공학석사학위논문

Single Stage Crushing and Separation Characteristics of Waste Mid-sized Refrigerators and Small Domestic Appliances

폐중형냉장고와 폐소형가전의 단일공정파쇄 및 선별 특성

2016 년 2 월

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Abstract

Single Stage Crushing and Separation Characteristics of Waste Mid-sized Refrigerators and Small Domestic Appliances

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Mechanical disintegration or shredding is an important aspect in the recycling process. Taking place at the beginning of the processing sequence, it significantly affects the efficiency of downstream processing stages. Each type of shredder shows specific characteristics, such as shear force or impact force. Currently, new types of vertical hammer-style shredders are being developed. These shredders use intense impact and shear force to handle most appliances. This study will examine the application of a single-stage crushing instead of the current recycling center's four-stage process. Several disposed appliances, including 75 L refrigerators and five major types of small domestic appliances (vacuum cleaners, videocassette recorders (VCRs), electric rice cookers, fans, and electric heaters) were shredded using high-speed vertical shredders under varying discharge clearance conditions. The fragments were analyzed according to their size, composition and degree of liberation. Also separation experiments were conducted for the small domestic appliance fragments. Based on the results, the high-speed vertical shredders performed sufficiently for single-stage shredding to substitute the current four-stage process, with the optimal conditions suggested according to the requirement or types of appliances.

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Keywords : recycling, crushing, shredding, separation, waste electrical and electronic equipment, refrigerators, domestic appliances

Student Number : 2014-20523

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1. Introduction

Mechanical disintegration or waste shredding is one of the main stages of all recycling plants, largely because this operation takes place at the beginning of the processing sequence, affecting the efficiency of downstream processing stages. The primary goal of mechanical disintegration is to acquire a high degree of liberation for the separation processes. It is also one of the primary energy consumption stages in the material processing flow. In addition, many separation processes require the processed fragments be consistent in size, in order to consider the process to be effective. Thus, there is a definite need to increase energy efficiency by applying adequate stress so that a high degree of liberation of the associated materials meeting appropriate size requirements can be achieved, without over–disintegration of the parts.

The described process is similar to that used for natural ores, where valuable minerals are separated from rocks. Since more than 50% of the total energy consumption in mineral processing is in the comminution process, extensive research has been undertaken in the fields of liberation and comminution characterization, and the modeling of mineral resources (King 1994, Fandrich, Bearman et al. 1997, King and Schneider 1998, Gay 2004). Similarly, fragment size reduction and liberation characterization are important to improve the efficiency and quality of the recycling process. However, not many studies have been conducted on the latter (Castro, Remmerswaal et al. 2005). Since almost all waste electrical and electronic equipment (WEEE) has printed circuit boards (PCBs), which is a significant material, several studies have addressed WEEE (Huang, Guo et al. 2009, Guo, Wang et al. 2011). Crushed TV scrap's characteristics for mechanical recycling has been investigated (Cui and Forssberg 2007), and distribution ratio and flow of one of the important materials in WEEE metals has been studied (Oguchi, Sakanakura et al. 2012). Also the "Intelligent Liberation" for personal computers and PCBs was tested and recommended (Zhang and Forssberg 1999).

In the case of WEEE recycling, the crushing and shredding processes are more difficult to study. This is mainly due to the complex composition of waste materials. For instance, unlike natural ores, WEEE products are not binary systems with only wanted and unwanted components, but a mixture of potentially valuable materials, such as plastics and metals, and many unwanted, glued or jointed fragments. Furthermore, waste electronic products are composed of many materials with different breakage properties.

Materials can generally be divided into two major types—brittle and ductile. Brittle materials fracture without appreciable deformation, whereas ductile materials deform plastically before fracturing. The application of compressive force on brittle materials can cause materials to fracture. On the other hand, shear force is more effective for causing ductile material to fracture. The stress application rate is more important for ductile materials than for brittle materials, as a high stress application rate may induce brittle fracture behavior, whereas the same stress, reached slowly, would allow for ductile behavior. Therefore, there are numerous shredder designs, but two main types are used in the management of municipal solid waste: high speed, low torque hammer mills; and low speed, high torque shear shredders.

Recently, new types of vertical hammer-style shredders have been developed that use intense impact and shear force to treat almost all categories of electronic and electrical wastes, from small devices to large machines, and achieve outstanding selective disaggregation. With enormous amounts of WEEE produced annually, the government is striving to increase the recycling rate in Korea up to the EU level (Lee, Song et al. 2007). However, in most of the recycling plants in Korea, shredders and impact mills are combined and employed to crush large household appliances using a multi-stage process. A recent analysis (Kim, Cho et al. 2014), revealed that the multi-stage process is energy-inefficient and potentially redundant as the last stage does not improve the degree of liberation but instead grinds up already-liberated material even more. This indicates that increased efficiencies can be achieved through the effective utilization of available technology. However, detailed assessments of the effectiveness of these devices for breaking down home appliances have not yet been conducted.

The work reported below details investigations on mid-sized refrigerators and five representative categories of small domestic appliances mostly not yet studied. Tests were conducted using a high-speed vertical shredder at various discharge clearance settings. The resulting products were analyzed in terms of composition, size and liberation characteristics. The aim of the study is to: 1) examine the effectiveness in breaking down entire refrigerators and small domestic appliances into small pieces in a single pass by using a high-speed vertical shredder; and, 2) based on the fragment characteristics, find the optimum shredding conditions for different requirements and study the separation characteristics in the subsequent process.

2. Experimental Procedure

2.1. KE−series High−speed Vertical Shredder

Kubota high−speed vertical shredders (Models KE−100) were employed to treat multiple types of household waste appliances and study the model's liberation performance. The KE−series shredders simultaneously use impact, shear, and compression force. They are used to treat a wide range of appliance size, from large (e.g. refrigerators) to small (e.g. vacuum cleaners). However, neither the efficiency nor the effectiveness of these shredders has been fully investigated.

2.2. Waste Refrigerator Samples

This experiment used 75 L refrigerators. In order to emulate a typical recycling facility's process, the compressor, refrigerant gas, internal shelf, PCBs, and packing rubber were manually removed from four similar-sized refrigerators prior to shredding. The compressor and refrigerant gas are removed as they can trigger explosions, while the internal shelf and packing rubber are removed as they can reduce process efficiency. Their size and weight are listed (Table 1).

Table 1 Size and weight of refrigerators used in the KE−100 shredding experiment.

No.	Width (mm)	Length (mm)	Height (mm)	Weight (kg)
1	460	475	800	13.7
2	460	480	805	15.1
3	535	480	850	15.0
4	480	465	820	14.9

2.3. Waste Small Domestic Appliance Samples

Taking into account small domestic appliance disposal amounts and availability in recycling facilities, five domestic appliances were chosen for this research — vacuum cleaners, videocassette recorders (VCRs), electric rice cookers, fans, and electric heaters. The average weights for each type of sample are shown (Table 2). In terms of their mass, the heaviest appliances were vacuum cleaners, while the lightest ones were electric heaters.

Table 2 Average weight of small domestic appliances used in the KE-100 shredding experiment.

Vacuum cleaner	VCR	Electric rice cooker	Fan	Electric heater
5.1 kg	4.7 kg	4.0 kg	2.9 kg	1.9 kg

2.4. Experiment Method

Refrigerators and small domestic appliances were crushed using the KE−100 series high−speed vertical shredder. According to the study (Kim, Cho et al. 2014), the fragment size range obtained in current recycling facilities is from less than 10 mm to larger than 320 mm. Fragment sizes depend largely on the discharge clearance in the cases of high−speed vertical shredders. KE−100 discharge clearances, for example, can be adjusted from 10−60 mm. For this experiment, the discharge clearance was modified for each shredder: 20 mm, 30 mm, 40 mm, and 50 mm for 75 L refrigerators; and 20 mm, 35 mm, and 50 mm for small domestic appliances using the KE−100 series.

The shredder was emptied before operation, and after crushing. Fragments were retrieved and manually classified. At each discharge clearance condition, one sample of each refrigerator or three samples of each of the five types of appliances were shredded. Crushing took place simultaneously in the case of the latter. Finally, those products obtained from each small domestic appliance showing imperfect liberation were the subject of separation experiments, which included magnetic separation, screening, eddy current separation, and gravity separation.

2.5. Analysis

After completely shredding the refrigerators and small domestic appliances under each condition, all fragments were collected and separated manually for a more accurate analysis. Two steps of size fractionation were applied given the large amount of shredded fragments. The first step was pre-size classification using a large vibrating screen. Next, shredded fragments in each screen were classified by measuring for size and composition, piece by piece. Composition categories were iron, plastic, urethane, aluminum, copper, PCB, electric wire, sponge, rubber, fragments with two or more components (mixtures), ceramic, magnets and other materials, such as paper and fiber.

The fragment shapes were not homogeneous, therefore the fragments were measured with a ruler and further classified into groups of <10 mm, 10–20 mm, 20–40 mm, 40–80 mm, 80–160 mm, 160–320 mm, and >320 mm by longest cord lengths. The <10 mm fragments were not categorized further as further size determination would have been difficult and they were present in only a small amount. In the case of fragments from small domestic appliances with two or more components, they were classified as plastic + PCB and iron + copper. Considering the types of mixtures, about 15–30 groups of fragments with two or more components were classified under each experiment. To understand the shredding tendencies of the machines, the composition and size of the samples obtained from the KE-100 shredders were compared with fragments obtained from current recycling facilities and analyzed.

3. Results and Discussion

3.1. Composition Analysis Results

The composition of all appliance fragments are shown (Fig. 1). While 60% of the materials in the 75 L refrigerators were composed of iron, 17% were plastic, 9% were urethane, and the remainder was made up of electric wires, copper, aluminum, and sponge, among other things, all of which were present in quantities of less than 1%. In every case, there were no mixtures under any of the experiment conditions for refrigerators and fragments <10 mm, accounting for 9−15% of the materials, post−shredding.

Regarding small domestic appliances, rice cookers had a higher proportion of plastic than iron. VCRs had a higher proportion of iron. Overall, plastic and iron made up the bulk of the materials, with the sum of both components being higher than 60% for electric rice cookers, and higher than 70% for the remaining appliance types. There were more than 10 components taken into account under each experiment condition, but no urethane was observed in small domestic appliances. Among them, about 10% of the total were categorized as <10 mm fragments, while the sum of materials other than iron and plastic equaled between 10−15% of the total for all the appliances, with the exception of electric rice cookers.

Therefore, the appliances studied were composed mainly of ductile iron and brittle plastic, which are the main components affecting the recycling process. In addition, although different brands for each appliance category were used, their unique composition properties show that they are very similar according to appliance category. For this reason, simultaneous operation of the impact and shear mechanisms should be considered for the shredding process.

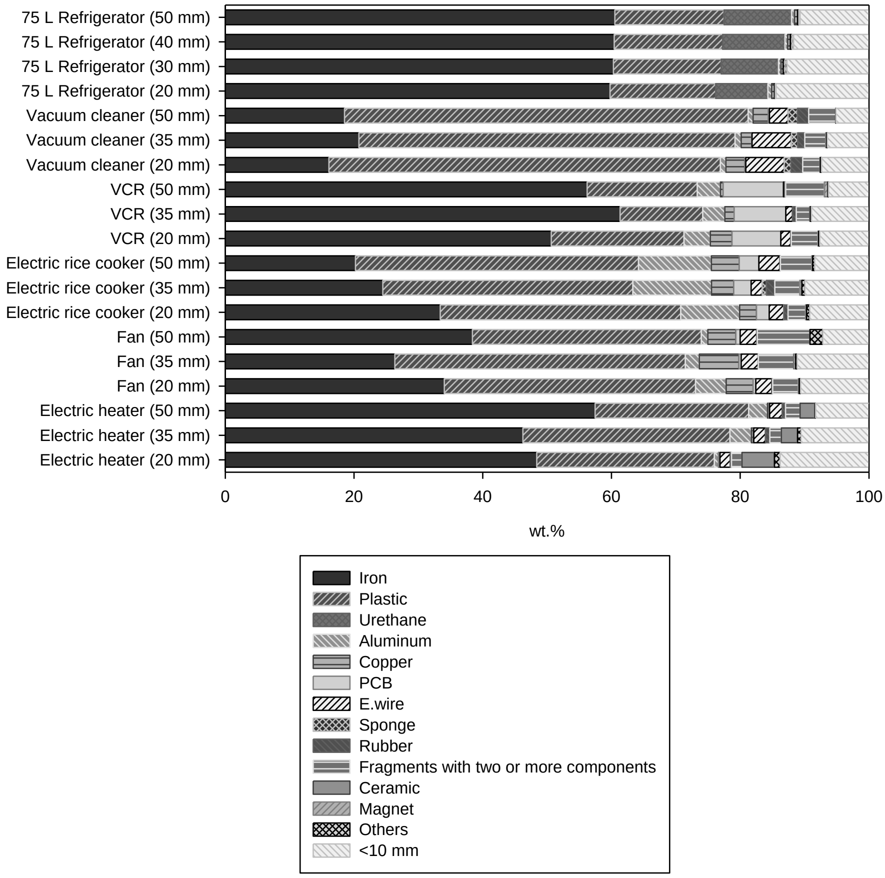


Fig. 1 Composition of shredded fragments under each discharge clearance for waste refrigerators and small domestic appliances.

