Korean J. Chem. Eng., **20**(3), 572-579 (2003)

Design and Performance Evaluation of Triboelectrostatic Separation System for the Separation of PVC and PET Materials using a Fluidized Bed Tribocharger

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(*Received 8 July 2002 • accepted 1 October 2002*)

Abstract−A triboelectrostatic separation system using a fluidized-bed tribocharger for the removal of PVC material in the mixture of PVC/PET plastics was designed and evaluated as a function of tribocharger material, air flow rate, electric field strength, and the mixing ratio of two-component mixed plastics. The test system consists of the fluidized-bed tribocharger, a separation chamber, a collection chamber and a controller. PVC and PET particles can be imparted negative and positive surface charges, respectively, due to the difference in the work function values of plastics suspended in the fluidized-bed tribocharger, and can be separated by passing them through an external electric field. Experimental results show that separation efficiency is strongly dependent on the tribocharger material, electric field strength and particles mixing ratio. In the optimum conditions of 150 *l*/m air flow rate and 2.6 kV/cm electric field strength, highly concentrated PVC (99.1%) can be recovered with a yield of more than 95% from the mixture of PVC and PET materials for a single stage of processing.

Key words: PVC/PET Electrostatic Separation, Fluidized-bed Tribocharger, Tribocharger Material, Air Flow Rate, Electric Field Strength, Mixing Ratio

INTRODUCTION

Waste plastics cause serious environmental problems due to the disposal by landfill or incineration. Incinerator combustion of PVC material generates hazardous hydrogen chloride gas, polychlorinated dibenzo-p-dioxins, and so on, which lead to air pollution and shorten the life of incinerators. Because of its large volume fraction, a significant part of the landfill cost is attributed to plastics. Further environmental concerns arise because the material degrades very slowly. Such concerns create a significant public pressure to recycle waste plastics. In order to reuse waste plastics, it is necessary to effectively separate them according to their qualities. Most commercial separators such as an air classifier, a centrifugal separator, and flotation system are based on the specific gravity. Recycling rate of industrial waste plastics is quite low because there is no economically satisfactory separation process.

A dry triboelectrostatic process is useful to separate PVC from the mixed plastics, which is based on the difference in the surface charge of various components of the powder mixture by the particle-to-particle impact and the particle-to-wall impact. Some of the mechanisms proposed for electrostatic contact charging include electron transitions between the materials coming into contact [Davies, 1969; Harper, 1967; Greason and Inculet, 1975; Lee, 2001] and ion exchange [Henry, 1953; Briick, 1981]. In a practical application of triboelectrification for plastic recycling, many researchers have studied the separation of various plastics using a tribocharger such as a fluidized bed [Lee, 2002], a cyclone [Pearse, 1978], a rotary blade [Matsushita et al., 1999], and a rotating tube [Inculet, 1994]. Also, Kang et al. [1999] and Lu et al. [1999] have investigated the particle flow behavior and the stability of operation of a perforated plate type suspension bed in three-phase fluidized beds, respectively.

The purpose of this paper is to investigate the optimal conditions for maximizing the separation efficiency in dry triboelectrostatic process to separate PVC and PET materials using fluidized-bed tribocharger. The laboratory scale electrostatic separation system consists of the fluidized-bed tribocharger, a separation chamber, a collection chamber, and a controller. Separation testing is conducted as a function of tribocharger material, airflow rate, electric field strength, and particle mixing ratio.

TRIBOELECTROSTATIC SEPARATION

Electrostatic separation is broadly applicable to dry processing

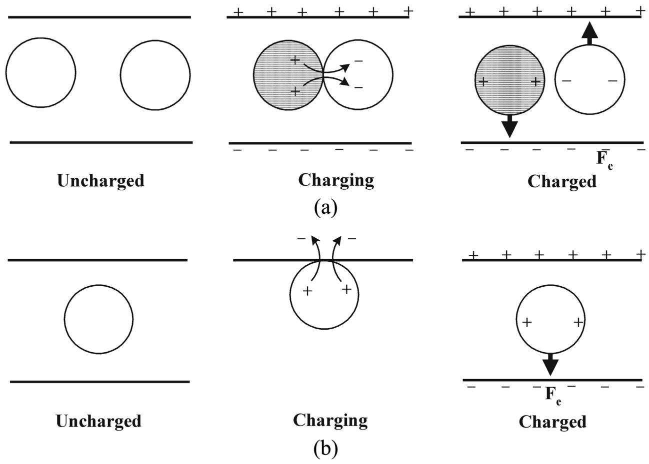

Fig. 1. The principle of triboelectrification [Kelly and Spottiswood, 1989] [(a) particle-to-particle impact, (b) particle-to-wall impact].

