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Article

Evaluation on Recovery of Glass and Plastics from Compact Fluorescent Lamps (CFLs) by Air Separation Unit

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Abstract. Compact Fluorescent Lamps (CFLs) are composed of glass, plastic, non-ferrous metal, ferrous metal, paper, plastic, rubber, and so on. In order to separate glass and plastic among CFLs components, air separation unit is applied using the difference in specific gravity. Since specific gravities of glass, plastic, non-ferrous metals, rubber, etc. were widely spread, it can be separated by the different specific gravity between 0.40 and 4.36. In air separation unit, particle size and air speed are controlled to recover glass and plastics among the components of CFLs. In other words, it can be removed paper and vinyl to recover glass and plastics. The specific gravities of paper and vinyl in CFLs are 0.45 and 0.88, respectively. And the specific gravities of glass and plastics are almost similar to be 2.2-2.6. In air separation unit, the used particle size of the components from CFLs is less than 6 mm. Since phosphor powder and ferrous metals are recovered prior to the air separation unit, the components are not involved those materials. By utilizing a vertical and zigzag type of air separation unit, thereafter, recovery of glass and plastics is estimated with changing air speed. As the air speed increased from 3.08 m/s to 6.75 m/s, separation efficiency of glass and plastics increased from 42.0% to 99.3%. Due to the experimental results of air separation unit, it can find that paper and vinyl from the components of CFLs be efficiently removed by the air separation unit.

Keywords: CFLs (Compact fluorescent lamps), air separation, glass, plastics, recovery.

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1. Introduction

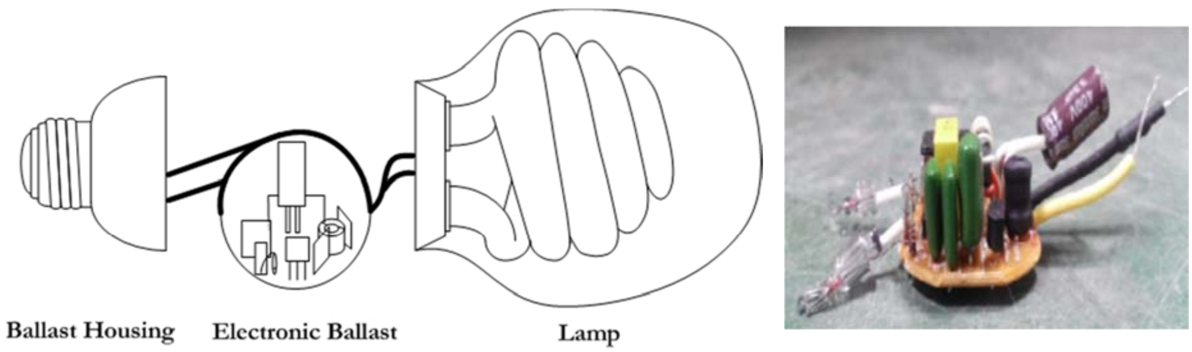
Lamps can be mainly classified by several types such as linear type, U type, compact type, and ring types. In Korea, about 28% of lamps among spent fluorescent lamps (SFLs) were estimated by compact type. The generation of SFLs was anticipated about 120 million lamps in 2013[1]. SFLs were managed by Extended Producer Responsibility (EPR) system from 2004 [2]. According to Ministry of Environment in Korea, approximately 30% of SFLs were recycled in 2013 but about 70% of SFLs may not manage properly. Therefore, the recycling rate of SFLs should be increased by applying the best available technology (BAT) sufficiently.

Before the recovery of ferrous or non-ferrous metals or other components from CFLs, mercury should be removed completely. Most of mercury in SFLs exists in phosphor powder so that the collection of phosphor powder may be crucial point using a special separation technology. Jang *et al.* [3] reported that 94% or more of total mercury remains in phosphor powder and glass matrix with very little mercury in vapor phase. When phosphor powder can be separated completely from the components of SFLs, the mercury concentration in the components except phosphor powder may be less than the regulatory level. In USA, Universal Waste Rule has controlled wastes containing mercury. In USEPA, high mercury wastes are classified by total mercury content which should be greater than 260 mg/kg [4, 5]. According to regulation of mercury in Korea, wastes containing mercury should be controlled below the limit of standard (0.005 mg/L), as determined by the Korea extraction test (KET) [2].

In order to recycle the valuable materials from SFLs such as glass, ferrous and non-ferrous metals, and plastics, Sweden, Germany and Austria have applied to use the Best Available Technology (BAT) [6, 7]. And wastes containing mercury after using BAT are treated in landfill site by using special containers [8, 9].