3.2. Results of the Refrigerators' Shredded Fragments

The mass percentage of 75 L refrigerator fragment size and the distribution of each shredded fragment are shown (Fig. 2). Under the 20 mm discharge clearance condition, the 20–40 mm range fragments accounted for the vast majority of fragments, making up 56% of the total, while under the 30 mm discharge clearance, 20–40 mm fragments accounted for approximately 47%. Under the same discharge clearance, the 40–80 mm fragments accounted for 30%. Therefore, less 20–40 mm and more 40–80 mm fragments were made using the 30 mm discharge clearance compared with the 20 mm discharge clearance.

In the case of the 40 mm discharge clearance, 20–40 mm and 40–80 mm size fragments accounted for around 39% of the fragments. In the case of the 50 mm discharge clearance, 20–40 mm and 40–80 mm fragments represented 30% and 49% of fragments, respectively. When comparing the 75 L refrigerator fragment size distribution graphs of each material (Fig. 2), with current recycling facilities' fragments from a previous study (Kim, Cho et al. 2014), the size distribution of 50 mm discharge was similar to those of stage two shredded fragments, while that of 20 mm discharge was similar to stage three, even though the iron which requires high load was separated in the current process. Also most of the electric wire with high flexibility was crushed to less than 40 mm. Overall, as the discharge clearance narrowed, smaller fragments increased such as 20−40 mm and 40−80 mm and there were also no mixtures even though it was after the single−stage shredding.

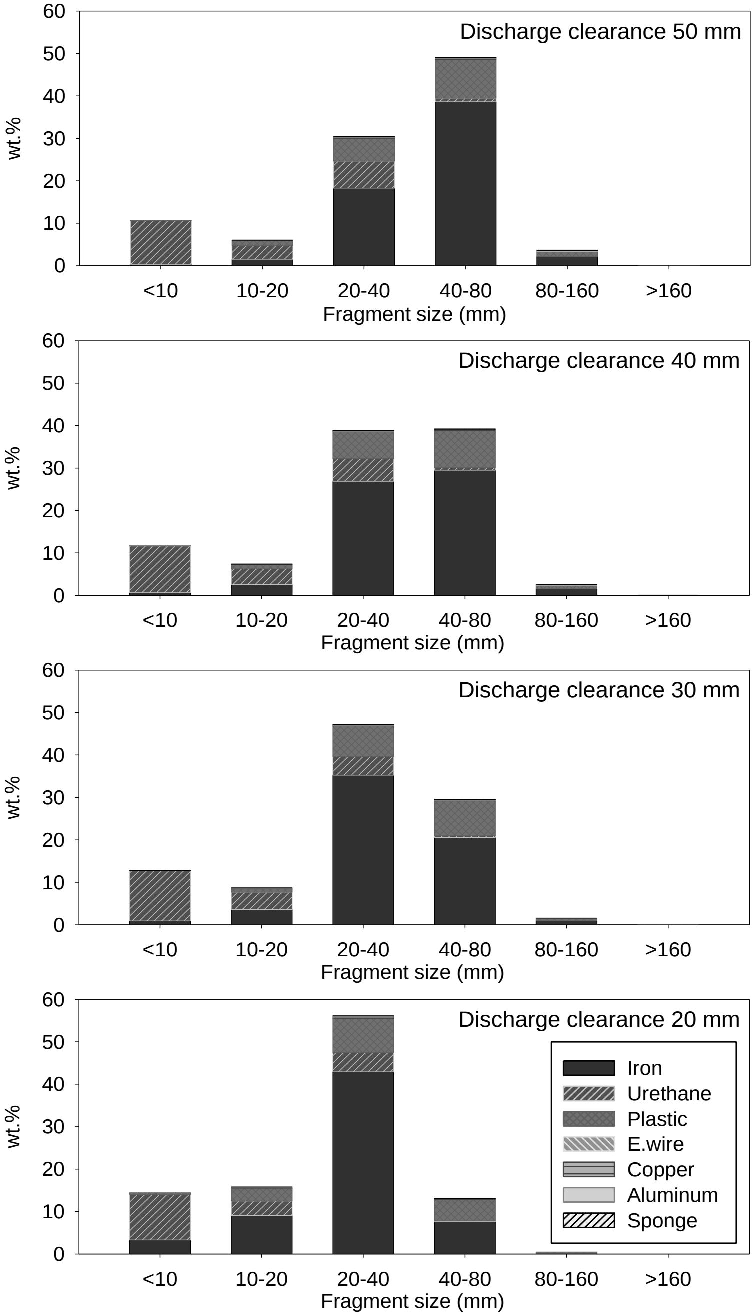


Fig. 2 Size distribution of shredded 75 L refrigerator fragments under the 50 mm, 40 mm, 30 mm and 20 mm discharge clearance.

The change in distribution by discharge clearance after 100% conversion of each material is shown (Fig. 3). In the case of iron and plastic, which represents the highest proportion of fragments under any discharge clearance, the percentage of <10 mm, 10–20 mm, and 20–40 mm ranges decreased, whereas the proportion of 40–80 mm, 80–160 mm, and >160 mm ranges increased, showing an overall increase in fragment sizes. This trend was also observed for other materials, with the exception of copper and aluminum.

This exception may be due to the discrepancy in the copper and aluminum components among the refrigerators. The four refrigerators tested were similar models, and while the structure and location of aluminum and copper, which are mainly used for refrigerant pipes, differed according to the model, iron and plastic used for the main frame did not. However, considering that iron and plastic are the primary materials used in a refrigerator, this variation has little influence on the overall result.

Regarding iron, plastic and sponge, the distribution of fragment sizes by composition showed that most fragments were in the 20–40 mm and 40–80 mm range, although some variations by discharge clearance were observed. Flexible materials, such as copper and electric wires, had bigger fragment sizes compared to other materials, with higher percentages in the 40−80 mm and 80−160 mm range, and in the 80−160 mm and >160 mm range, respectively. This shows the tendency of neither material to be sheared nor crushed.

On the other hand, since urethane is easy to break and aluminum is easy to agglomerate, they showed narrower size distributions. Under each condition, most urethane fragments fell into the <10 mm size range, while aluminum fragments fell between the 10−20 mm and 20−40 mm size range. Overall, most major components, except for electric wires, showed the appropriate size range: less than 80 mm for the subsequent separation process.

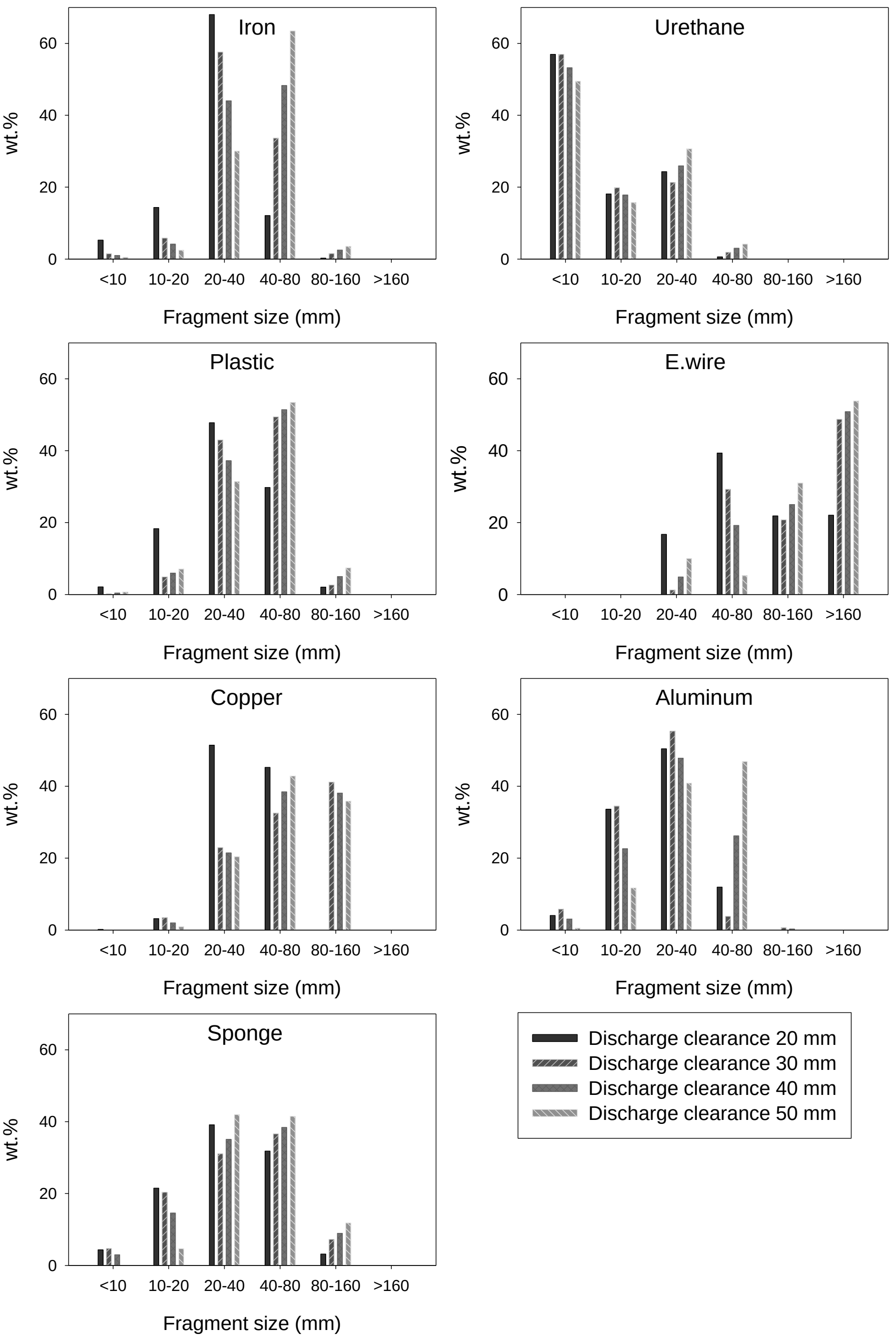


Fig. 3 Weight percentage of a 75 L refrigerator' s individual material fragments from the KE-100 shredder according to fragment size, by discharge clearance.

3.3. Results of Shredded Fragments of Small Domestic Appliances

The size distribution of shredded small domestic appliances under each discharge clearance is shown (Figs. 4−8). Most fragments were concentrated in the 20−40 mm and 40−80 mm size range. The number of fragments in the <10 mm and 20−40 mm range increased while the 40−80 mm decreased as the discharge clearance decreased from 50 mm to 20 mm. However, fragments larger than 80 mm remained after the shredding process, therefore, a secondary shredding process may be needed otherwise these remaining fragments can be problematic for subsequent separation processes. In the case of the other types of appliances, similar trends were observed.

Approximately, the fragment size distribution of small domestic appliances under the 35 mm and 50 mm discharge clearance were similar to the distribution of fragments after stage−two shredding, and the 20 mm discharge clearance results are analogous to the fragment distribution after stage−three shredding in the previous study (Kim, Cho et al. 2014). It is difficult to manually separate fragments less than 10 mm in size. In the case of the 20 mm discharge clearance, most fragments were in a 10−80 mm size range, indicating that a single−step shredding process using a high-speed vertical shredder is sufficient. Also, the main difference with refrigerators was that there are about 5% of fragments with two or more components in small domestic appliances fragments.