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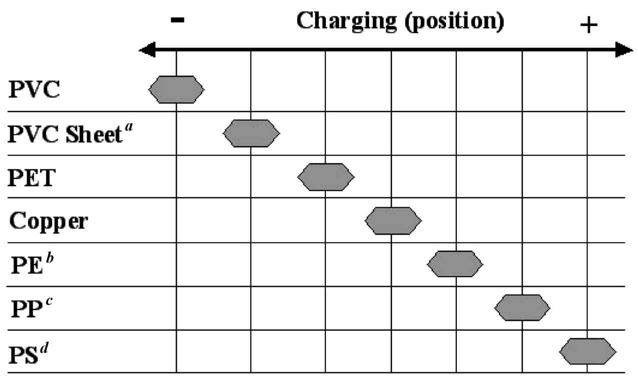
in recycling plastic wastes, mineral processing industry, and coal beneficiation [Gupta et al., 1993]. This process separates materials based on one or more of their electrical properties such as work function or triboelectric charging series.

Fig. 1 shows the principle of triboelectrification by the particle-to-particle impact and the particle-to-wall impact. Tribocharging or frictional charging is the process whereby a charge exists on a material after the part of a solid/solid contact. When two materials are brought into contact, charge is transferred between them until their Fermi levels equalize. The material having a higher work function gains electrons and is charged negatively, while the material having the lower work function loses electrons and is charged positively. The work function or contact potential is defined as the difference between the energy of an electron at the Fermi level inside the surface of the material and an electron at rest in vacuum outside the material. The Fermi level is defined as the level at which the probability of finding an electron is 0.5. Therefore, the material of a higher work function means having higher affinity for the electron, and gains the electron from the material of a lower work function. When two materials with different work functions come into contact, electrons will flow from one of the higher work function to the other until the Fermi levels of the materials will be equilibrated [Mukherjee, 1987; Fraas, 1962].

Fig. 2 shows the triboelectric charging sequence of various materials [Brandrup, 1996]. In principle, all the plastics listed may be separated from each other, regardless of their density. The qualitative representation should be interpreted as follows: when two plastics come into contact the left one becomes negatively charged while the right one positively. The farther apart, the easier the selective charge exchange between two particles takes place. For example, if PVC is put into contact with PET, the PVC becomes negative and the PET positive. On the other hand, if PET is put into contact with PS, the PET becomes negative and the PS positive.

Fig. 3 shows the principle of electrostatic separation for separating PVC and PET particles from the mixed plastics. It consists of the tribocharger to impart the charge on the particles and a separation chamber to collect the separate particles. When PVC and PET particles come into contact with one another in the fluidized-bed tribocharger, the PVC becomes negative and the PET positive. And both PVC and PET particles can be separated by passing them through an external field in the electrostatic separation plates.



^a PVC Sheet : PVC (60%) + Plasticizer (30%) + Softener etc. (10%)
^b PE : Polyethylene
^c PP : Polypropylene
^d PS : Polystyrene

Fig. 2. Triboelectric charging series of plastics [Brandrup et al., 1996].

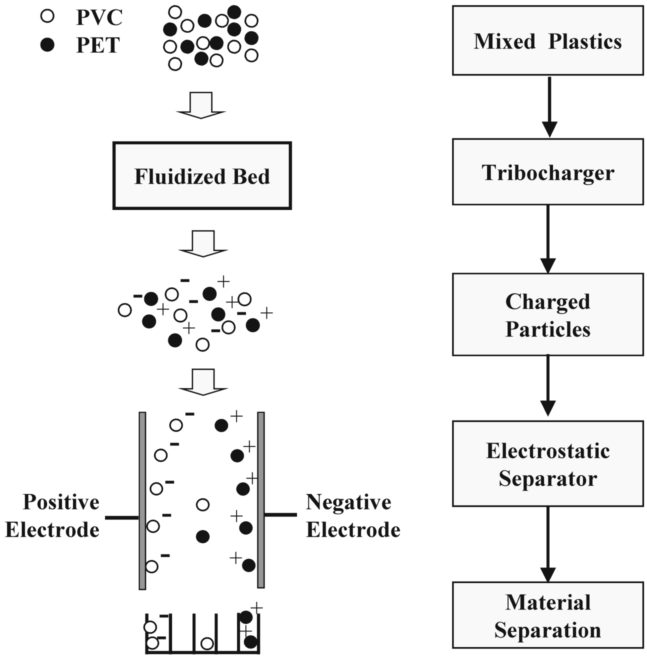


Fig. 3. Schematic diagram of the experimental system for electrostatically separating PVC from the mixed PVC/PET plastics.