In general, compact fluorescent lamps (CFLs) are composed with lamp, electronic ballast, and ballast housing as shown in Fig. 1. In electronic ballast, there was included capacitor, resistor, transformer and transistor to flow the current to filament in lamp. In lamp, there existed filament, glass, phosphor powder, and mercury. Although recycling companies have tried to recover valuable materials from CFLs over several decades, those were not recovered efficiently because the essential components such as resistor and transformer in electronic ballast had complex structures with several materials such as copper, film, and paper to produce current flow.

In this study, CFLs from 3 manufactures (A, B, C) were crushed by hammer crusher and phosphor powder was separated from the components of CFLs to eliminate mercury efficiently. Before carrying out air separation, the weight, specific gravity and particle size of major components of CFLs are examined. The yield and reject rate of materials from CFLs with air speed were investigated to estimate the separation efficiency of materials. In air separation unit, light materials such as paper and film can be readily separated from heavy materials such as glass, plastics, and metals.



(a) CFLs structure (b) Electronic ballast

Fig. 1. The structure of electronic ballast in CFLs.

2. Theoretical Background

In order to separate paper and film from the components of CFLs, the theory of a binary separation system can be applied. The objective of the binary separation system is to split a binary-feed material into the individual different components by exploiting some difference in the material properties. Measurement of how well the separation works was used by two parameters; recovery and purity. The two components x (paper and film) and y (the other components from CFLs) in the binary-feed materials are separated so that x goes to recovery stream 1 and y goes to reject stream 2. Unfortunately, some of the y mistakenly ends up in recovery stream 1 and some of the x comes out in reject stream 2. The recovery rate of component x in recovery stream 1 is defined as Eq. (1). Similarly, the recovery rate of material y in reject stream 2 can be expressed by Eq. (2).

Recycling efficiency in the binary separation system can be described by Worrell and Rietema, Recycling efficiency of paper and film can be derived from a definition of a "degree of segregation". The recycling efficiency by Worrell can be expressed as Eq. (3) and the recycling efficiency by Rietema can be expressed as Eq. (4).

$$\text{Recovery rate (X)} = \mathrm{R}(x_1) = \left(\frac{x_1}{x_0}\right) \times 100\% \tag{1}$$

$$\text{Recovery rate (Y)} = \mathrm{R}(y_2) = \left(\frac{y_2}{y_0}\right) \times 100\% \tag{2}$$

$$\text{Worrell Efficiency(E)} = \left(\frac{x_1}{x_0}\right) \times \left(\frac{y_2}{y_0}\right) \times 100\% \tag{3}$$

$$\text{Rietema Efficiency(E)} = \left|\left(\frac{x_1}{x_0}\right) - \left(\frac{y_1}{y_0}\right)\right| \times 100\% \tag{4}$$

3. Material and Method

3.1. Materials

Compact fluorescent lamps (CFL, 20 W) from 3 manufactures are used in the air separation unit. The major components of CFL from 3 manufactures (A, B, C) are shown in Table 1 [10]. The total mass of CFL can be varied with lamp manufacture s [11]. Also, mass of the components from CFLs is different from lamp manufactures. From Table 1, it can be found that lamp manufactures used different materials to produce CFLs. Regardless of lamp manufactures, the mass of glass was the highest as an average value of 41 g and the mass of plastics was about 17 g. Hence, the portion of glass and plastic in CFL was almost 70% in weight.

Before the air separation experiment, among the components of CFLs, ferrous metals were separated by a magnetic separator and non-ferrous metals were collected by an eddy current unit. Hence, the components used in the air separation experiment have not ferrous and non-ferrous metals as shown in Table 2.

The components from CFLs used in the air separation unit can be classified by specific gravity. Since specific gravity of paper and film is less than 1.0, those materials can be described as light materials. Since specific gravity of glass, plastics, binder, and rubber is higher than 1.0, on the contrary, those materials can be described as heavy materials. From the based on the specific gravity of the components from CFLs, the possibility of separation of paper and film may be reasonable in the air separator unit.

Table 1. The major components of compact florescent lamps (g).

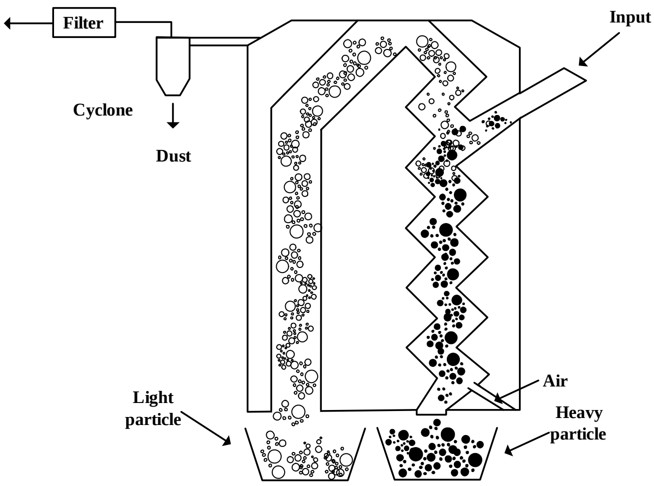
Component	Company			Average
	A	B	C	
Glass	37.85	45.43	40.10	41.13
Phosphor powder	0.51	0.69	0.57	0.59
Non-ferrous metals	3.36	4.83	3.95	4.05
Ferrous metals	8.95	12.76	9.54	10.42
Plastics	16.01	17.51	16.43	16.65
Paper	1.37	1.67	1.43	1.49
Vinyl	0.64	0.76	0.79	0.73
Binder	2.40	4.69	2.97	3.35
Rubber	4.81	5.70	5.63	5.38
Total	75.90	94.04	81.41	83.79