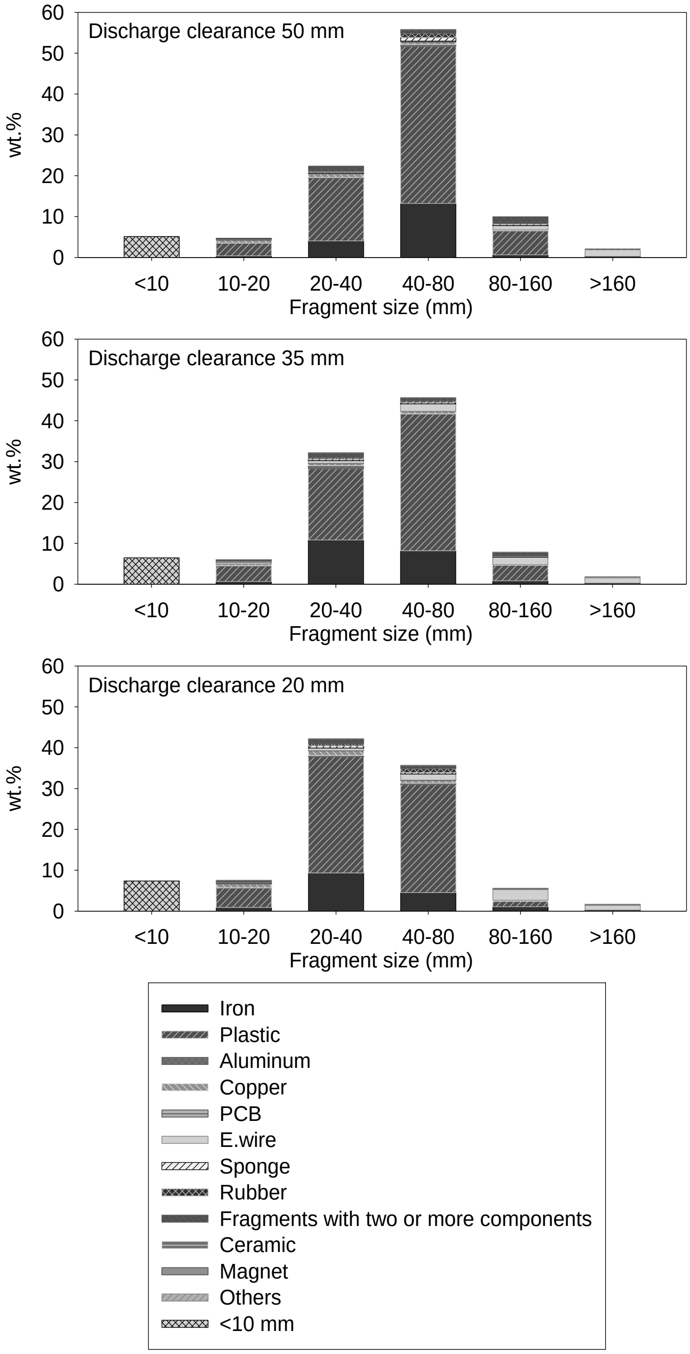


Fig. 4 Size distribution of shredded vacuum cleaner fragments under the 50 mm, 35 mm and 20 mm discharge clearance.

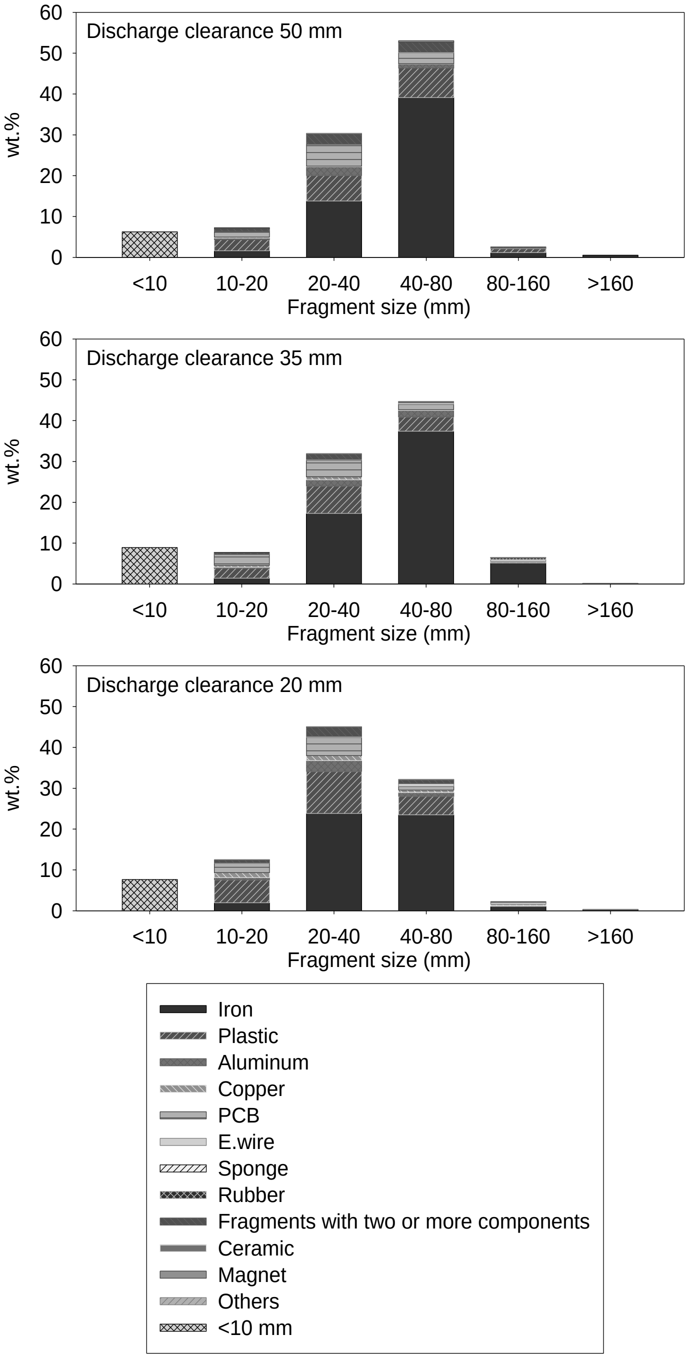


Fig. 5 Size distribution of shredded VCR fragments under the 50 mm, 35 mm, and 20 mm discharge clearance.

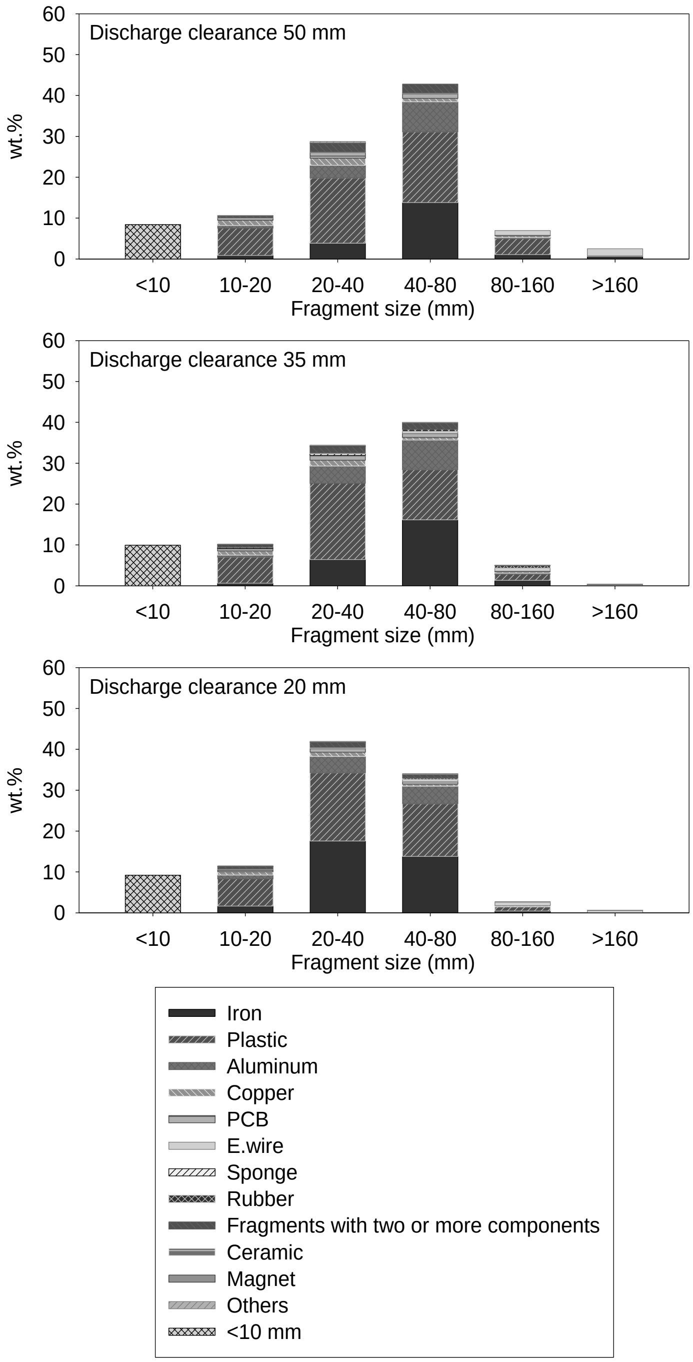


Fig. 6 Size distribution of shredded electric rice cooker fragments under the 50 mm, 35, mm and 20 mm discharge clearance.

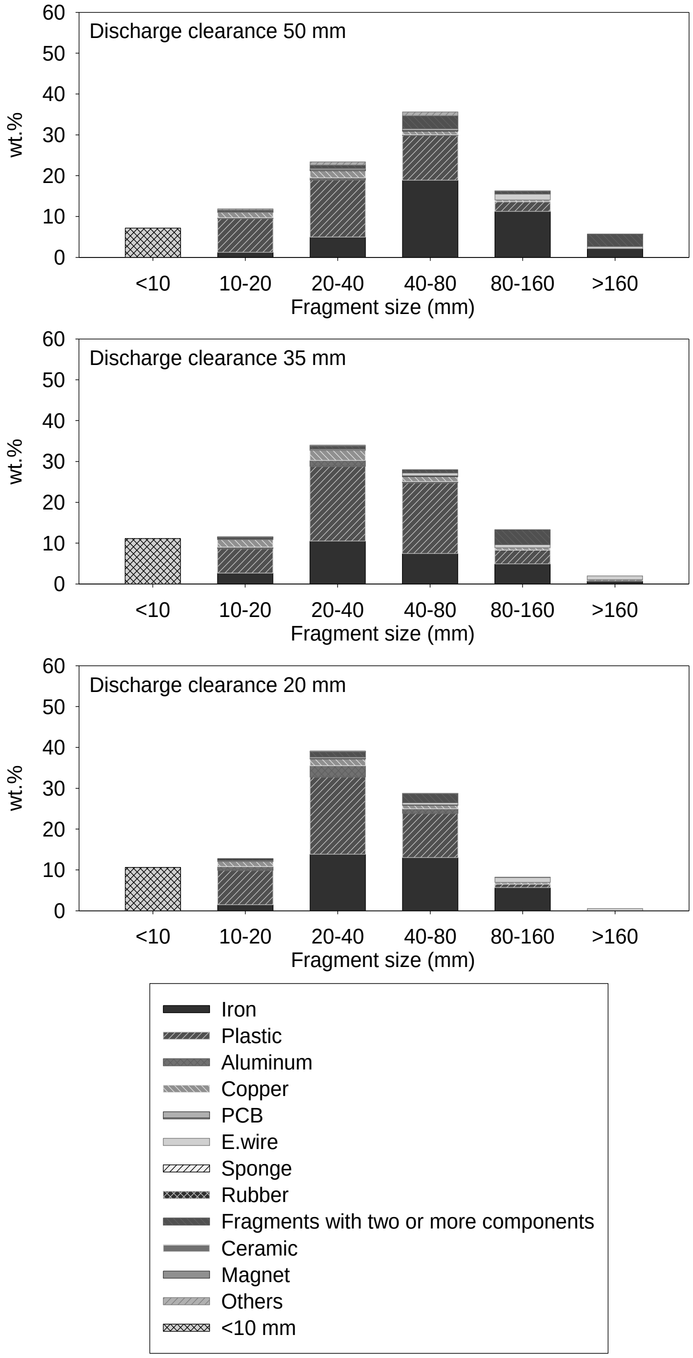


Fig. 7 Size distribution of shredded fan fragments under the 50 mm, 35 mm, and 20 mm discharge clearance.