EXPERIMENTAL

1. Triboelectrostatic Separation System

Fig. 4 shows the schematic diagram of the laboratory scale triboelectrostatic separation system to separate PVC materials from

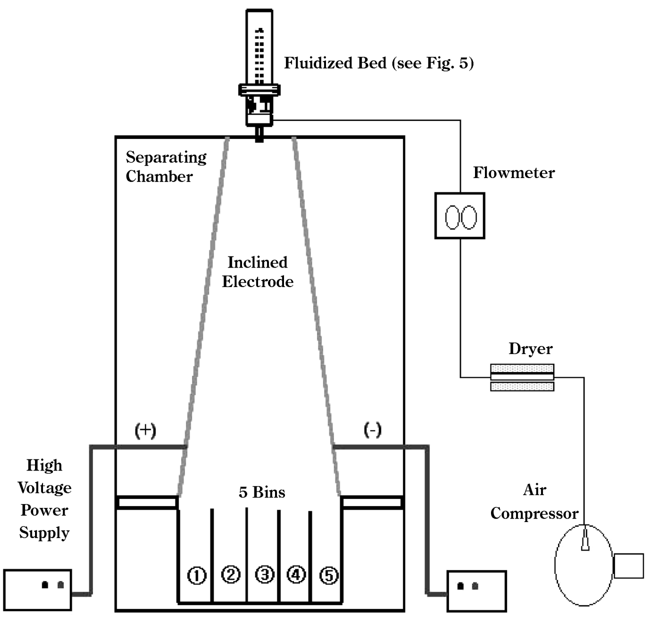


Fig. 4. Schematic diagram of electrostatics separation system using the fluidized bed tribocharger.

mixed plastics. It consists of the fluidized-bed tribocharger, the separation chamber (650×470×1,000 mm^3) with two plate electrodes (450×1,000×5 mm^3), the collector (600×450×240 mm^3) and the high voltage power supply. The separation chamber contains two inclined aluminum plates which are applied a high voltage and disposed 150 mm apart from both sides of the separation chamber. The inclined plate electrodes with 5^o inclined angle are maintained at potentials of up to ±30 kV, thus producing a maximum potential difference of 60 kV between the electrodes. The collector containing five collection bins is placed at the bottom of the separation chamber to catch any entrained plastic particles. Plastic particles are fluidized and charged inside the fluidized-bed tribocharger. The charged particles are entrained in the separation chamber. As the particles fall through the chamber, they are deflected forward one electrode or the other, depending upon their charge. The particles charged positively during the fluidization process are deflected toward the negative electrode while the negatively charged particles toward the positive electrode. The bins closely located to the positive high voltage electrode collect the negatively charged material, while the opposite side bins collect the positively charged material. Materials having insufficient charge for separation are collected in the central area. After separation tests, the efficiency of the electrostatic separation can be obtained by measuring the mass of collected particles in each bin with an electrical digital balance (OHAUS-GT 4100).

Fig. 5 shows the schematic diagram of the fluidized-bed tribocharger to impart the charge on test particles. The discharge from the fluidized bed is accomplished by means of a central pipe in the fluidized bed which is gradually moved downwards allowing the fluidized material to flow through the pipe while retaining its acquired charges. The fluidized bed consists of an acrylic and copper vessel (Φ 50, 250 mm length). The copper vessel with the PVC sheet added plasticizers and softeners inside the vessel is used in this study. The bed is supported on the perforated plate used as an air distributor with an opening size of 1.5 mm. To minimize charge leakages by conduction, the fluidization column is insulated from the supports by means of a thick layer of silicone rubber. During fluidization, the plastic particles acquire electrostatic charge due to triboelectrification. The introduction of a fluidizing gas, typically compressed air, should not introduce a significant charge to the bed of particles. When plastic particles are fluidized by compressed air over minimum fluidizing air flow rate inside the fluidized-bed tribocharger, plastic particles traveling upward in the wake of air bubbles are replaced by particles traveling downward and charged by particle-particle and particle-wall frictional contact. Increasing the air bubble size brings about an increase in the degree of charging. Since bubbles of greater diameter rise more rapidly, then the intensity of the bed-particle movement in the vicinity of the bubble must also increase. The mechanism by which charges segregate when two materials are brought into contact has been explained in terms of electron exchange. The number and direction of the electrons that transfer between two materials depend on numerous variables such as the bulk chemical composition of materials, surface moisture and roughness, particle size and sharpness, tribocharger type, orientation of materials during contact, area and duration of contact, and relative velocity of materials.

