for the inlet port. The arc length of the contact surface between the waste layer and the kiln wall is estimated with the layer thickness. The values of H_w and L_w estimated under the conditions shown in Table 5 are plotted in Fig. 7 as a function of the distance from the inlet port of the kiln. H_w was calculated to be about 1.0 m and L_w was calculated to be about 3.1 m at the inlet port. Using these results, we calculated the number of lifters n which satisfied the condition $L_i/L_w=1$. n was estimated to be 2 at the inlet port, as shown in Fig. 8. Three lifters were required 15 m from the inlet port because n was limited to an integer value. Four lifters were required in the region from 15 m to 18 m from the inlet port, five from 18 m to 19 m, and six to the end of the drum. H_i can be determined to satisfy the condition $H_i/H_w > 0.45$ by using the height of wastes shown in Fig. 7. A commercial continuous-type kiln designed using these results should achieve optimal performance.

Table 5 Design specifications

Item	Specification
Kiln inner diameter	2 m
Kiln length	20 m
Kiln revolution	3 rpm
Waste feed speed	70 kg/min
Waste bulk density	150 kg/m ³
Waste angle of repose	40 °

Fig. 6 Conceptualization to determine layer height

Fig. 7 Relationship between distance from inlet port and estimated value of H_w and L_w

Fig. 8 Relationship between distance from inlet port and number of lifters

4. Conclusions

We examined the influence the internal structure and rotating speed of an externally heated rotary kiln on pyrolysis time and overall heat transfer coefficient k_{m-w} from the kiln to the wastes, and drew the following conclusions.

- (1) When six lifters 200 mm in height were installed in the kiln and the rotating speed was 4.0 rpm, the pyrolysis time was shortened and was the same time as obtained when the pyrolysis temperature was increased from 555 °C to 630 °C.
- (2) The overall heat transfer coefficient k_{m-w} increased with the number of lifters and their height. The number of lifters had a significant effect on k_{m-w} .
- (3) The overall heat transfer coefficient k_{m-w} was improved more than 10% by designing the lifters so that the ratio of their height H_l to the layer height of the waste H_w exceeded 0.45. In addition k_{m-w} was also improved by more than 10% when the ratio of the arc length between two lifters L_l to the arc length of the contact surface of the kiln and the waste layer L_w was less than 1.

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