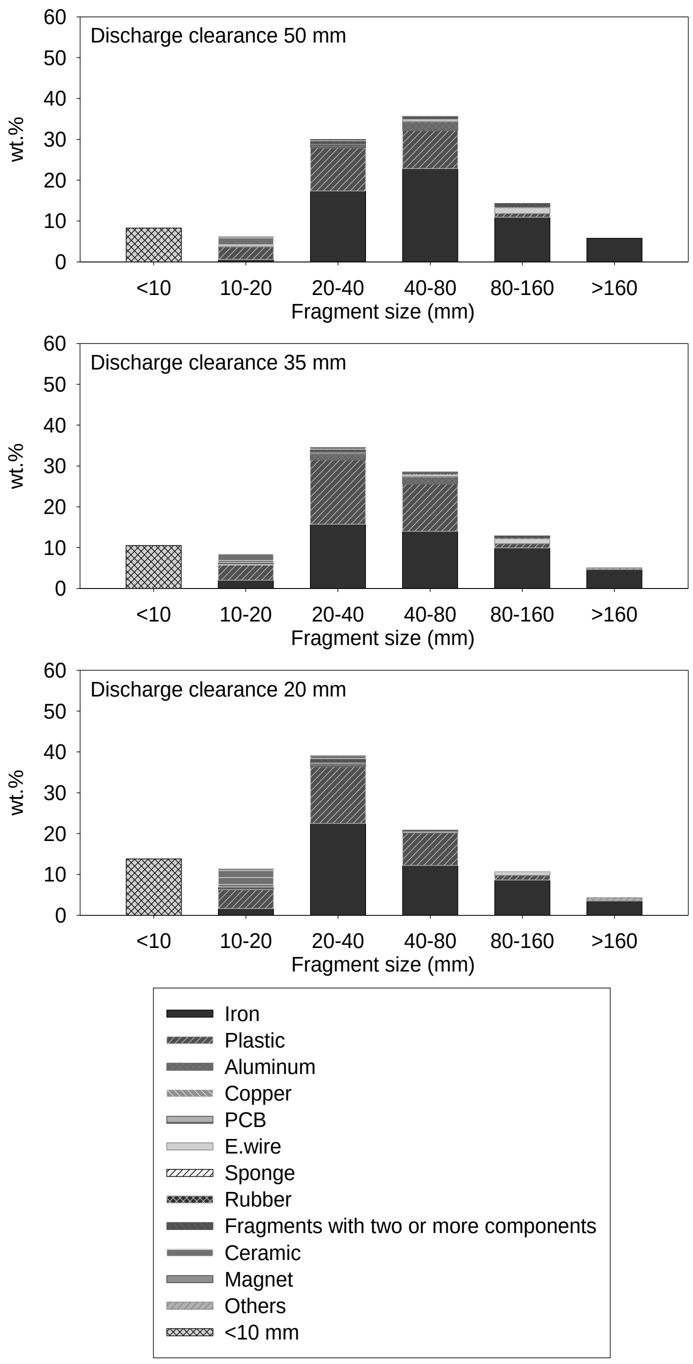
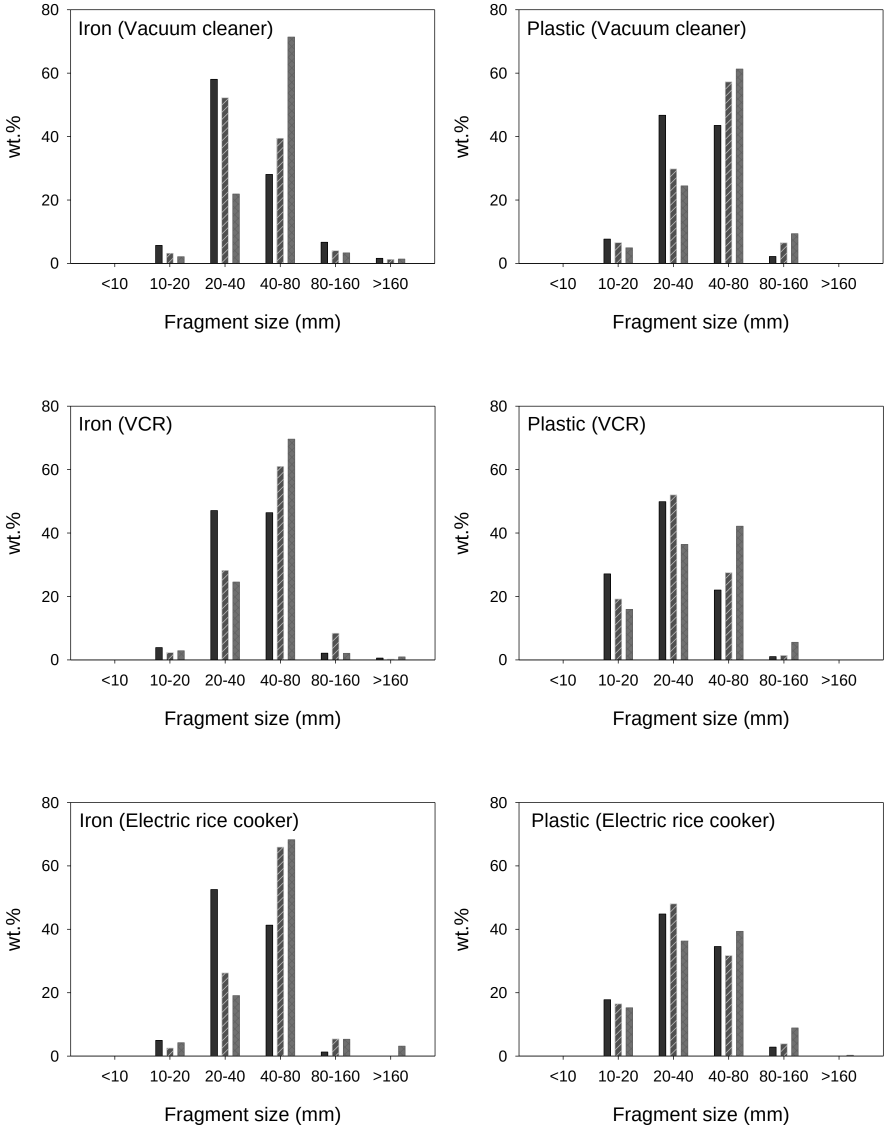


Fig. 8 Size distribution of shredded electric heater fragments under the 50 mm, 35 mm, and 20 mm discharge clearance.

The fragment size distribution of each component for every small appliance is shown (Fig. 9). For all appliances, most of the iron and plastic fragments were in the 20−40 mm and 40−80 mm range. As the discharge clearance reduced from 50 mm to 20 mm, fragments in 20−40 mm increased and 40−80 mm decreased. Similar trends were observed for all of the appliances except iron in fans and plastics in VCRs, electric rice cookers, and fans. These results show that the general size distribution of the small domestic appliances' major component depends not only on the discharge clearance used during the shredding process, but also on the types of appliances.


Iron (Vacuum cleaner)
Plastic (Vacuum cleaner)
Iron (VCR)
Plastic (VCR)
Iron (Electric rice cooker)
Plastic (Electric rice cooker)
wt.%
0
20
40
60
80
<10
10-20
20-40
40-80
80-160
>160
Fragment size (mm)

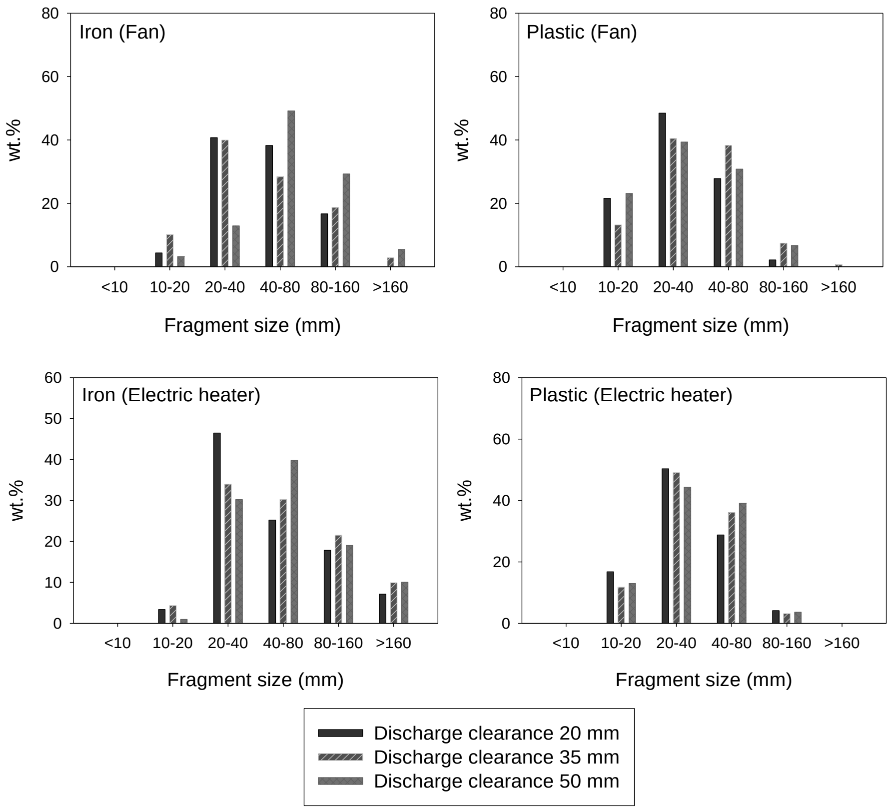


Fig. 9 Weight percentage of small domestic appliances' individual material fragments from the KE-100 shredder according to fragment size, by discharge clearance.

3.4. Results of Rosin–Rammler Distribution Analysis

The cumulative fragment size distribution of all the products followed the Rosin–Rammler equation (Rosin and Rammler 1933, Vesilind 1980) which states that:

$$Y = 1 - exp[-(\frac{x}{b})^n] \quad (1)$$

where: x is the particle size; Y is the cumulative passing of each particle size in weight percentage; n is the distribution modulus; and b is the size modulus ("the size at which 63.2% of the particles are smaller") (Rosin and Rammler 1933, Vesilind 1980).

The coefficient of determination, and modulus n and b obtained for each shredding experiment are shown (Tables 3–5). All coefficients of determination were higher than 0.949, showing that the data fitted the Rosin–Rammler distribution well. In the case of the 75 L refrigerators, as the discharge clearance decreased, the constant n increased slightly. These values were also similar in small domestic appliances since there were more exceptions in these cases. This comparison indicates that as the discharge clearance decreases, the uniformity of fragments increases, with the result that separation and control of uniformity of small domestic appliances are more difficult to achieve than for refrigerators. Based on their n values, electric heaters showed the widest fragment size distribution, and VCRs showed the narrowest distribution.

In addition, the 75 L refrigerators' constant b decreased from 45.56 mm to 30.81 mm as the discharge clearance decreased. In the case of small domestic appliances, they were much larger. In other words, refrigerators' relatively simpler components and shapes led to smaller shredded fragments and minimal fragments containing two or more components. As the discharge clearance decreased, the Rosin−Rammler size modulus b decreased. VCRs, which had smaller b values, were shredded into finer sizes. Electric heaters, which showed the largest b values, had the coarsest average fragment size. The b values act as a function of the discharge clearance. As the discharge clearance decreased, b values almost linearly decreased. It means that we can predict shredded fragment sizes easily by controlling the discharge clearance. The ratio of size reduction to discharge clearance was similar for all appliances, with the exception of the VCRs, mainly as a result of the amount of complex electronic components.

Table 3 Coefficient of determination of the Rosin−Rammler distribution.

Discharge clearance	20 mm	30 mm	35 mm	40 mm	50 mm
75 L Refrigerator	0.9821	0.9715		0.9656	0.9496
Vacuum cleaner	0.9817		0.9792		0.9667
VCR	0.9950		0.9777		0.9732
Electric rice cooker	0.9914		0.9870		0.9928
Fan	0.9925		0.9934		0.9937
Electric heater	0.9750		0.9817		0.9819

Table 4 Distribution modulus n of the Rosin−Rammler distribution.

Discharge clearance	20 mm	30 mm	35 mm	40 mm	50 mm
75 L Refrigerator	1.76	1.70		1.66	1.64
Vacuum cleaner	1.77		1.75		1.79
VCR	1.88		1.64		1.92
Electric rice cooker	1.72		1.62		1.58
Fan	1.43		1.30		1.34
Electric heater	1.15		1.25		1.35

Table 5 Size modulus b of the Rosin−Rammler distribution.

Discharge clearance	20 mm	30 mm	35 mm	40 mm	50 mm
75 L Refrigerator	30.81	36.70		41.16	45.56
Vacuum cleaner	47.05		52.94		60.22
VCR	40.40		48.06		47.37
Electric rice cooker	40.95		44.41		49.60
Fan	45.83		51.76		65.37
Electric heater	50.46		58.56		65.57

3.5. Liberation Characteristics and Fragments with Two or More Components

The degree of liberation is defined as the weight of liberated fragments divided by the total fragments' weight as shown in (2).

$$Degree\ of\ liberation = \frac{Weight\ of\ liberated\ fragments}{Weight\ of\ total\ fragments} \quad (2)$$

In the 75 L refrigerator, there were no mixtures under any of the experiment conditions. However, some fragments with two or more components were present in the small domestic appliance fragments (Fig. 1). The degrees of liberation for each case are shown (Fig. 10). As the discharge clearance decreased, the degree of liberation increased, and, in each case, was higher than 91%. The only observed exception was for VCRs, again, mainly due to their complex electronic components.

To obtain more than a 95% degree of liberation, a 50 mm discharge clearance was sufficient for vacuum cleaners, electric rice cookers, and electric heaters. A 20 mm and 35 mm discharge clearance was sufficient for fans and VCRs, respectively. Fans and VCRs showed the lowest degree of liberation among all the small domestic appliances. In particular, the non-liberated materials came from the fan motors and from PCBs connected to electric wires for VCRs. A 20 mm discharge clearance achieves a degree of liberation greater than 95% for any of the domestic appliances.