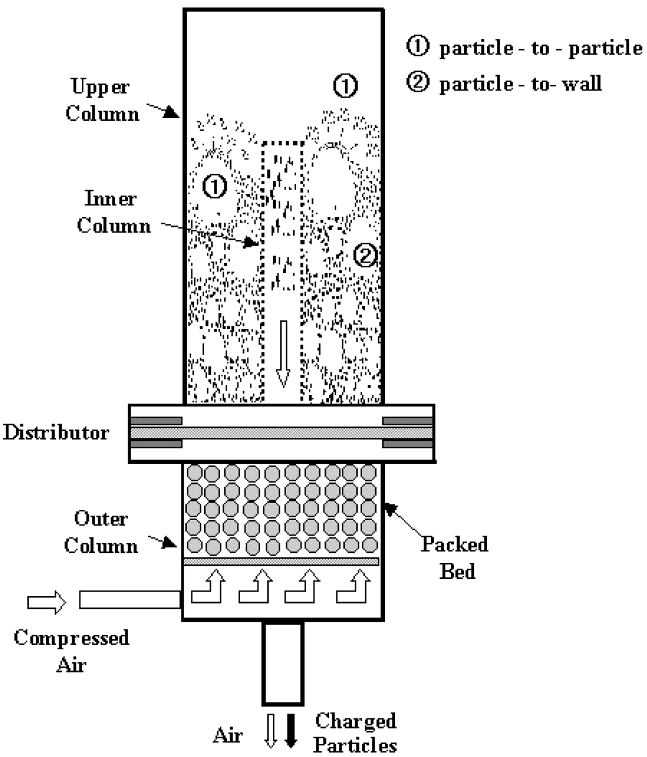


Fig. 5. Schematic diagram of the fluidized bed tribocharger for charging mixed plastic particles.

2. Test Material and Conditions

Table 1 shows the experimental conditions for separating PVC and PET particles from two-component mixed plastics by using the fluidized-bed tribocharger. Polyvinylchloride (PVC) and polyethylene terephthalate (PET) plastic particles are used in this study. Experiments are carried out with particles in granular form, of irregular sharp, and of the size range of 1.4-2 mm. Since triboelectric charging depends not only on the chemical constitution of the particles to be separated, but also on their surface condition, particles are washed out with water and dried to remove the charge and ensure a similar surface state of particles before each experiment. The range of air flow rate and electric field strength are 110-190

Table 1. Experimental conditions in separation of two component mixed plastics

Parameters	Specification
Particle materials	PVC[a], PET[b]
Specific gravity	1.30-1.40 (PVC)
	1.38-1.41 (PET)
Particle size	1.4-2 mm
Particle feeding rate	10 g/min
Tribocharger materials	Copper, PVC sheet
Electric field strength	0.6, 1.7, 2.6 kV/cm
Air flow rate	110, 150, 190 *l*/m
Particle mixing ratio (PET/PVC)	1, 3, 5, 7
Temperature	18 °C
Relative humidity	30%

[a]PVC: Polyvinylchloride
[b]PET: Polyethylene terephthalate

lpm and 0.6-2.6 kV/cm, respectively. All experiments are performed at a temperature of 18 °C and relative humidity of 30%. The fluidizing air is dried in a tower packed with silica-gel in the inlet to the apparatus.

RESULTS AND DISCUSSION

The quality and effectiveness of the electrostatic separation process can be described in terms of the extract content and the yield defined below:

$$\text{Extract content} = \frac{\text{Mass of the sought component in the extracted fraction(s)}}{\text{Mass of the extracted fraction(s)}} \quad (1)$$

$$\text{Yield} = \frac{\text{Mass of the sought component in the extracted fraction(s)}}{\text{Mass of the sought component in the processed mixture}} \quad (2)$$

Fig. 6 illustrates the nomenclature for the data analysis of the separation test. PVC yield in bin #1 is described by the ratio of PVC mass collected in bin #1 by PVC mass collected in bins #1-5. By weighing the mass collected in each of bins and taking into account the respective extract contents, the extract content and yield for each component can be calculated.