Table 2. Specification of sample for experiment.

Component	Weight		Specific gravity
	(g)	(%)	
Glass	41.13	59.84	2.39~2.77
Plastics	16.65	24.23	1.19~1.67
Paper	1.49	2.17	0.40~0.51
Vinyl	0.73	1.06	0.92~0.95
Binder	3.35	4.87	1.05~1.20
Rubber	5.38	7.83	1.45~2.40
Total	68.73	100.00	-

3.2. Experimental Apparatus

An experimental apparatus of air separation unit for the separation of the components of CFLs used in this study is as shown in Fig. 1. The experimental apparatus is composed of input guide assembly for inserting the components of CFLs, air injection assembly for blowing the components, cyclone to collect dust in air effluent, and filter system to prevent dust emitting to the atmosphere. In the experimental apparatus, heavy materials among the components of CFLs could not follow with air flow but light materials could follow with air flow. The particle size and specific gravity could give an influence to the separation of the components of CFLs in the experimental apparatus.



(a) A schematic diagram

(b) A picture of experimental apparatus

Fig. 1. An experimental apparatus for CFLs.

3.3. Experimental Method

In the experiments, at first, particle size distribution was examined for the components of CFLs. And air flow rate in air separation unit can be changed from 1.5 m/sec to 7.0 m/s to remove paper and vinyl from other components. In order to recycle heavy materials, specific gravity of the components was also estimated. Specific gravity of paper and vinyl was less than that of water so that those may be readily separated by air flow. To obtain the average value for the components, 3 test sets were carried out for each sample because the weight of the components of CFLs might be changed significantly from one lamp to another. The separation efficiency of the air separation unit used in the experiment was evaluated by Worrell and Rietema equations.

4. Result and Discussion

4.1. Particle Size Distribution

Particle size distribution of the components for mixed CFLs from several manufactures (A, B, C) was evaluated by sieving test. From 3 test sets in sieving test, it can decide the particle size distribution of the components for CFLs with cumulative weight fraction. As shown in Fig. 2, particle size distribution can be divided by 2 groups. The 1st group was paper, vinyl, and rubber and the 2nd group was the others such as glass, plastics, and binder. The specific gravity of the 1st group except rubber was less 1.0 but that of the 2nd group was higher than 1.0. Hence, it may separate the 1st group from the 2nd group by air separation.

As shown in Table 3, the mean particles size and the characteristics particle size of the 1st group were 3.6 mm and 3.9 mm, respectively. The mean particles size and the characteristics particle size of the 2nd group were 2.7 mm and 2.9 mm, respectively. As the particle size of the components is decreases, hence, the specific gravity of the components is increased except rubber. With respect to rubber, the specific gravity is higher than 1.0 but the particle size distribution was belongs to the 1st group.

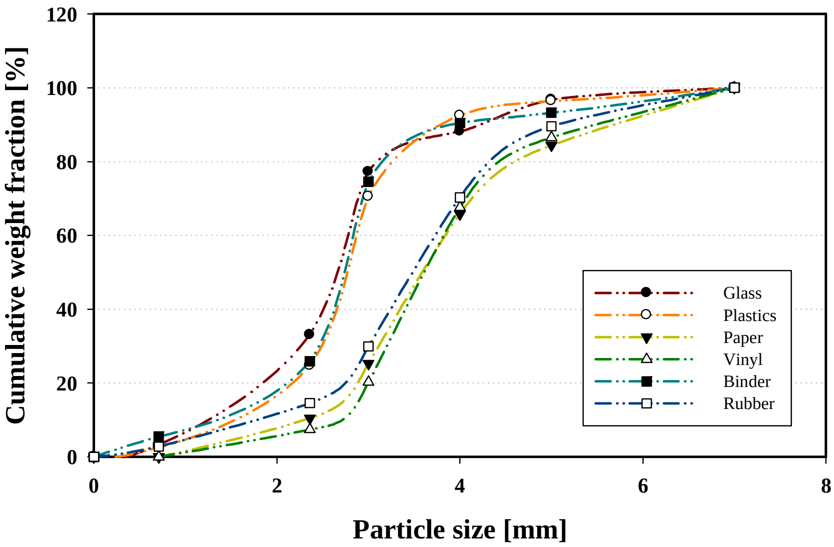


Fig. 2. Particle size distribution of the components of CFL with cumulative weight fraction.