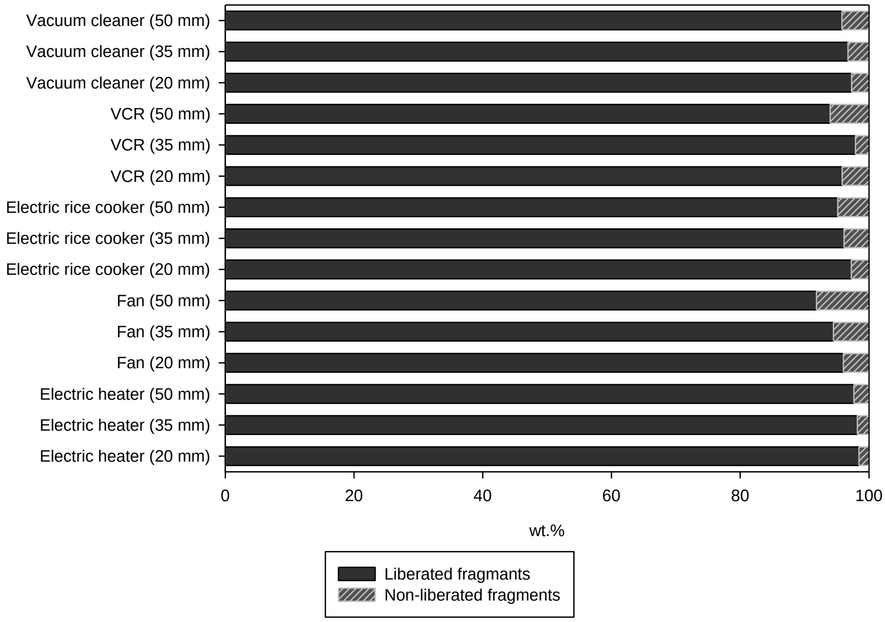
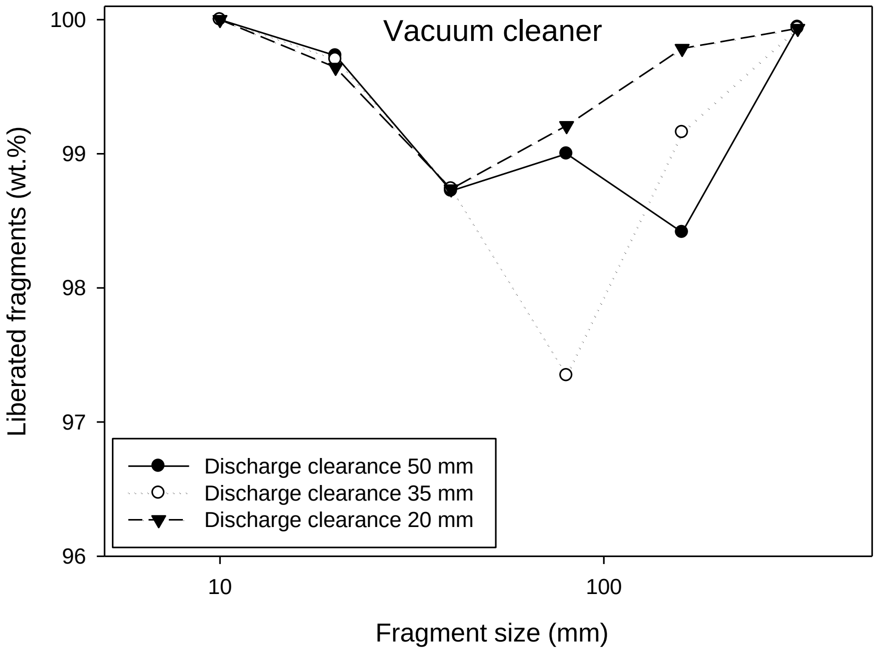
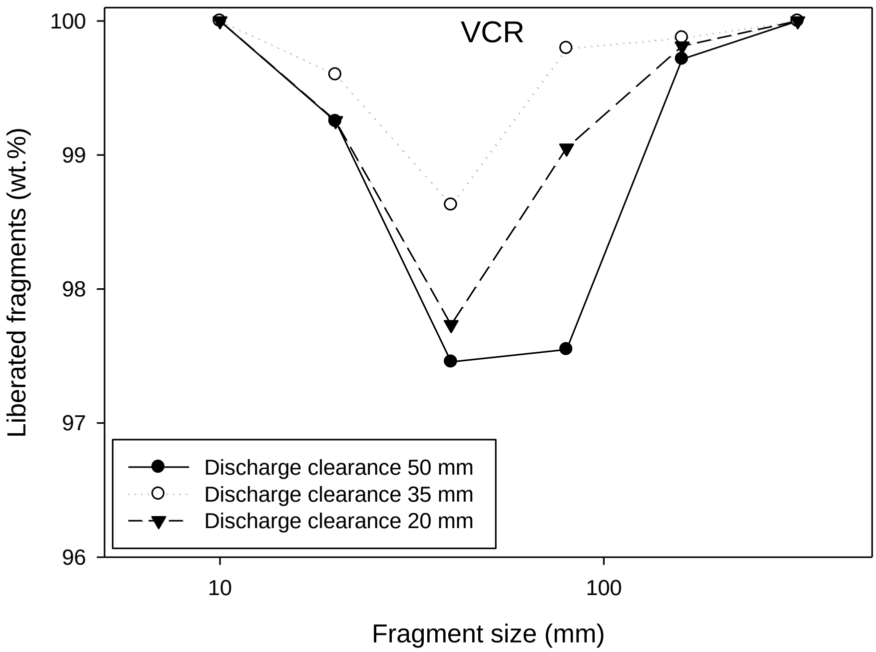


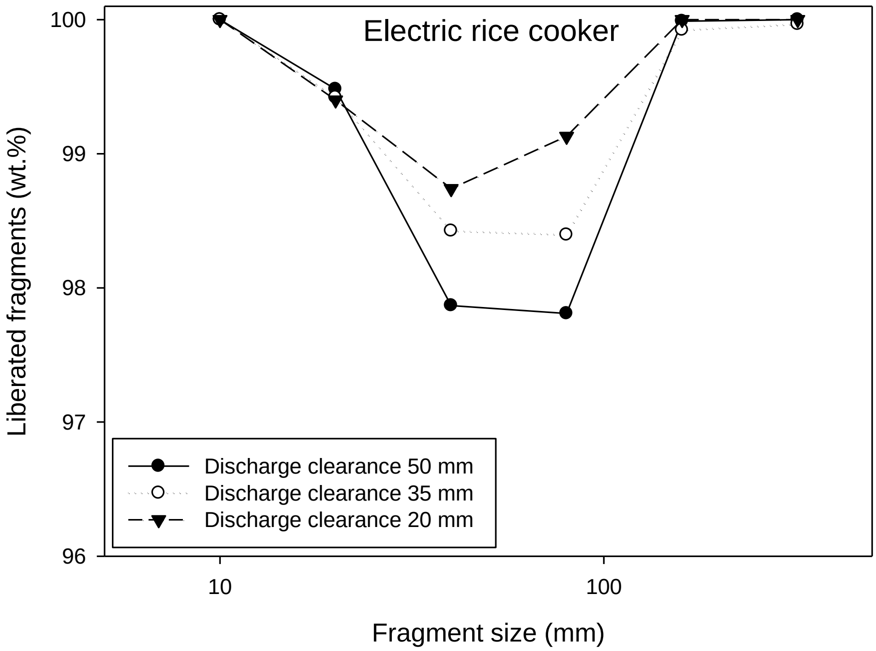
Fig. 10 The percentage of liberated particles and non−liberated particles (degree of liberation) in small domestic appliances fragments.

The weight percentages of liberation fragments according to size, for each of the small domestic appliances, are shown (Fig. 11). The majority of non-liberated fragments were 40-80 mm in size, showing the largest deviation. Electric rice cookers, which have a sphere-like shape and a relatively simple structure, showed reducing amounts of mixtures in each size range as discharge clearances decreased. However, there were fragments larger than 100 mm in vacuum cleaners and electric heaters because of non-brittle materials such as fabric filters, or rubber, sponge, and wire netting.

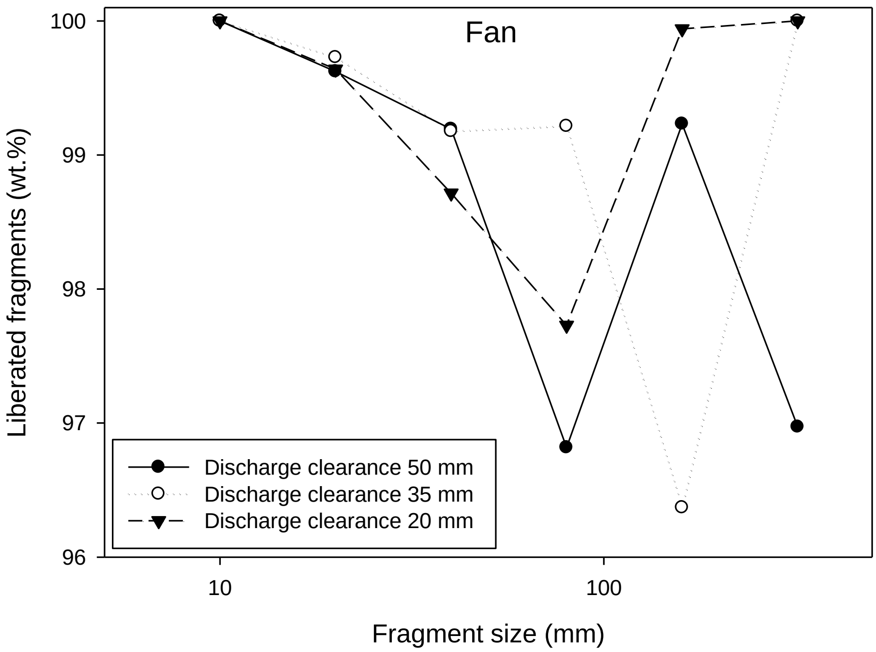
Also there was no tendency between discharge clearance and size of mixtures. This trend was also observed in the case of fans. In VCR fragments, most of the mixture fragments were smaller than 100 mm, but showed a lower degree of liberation with non-regularity, with respect to discharge clearance due to PCBs connected to electric wires. Concerning the size range of mixtures, the 50 mm discharge clearance shows large-sized and easy-to-separate fragments with two or more components and 20 mm shows a small amount of mixtures even though they are more difficult to separate because of their smaller size.


Vacuum cleaner
Liberated fragments (wt.%)
100
99
98
97
96
10
100
Fragment size (mm)
Discharge clearance 50 mm
Discharge clearance 35 mm
Discharge clearance 20 mm


VCR
Liberated fragments (wt.%)
100
99
98
97
96
10
100
Fragment size (mm)
Discharge clearance 50 mm
Discharge clearance 35 mm
Discharge clearance 20 mm



Electric rice cooker
Liberated fragments (wt.%)
100
99
98
97
96
10
100
Fragment size (mm)
Discharge clearance 50 mm
Discharge clearance 35 mm
Discharge clearance 20 mm



Fan
Liberated fragments (wt.%)
100
99
98
97
96
10
100
Fragment size (mm)
Discharge clearance 50 mm
Discharge clearance 35 mm
Discharge clearance 20 mm

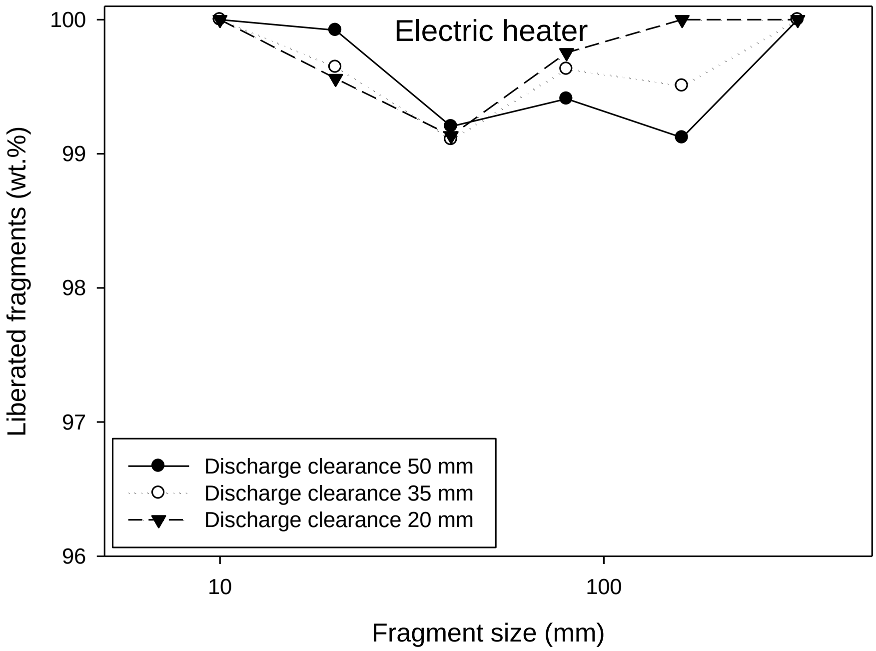


Fig. 11 Weight percentage of small domestic appliance liberated fragments, according to size.

The range of mixture types per number of components for different appliances and discharge clearances are shown (Fig. 12). Most of the mixtures had two or three components. VCRs had the most varied non-liberated components, while fans and electric heaters had the least. However, each appliance type had about 20–30 multi-components, which is not small. Because of different brands of appliances, no clear trend was observed relating to the discharge clearance and the quantity of mixture types. However, the number of four-component mixtures was reduced in accordance with a decrease to the discharge clearance.

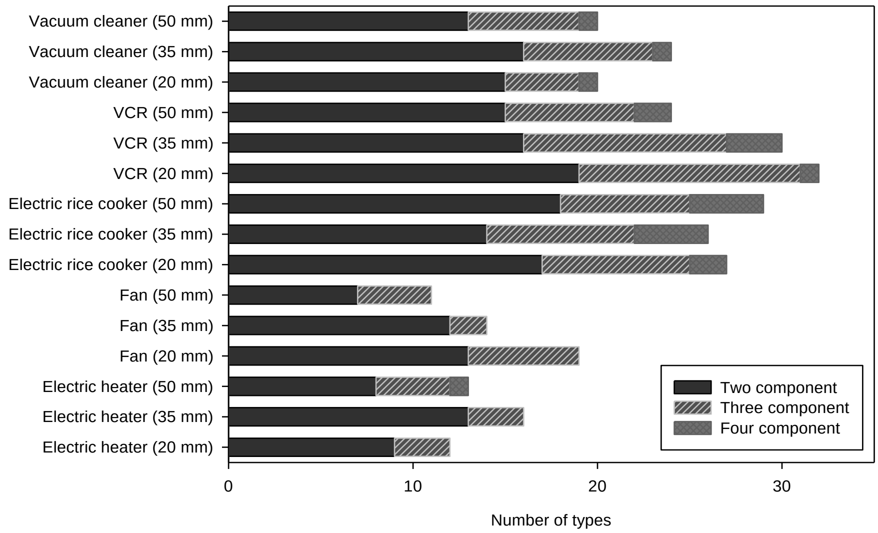
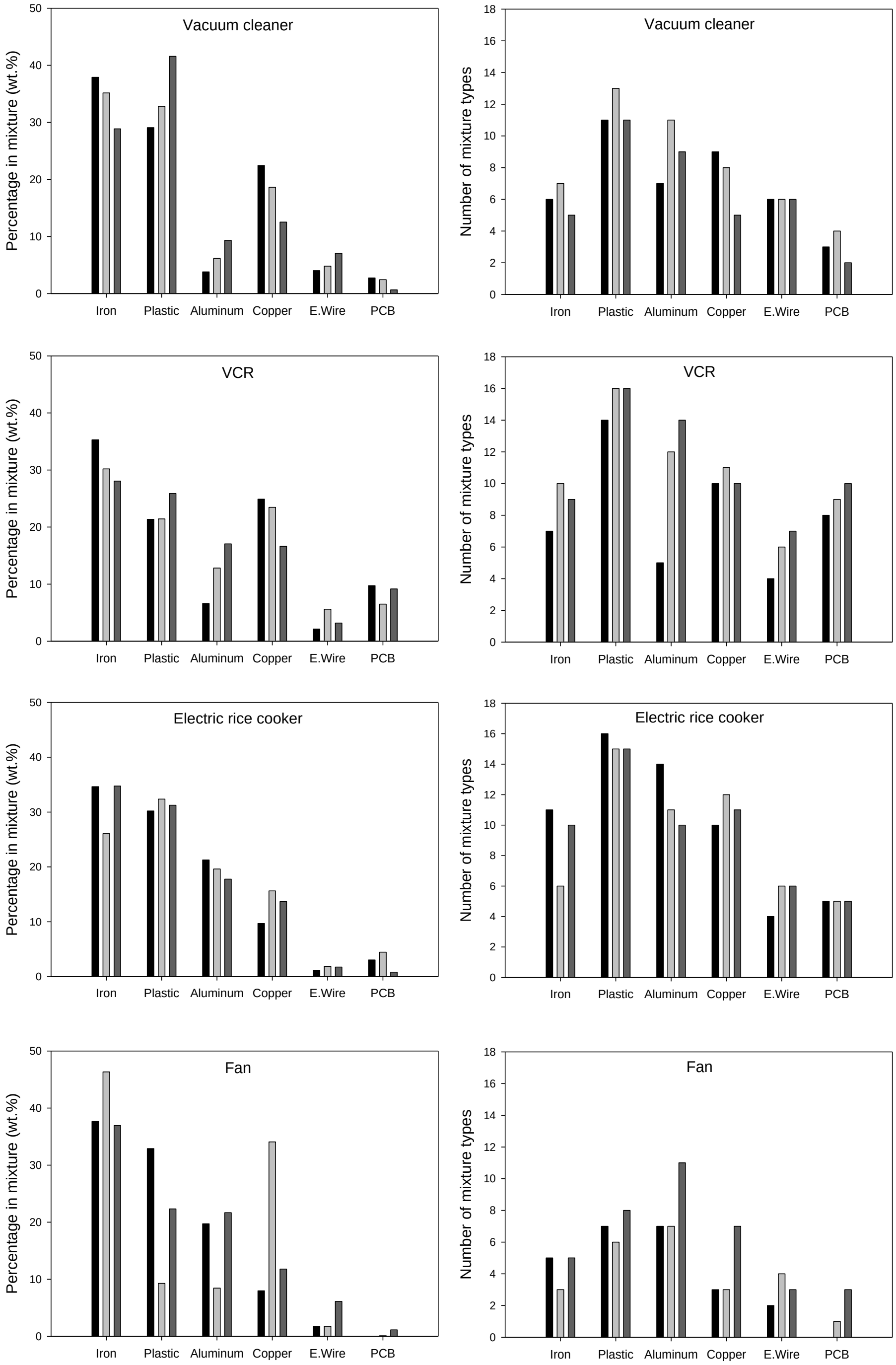


Fig. 12 Number of types of fragments with two or more components obtained for the different discharge clearances for every small domestic appliance.

More specifically, the weight percentage and number of mixture type containing each material for small domestic appliances were investigated (Fig. 13). The main components of fragments with two or more components were iron and plastic and the number of types was much larger in the case of plastic. Because of a low presence of other materials in mixtures and the complexity of the compositions, these other materials can be neglected during the recovery process. Therefore even when the discharge clearance was decreased, no clear trend was observed. However, it is interesting to note that more than 60% of mixtures contain plastic and iron, which means that if mixtures containing irons and plastics can be successfully separated using magnets, gravity, or air tables, then this would be economically effective.


Vacuum cleaner
Percentage in mixture (wt.%)
Number of mixture types
VCR
Electric rice cooker
Fan
Iron
Plastic
Aluminum
Copper
E.Wire
PCB
0
10
20
30
40
50
0
2
4
6
8
10
12
14
16
18

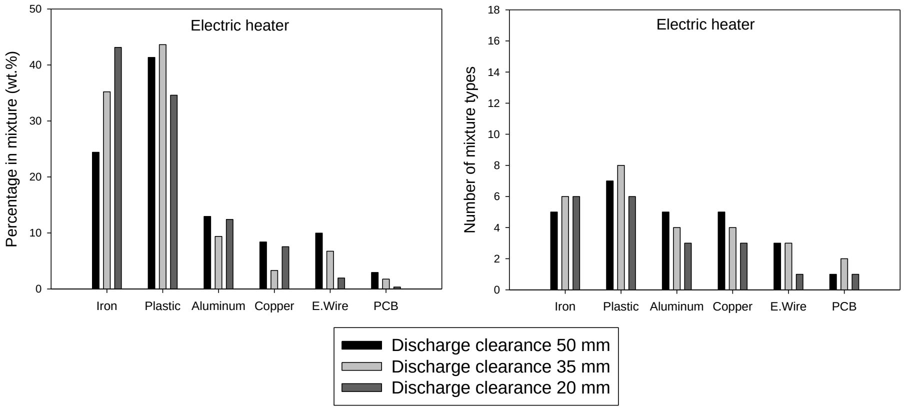


Fig. 13 Weight percentage and number of types of mixture containing every material for small domestic appliances.

3.6. Residence Time Consumption

Since the shredding process requires a large amount of energy, time is an important economic factor, and therefore time consumption should be considered when designing a shredding process or establishing optimal operating conditions, as will be elaborated later. The KE−series high−speed vertical shredder injects samples vertically and outputs the shredded fragments downwards. At this point, partially shredded bouncing fragments may remain in the cylinder without being outputted, due to the rotating breakers. For this reason, measuring the elapsed time may be difficult until all shredded fragments are completely released.

However, there is a current loading monitor and an automatic shut−off system to check the current sent to the motor, and to prevent overloading of the current flow. The shredding time could be measured or estimated using this equipment. The time consumption for each shredding condition is shown (Table 6). As a result, for the 20 mm, 30 mm, and 40 mm discharge clearance cases, the elapsed time was similar at around two and a half minutes, whereas for the case of the 50 mm discharge clearance, the time elapse was reduced to approximately two minutes for the 75 L refrigerator.

The maximum average shredding time was about three minutes for three VCRs, and the minimum average shredding time was about one minute for three fans. The general trend shows that shredding times increase as discharge clearances decrease. In particular, time consumption increased drastically when discharge clearance decreased from 35 mm to 20 mm. If at least a 95% degree of liberation is to be achieved in the least amount of shredding time, up to 30 75 L refrigerators or 150 small appliances can be shredded per hour. It is expected that the quantity processed could increase under a continuous feeding system.

Table 6 Operating conditions and time consumption for a 75 L refrigerator and three small domestic appliances.

Discharge clearance	20 mm	30 mm	35 mm	40 mm	50 mm
75 L Refrigerator	150 s	150 s		150 s	120 s
Vacuum cleaner	160 s		110 s		100 s
VCR	220 s		180 s		150 s
Electric rice cooker	210 s		100 s		90 s
Fan	70 s		60 s		80 s
Electric heater	110 s		110 s		90 s

3.7. Optimal Shredding Conditions

The optimal shredding condition for subsequent separation processes aims to maximize the degree of liberation while minimizing the operating time and fragment size. It was not necessary, however, to consider the degree of liberation for finding the optimal operating conditions for the KE-100 regarding waste refrigerators, considering a 100% degree of liberation was achieved under every condition. As a result, fragment size distribution becomes the most important factor when determining optimal operating conditions.

Iron can be easily separated through magnetic separation, which is not largely affected by the fragment size, and thus no major problems occur under any operating condition. In the case of urethane, pneumatic separation is widely used and the separation efficiency increases as the fragment size decreases. In the case of the KE-100 shredder, urethane showed similar results under all experiment conditions, and the majority of fragments were within 10 mm. Therefore, as in the case of iron, no major problems are expected under any type of condition.

Except for iron and urethane, the fragment size distribution of each sample is shown (Fig. 14). Fragment size distribution is the most important factor in determining the separation efficiency for an actual process. Thus, optimal operating conditions can be applied according to a particular separation process.

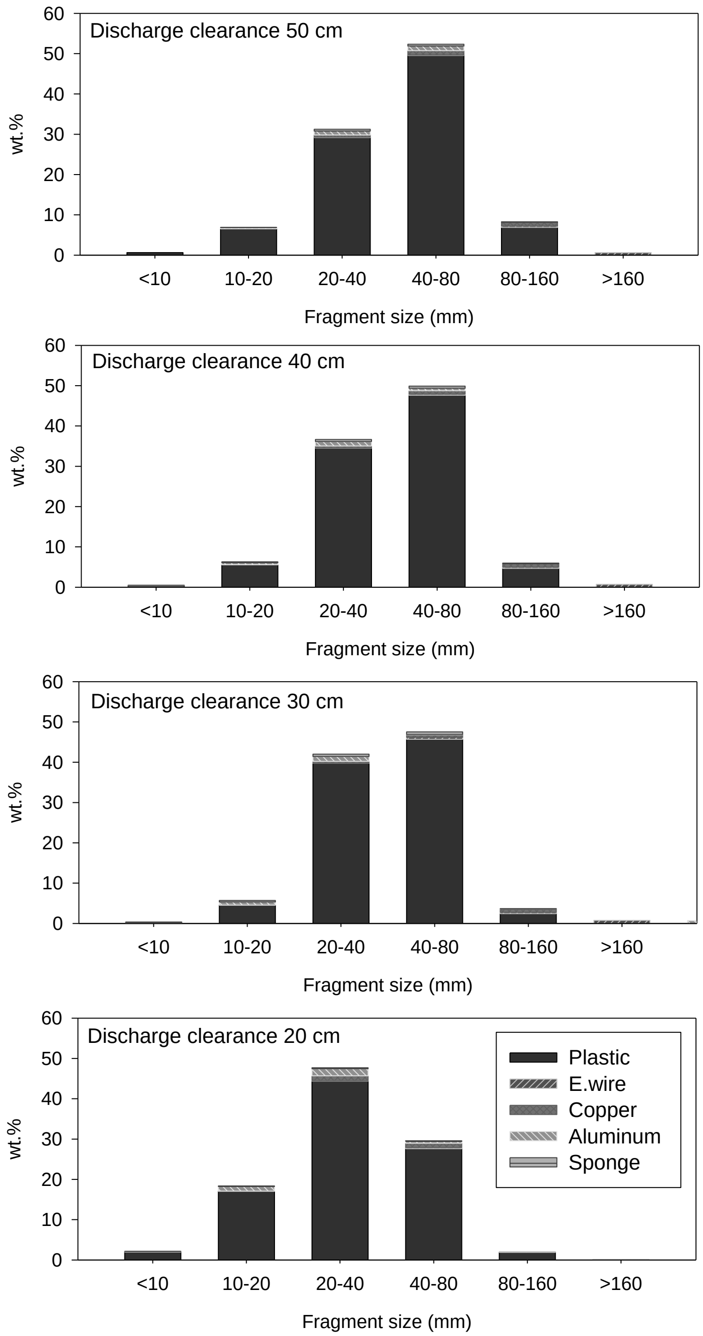


Fig. 14 Size distribution of 75 L refrigerator fragments by particle size and composition, except for iron and urethane.