Table 3. Mean and characteristic particle size of components of CFLs

Particle Size	Components					
	Glass	Plastics	Paper	Vinyl	Binder	Rubber
Mean particle Size [mm]	2.65	2.78	3.57	3.62	2.73	3.48
Characteristic particle size [mm]	2.82	2.90	3.93	3.89	2.87	3.80

4.2. Binary Separation System

Binary separation system can apply to estimate the separation efficiency for the components of CFLs in the sir separation unit. The input materials into air separation unit are consisted of the mixture of X and Y [12]. The target wastes of recovery and reject were called by X and Y, respectively. When airflow rate in air separation unit can be changed from 1.86 m/s to 6.75 m/s, recovery and reject for the components of CFLs were investigated as shown in Table 4.

In the case of airflow rate of 1.86 m/s, paper and vinyl as the 1st group were rejected by 0.93gram out of 2.22 gram but the rest components were not rejected at all. When airflow rate in the separation unit was 4.30 m/s, the reject of paper and vinyl as the 1st group was increased a little bit by 2.02 gram but the rest components were still not rejected. When airflow rate in the separation unit was 5.53 m/s, however, the reject of paper and vinyl as the 1st group was completely done and glass among the 2nd group was rejected by 0.09gram but the other components among the 2nd group were not still rejected at all. Hence, it may be desirable to decide the air flow rate between 4.30 m/s and 5.53 m/s.

From the binary separation system, as shown in Table 5, both Worrell efficiency and Rietema efficiency for the air separation unit were estimated for the components of paper and vinyl. In the case of airflow rate of 4.30 m/s, the recovery rate of paper and vinyl among the 1st group was estimated by 99.86% and the reject rate of the other components of CFL was estimated by 90.99%. However, the recovery rate of paper and vinyl was estimated by 99.37% at the airflow rate of 5.53 m/s and the other components of CFL was completely rejected when the airflow rate is higher than 5.53 m/s. Both Worrell efficiency and Rietema efficiency in the case of airflow rate of 5.53 m/s were estimated more than 99.0%. If airflow rate was greater than 5.53 m/s, both Worrell efficiency and Rietema efficiency were slightly decreased to be estimated more than 97.0%. Hence, it could be found that the optimal condition of airflow rate in the separation unit was 5.5 m/s to separate paper and vinyl from the mixed components of CFLs.

Table 4. The recovery and reject rate of components from CFL with air speed.

Air Velocity [m/s]	**Recovery /Reject**	**Components [g]**				
		Glass	**Plastics**	**Paper & Vinyl**	**Binder**	**Rubber**
1.86	Recovery	41.13	16.65	1.29	3.35	5.38
	Reject	0.00	0.00	0.93	0.00	0.00
3.08	Recovery	41.13	16.65	0.63	3.35	5.38
	Reject	0.00	0.00	1.59	0.00	0.00
4.30	Recovery	41.04	16.65	0.20	3.35	5.38
	Reject	0.09	0.00	2.02	0.00	0.00
5.53	Recovery	40.71	16.65	0.00	3.35	5.38
	Reject	0.42	0.00	2.22	0.00	0.00
6.75	Recovery	39.77	16.60	0.00	3.35	5.33
	Reject	1.36	0.05	2.22	0.00	0.05

Table 5. The efficiency of materials with air velocity.

Type	**Air velocity [m/s]**				
	1.86	**3.08**	**4.30**	**5.53**	**6.75**
X recovery [%]	100.00	100.00	99.86	99.37	97.80
Y reject [%]	41.89	71.62	90.99	100.00	100.00
Worrell efficiency [%]	41.89	71.62	90.87	99.37	97.80
Rietema efficiency [%]	41.89	71.62	80.86	99.37	97.80

5. Conclusions

Using the air separation unit, paper and vinyl could be separated from the mixed components of CFLs with considering particle size distribution and airflow rate. The optimum of airflow rate in the air separation unit could be decided by estimating the separation efficiency. The results on the separation of paper and vinyl among the components of CFLs can be summarized as follows:

1. The particle size distribution for the mixed components of CFLs could be divided by 2 groups using the mean and characteristic particle size and the specific gravity.
2. The specific gravity of the components of CFLs was increased with decreasing the particle size except rubber.
3. The optimal condition of airflow rate in the air separation unit was decided to be 5.5m/s to separate paper and vinyl from the mixed components of CFLs.
4. It is desirable that paper and vinyl among the mixed components of CFLs separated by air separation technology because the separation efficiency of air separation unit was more than 99.0%.

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