3.7.1. Optimal Shredding Conditions for Waste Refrigerators

Currently, the separation process in recycling facilities is optimized to achieve fragments with an average size of 35 mm. Therefore, in the case of current recycling facility separation processes, 20 mm discharge clearances, which mostly produce fragments between 20–40 mm, seems to be the most suitable. Even if there are a number of 10–20 mm– and 40–80 mm–sized fragments, it is unlikely that there will be many problems given that current separating processes classify fragments into three groups (e.g., small, medium, and large fragment sizes).

When using a separation process that demands a narrow fragment size distribution without any size classification such as screening, the most appropriate condition employs a 30 mm discharge clearance as this size shreds fragments in the 20–40 mm and 40–80 mm range.

When using a highly efficient separation process, such as those allowing color or near–infrared sorting, a viable option is to operate the shredder using a 50 mm discharge clearance, since most of the shredded fragments are between 40–80 mm in size. Moreover, under this condition, further economic benefits can be expected as the average operating time is reduced by about 30 s in comparison to the 20, 30, and 40 mm discharge clearance conditions.

3.7.2. Optimal Shredding Conditions for Small Domestic Appliances Waste

However, in the case of small domestic appliances, the degree of liberation was lower than for refrigerators. The shredded fragments with two or more components were strongly joined, numerous, and had low economic value. Therefore, the discharge clearance should be reduced to at least 20 mm, which results in less than 5% of the fragments being mixtures, indicating that this is the optimal shredding condition for all small domestic appliances. If appliances are shredded separately, the most effective conditions employ a 50 mm discharge clearance for vacuum cleaners, electric rice cookers, and electric heaters, a 35 mm discharge clearance for VCRs, and a 20 mm discharge clearance for fans, while simultaneously considering the minimum residence time.

3.8. Separation Process

Since there were some fragments with two or more components, separation experiments were conducted using the shredded fragments from each of the small domestic appliances obtained from their optimal shredding conditions. The first step of the separation process was magnetic separation for iron, and mixtures containing iron. After magnetic separation, fragments less than 10 mm and greater than 80 mm were screened out so that they would not be problematic for subsequent processes; fragments between 10–80 mm were kept for subsequent steps. Next, eddy current separation was employed for classifying non-ferrous metals and their mixtures and non-conductive materials. The final step was to separate the remaining fragments by gravity, using a magnetite solution.

The separation process and weight percentage of each of the steps is shown for each small appliance (Figs. 15–19). The purity of magnetic separation ranged from about 75% to 95% due to the presence of iron powder, magnets, iron containing mixtures, and PCBs containing iron (Table 7). Screening for the separation of electric wires was not effective due to their low quantity, with a yield of only about 10%. Therefore, other separation methods, such as air tables, are needed.

The range in purity was greatest for eddy current separation, with results anywhere from about 50% to 100%. The aluminum was affected by the type and structure of the small domestic appliances, while the copper was not a target material for eddy current separation.

There were several reasons for this: most of the copper was thin copper wires, which were difficult to separate by eddy current separation; copper fragment shapes were not flat, making them inappropriate for eddy current separation; and, although both aluminum and copper was subject to magnetic repulsive forces, generally only aluminum could be separated, due to the higher density of the copper.

Regarding plastics, they could be almost perfectly separated through float groups using gravity separation in the final step, producing an average yield higher than the previous steps. Even though further study is needed regarding the separation process, the overall yield and purity was successful to a degree.

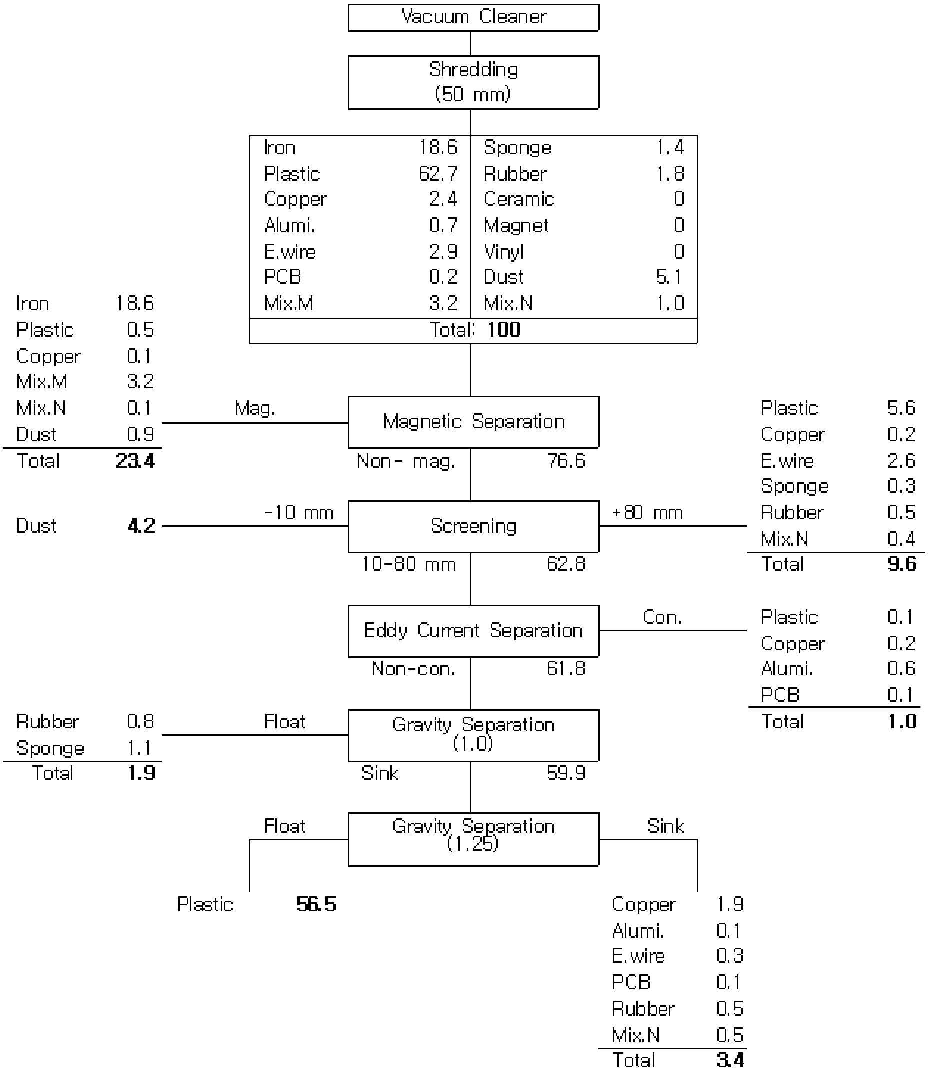


Fig. 15 Separation process for a vacuum cleaner.

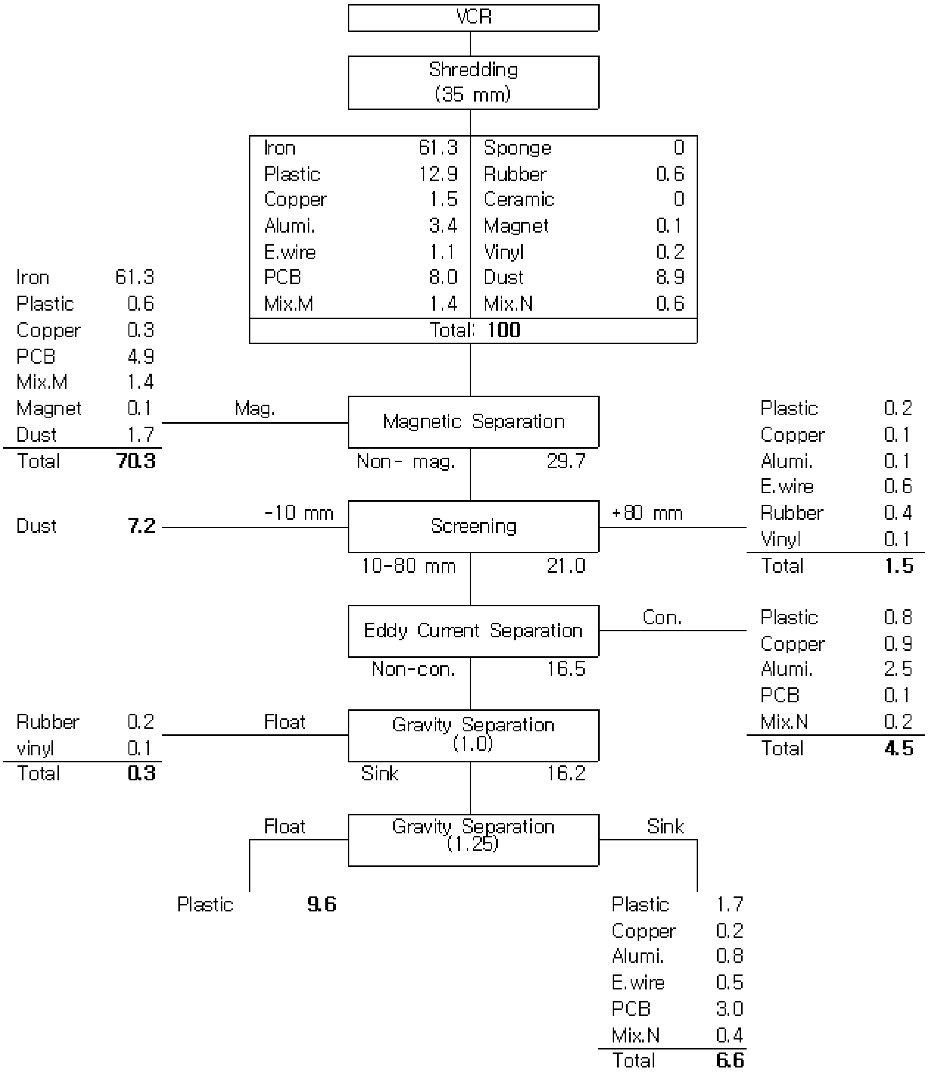


Fig. 16 Separation process for a VCR.

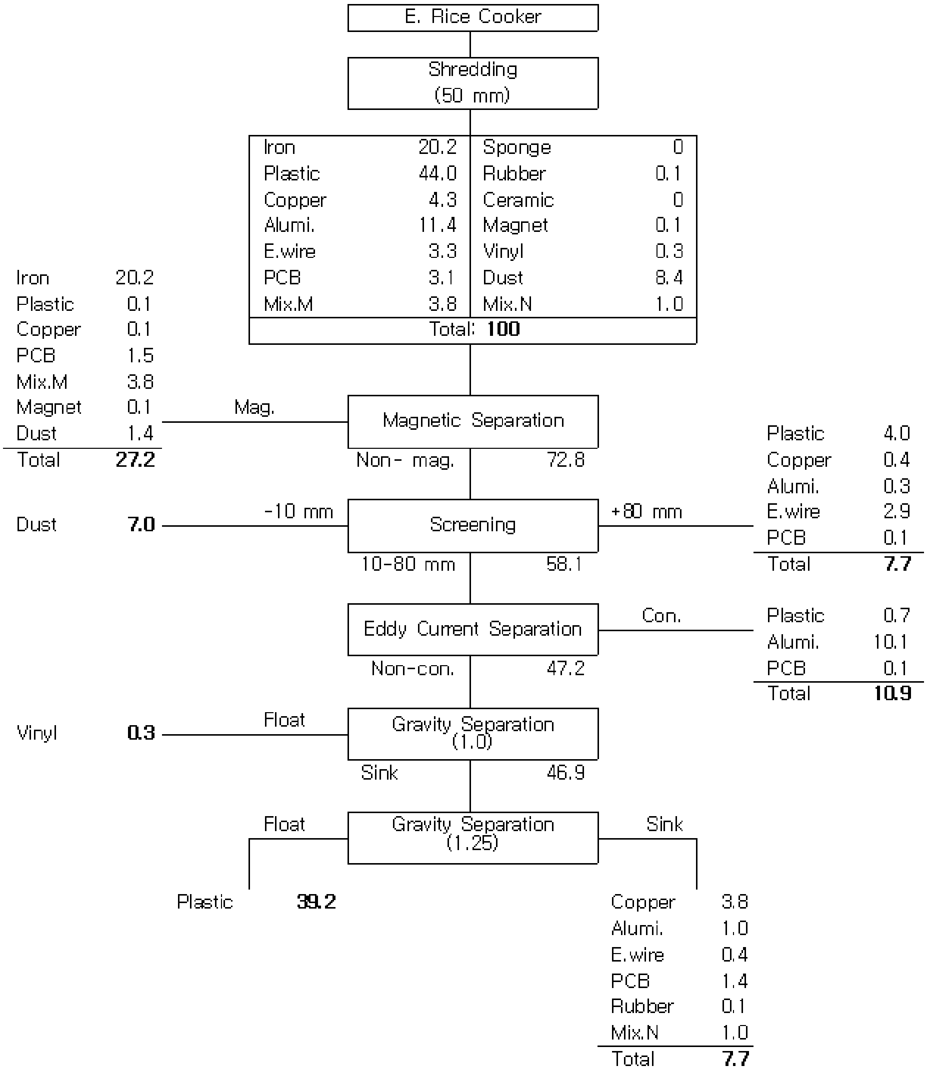


Fig. 17 Separation process for an electric rice cooker.

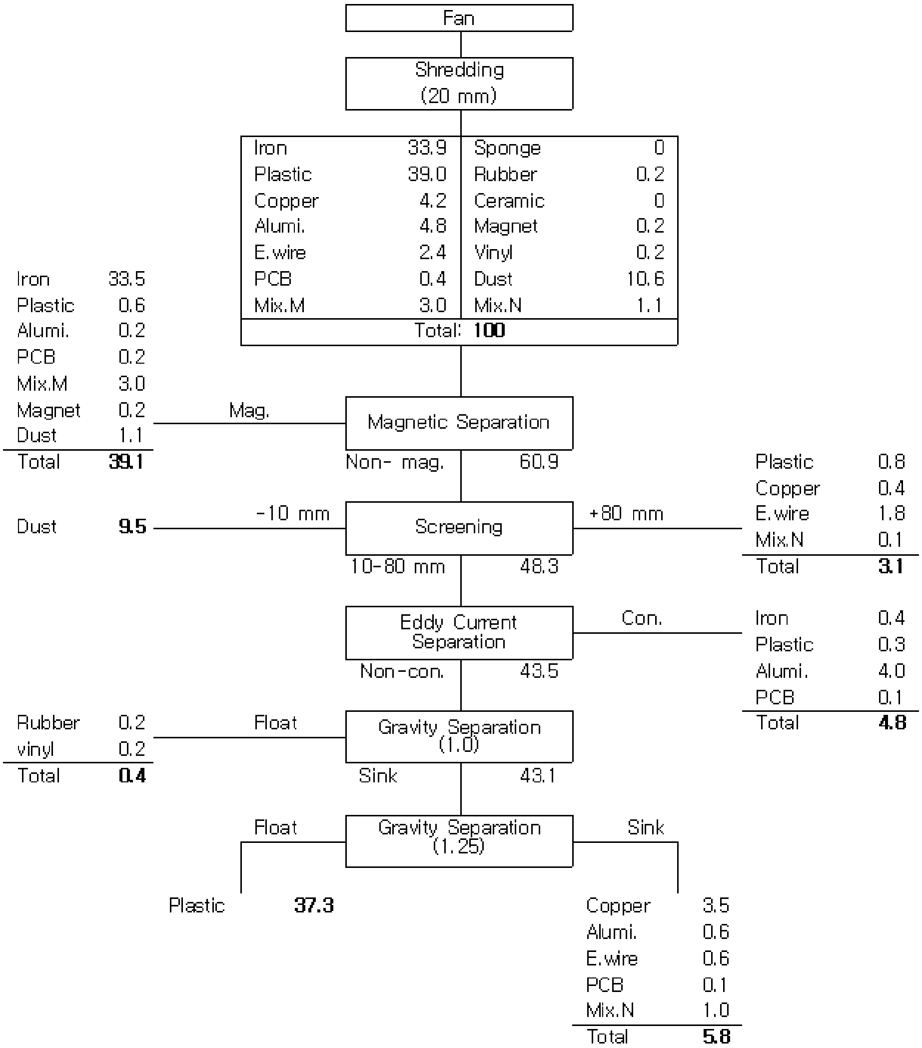


Fig. 18 Separation process for a fan.

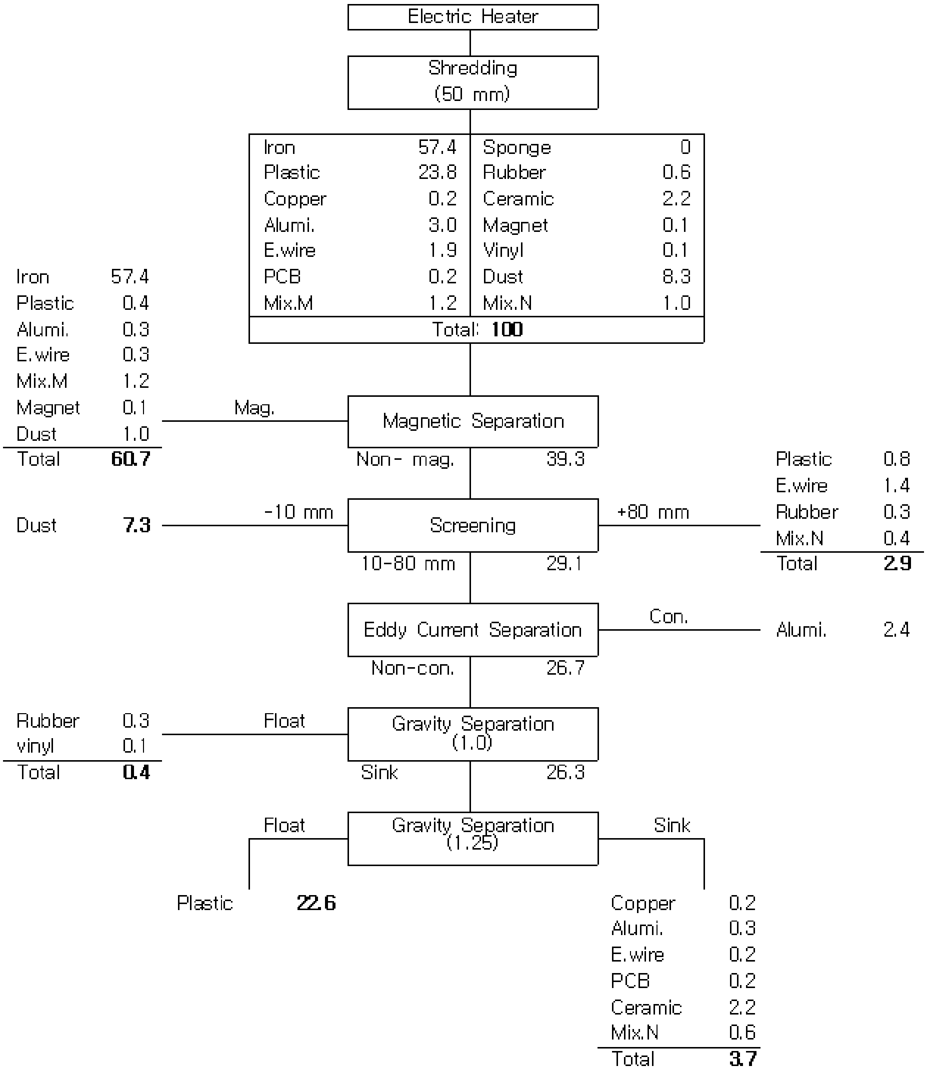


Fig. 19 Separation process for an electric heater.

Table 7 Yield and purity of each separation step for every small domestic appliance.

	Separation step	Target material	Yield (%)	Purity (%)
Vacuum cleaner	Magnetic separation	Iron	23.4	79.5
	Screening	Electric wire	12.5	27.1
	Eddy current Separation	Aluminum	1.6	60.0
	Gravity separation	Plastic	94.3	100.0
VCR	Magnetic separation	Iron	70.3	87.2
	Screening	Electric wire	5.1	40.0
	Eddy current Separation	Aluminum	21.4	55.6
	Gravity separation	Plastic	59.3	100.0
Electric rice cooker	Magnetic separation	Iron	27.2	74.3
	Screening	Electric wire	10.6	37.7
	Eddy current Separation	Aluminum	18.8	92.7
	Gravity separation	Plastic	83.6	100.0
Fan	Magnetic separation	Iron	39.1	85.7
	Screening	Electric wire	5.1	58.1
	Eddy current Separation	Aluminum	9.9	83.3
	Gravity separation	Plastic	86.5	100.0
Electric heater	Magnetic separation	Iron	60.7	94.6
	Screening	Electric wire	7.4	48.3
	Eddy current Separation	Aluminum	8.2	100.0
	Gravity separation	Plastic	85.9	100.0

4. Conclusions

While the high–speed vertical shredders managed to achieve similar fragment size distribution to current recycling centers, the one–step process did so at more than a 95% degree of liberation for mid–sized refrigerators and small domestic appliances. The experiment also determined the optimal operating conditions. Under each optimal crushing condition, up to 30 75 L refrigerators or 150 appliances could be shredded per hour. This amount has the potential to increase when a continuous feeding process is applied. Even if further study is needed in some parts, the described separation process shows that each material can be successfully retrieved. Therefore, considering the crushing performance, a sufficiently high degree of improvement in the performance was obtained to suggest substituting the current four–stage shredding process with this one–stage process. This study's results are important in helping with the application of a single–stage crushing and subsequent separation process by showing the results from using a high–speed vertical shredder or other similar shredding machine to achieve desired fragment characteristics under real circumstances.

References

King, R. P. (1994). "Comminution and liberation of minerals." Minerals Engineering **7**(2-3): 129-140.

Fandrich, R. G., et al. (1997). "Mineral liberation by particle bed breakage." Minerals Engineering **10**(2): 175-187.

King, R. P. and C. L. Schneider (1998). "Mineral liberation and the batch communition equation." Minerals Engineering **11**(12): 1143-1160.

Gay, S. L. (2004). "A liberation model for comminution based on probability theory." Minerals Engineering **17**(4): 525-534.

Castro, M. B., et al. (2005). "A simulation model of the comminution-liberation of recycling streams: Relationships between product design and the liberation of materials during recycling." International Journal of Mineral Processing **75**(3-4): 255-281.

Huang, K., et al. (2009). "Recycling of waste printed circuit boards: A review of current technologies and treatment status in China." Journal of Hazardous Materials **164**(2-3): 399-408.

Guo, C., et al. (2011). "Liberation characteristic and physical separation of printed circuit board (PCB)." Waste Management **31**(9-10): 2161-2166.

Cui, J. and E. Forssberg (2007). "Characterization of shredded television scrap and implications for materials recovery." Waste Management **27**(3): 415-424.

Oguchi, M., et al. (2012). "Fate of metals contained in waste electrical and electronic equipment in a municipal waste treatment process." Waste Management **32**(1): 96-103.

Zhang, S. L. and E. Forssberg (1999). "Intelligent Liberation and classification of electronic scrap." Powder Technology **105**(1-3): 295-301.

Lee, J., et al. (2007). "Present status of the recycling of waste electrical and electronic equipment in Korea." Resources Conservation and Recycling **50**(4): 380-397.

Kim, K., et al. (2014). "Size, Shape, Composition and Separation Analysis of Products from Waste Refrigerator Recycling Plants in South Korea." Materials Transactions **55**(1): 198-206.

Rosin. P. and Rammler. E. (1933). “The laws governing the fineness of powdered coal.” Journal of the Institute of Fuel **7**: 29-36.

Vesilind, P. A. (1980). "The Rosin-Rammler particle size distribution." Resource Recovery and Conservation **5**(3): 275-277.

요약(국문초록)

기계적인 분해와 파쇄는 연속공정의 초반에 이루어짐으로써 후속단계의 효율에 큰 영향을 주기 때문에 재활용 공정에서 매우 중요한 과정이다. 각 파쇄기에는 전단기작이나 충격기작과 같은 특징이 있으며, 최근 들어 새로운 형태의 수직해머형 파쇄기가 개발되고 있다. 이러한 파쇄기는 대부분의 가전제품들을 처리하기 위해 강한 충격력과 전단력을 이용한다. 본 연구에서는 현재 리싸이클링센터의 4단계 공정을 대신할 단일파쇄공정의 적용을 시험하였다. 몇 종류의 폐가전제품, 75 L 냉장고와 다섯 종류의 소형가전제품(진공청소기, 비디오카세트 녹화기(VCR), 전기밥솥, 선풍기, 전기히터)이 고속수직형 파쇄기를 이용하여 여러가지 배출간격 조건에서 파쇄되었으며, 파쇄물들은 입도와 조성 및 단체분리도에 따라 분석되었다. 또한 소형가전제품 파쇄물들에 대하여 선별실험이 이루어졌다. 실험결과에 의하면 고속수직형 파쇄기는 현재의 4단계 공정을 대체할 수 있는 단일파쇄공정을 위한 충분한 성능을 보여주었다. 또한 요구되는 조건과 가전제품의 종류에 따라 최적조건이 제안되었다.

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주요어 : 재활용, 파쇄, 선별, 폐가전, 냉장고, 소형가전

학 번 : 2014-20523