1. Extract Content and Yield of PVC/PET Separation

Fig. 7 shows the fractional extract content and yield of PVC and PET materials among the five collection bins placed at the bottom of the separating chamber. The separator is operated in this case with a 50/50% mixture by mass of PVC and PET at 2.6 kV/cm electric field strength, 10 g/min particle feeding rate and copper tribocharger. For the extract content shown in Fig. 7(a), bin #1 collects 91.9% pure PVC, whereas bin #5 collects 99.2% pure PET. For the

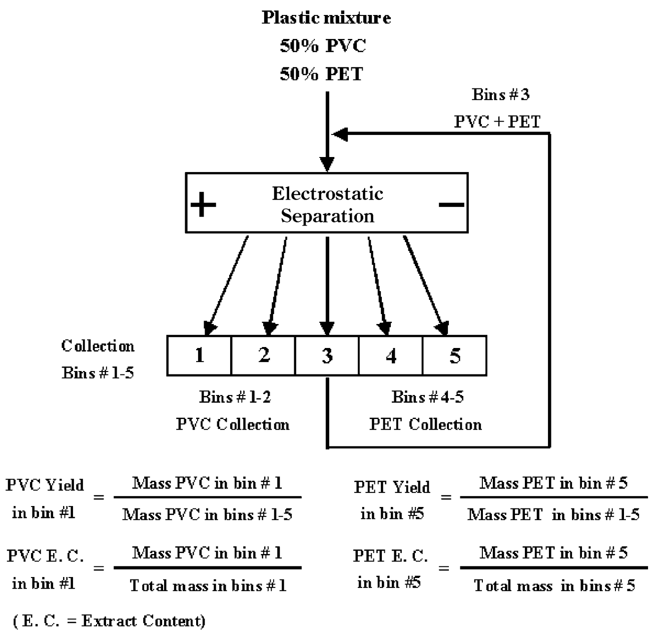


Fig. 6. Nomenclature used for the analysis of the results and the equations for the calculation of the yield and the extract content.

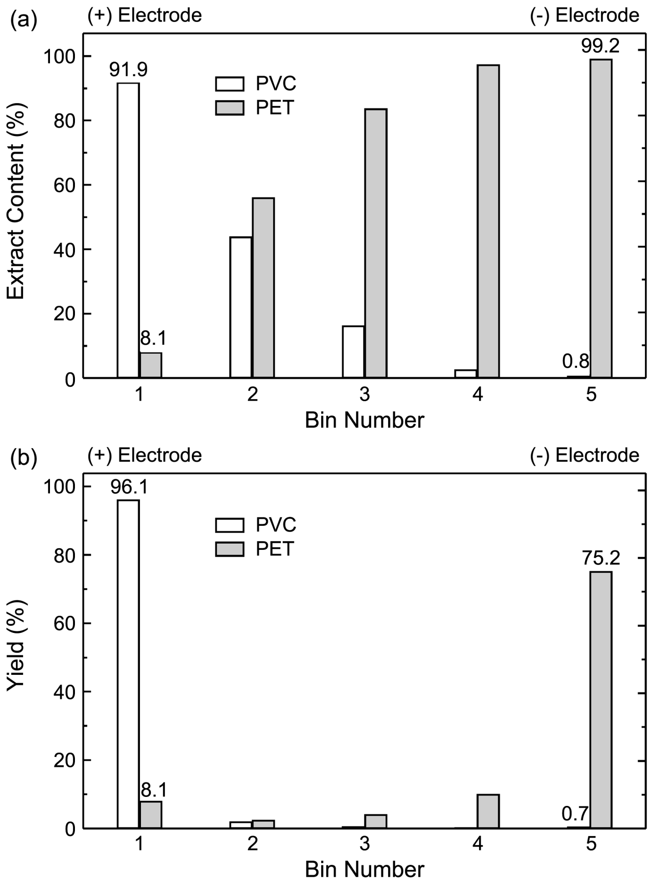


Fig. 7. Fractional extract contents and yield in five collection bins for PVC and PET [(a) extract content, (b) yield].

yield of PVC and PET as shown in Fig. 7B, bin #1 collects 96.1% from the mass of PVC supplied, whereas the rest of bins #2-5 collect 3.9%. In case of PET, bin #5 collects 75.2% from the mass of PET supplied. Most of PVC particles (the left one of the triboseries) become negatively charged and are collected in bins #1 and #2, while PET particles (the right one of triboseries) become positively charged and are collected in bins #4 and #5 as shown in Fig. 7(b). The highly concentrated PVC (91.9%) with a yield of about 96.1% from the mixture of PVC and PET material is obtained in bin #1. In the central bin #3, the extract content of PVC is low and would require a second stage of processing.

Fig. 8 shows the separation results of the cumulative extract content and yield for a mixture of 50% PVC and 50% PET particles measured in each of the individual collection bins #1 to #5. That is, in Fig. 8(a), the cumulative yield of PVC in bin #2 can be obtained from the ratio of PVC mass in two bins #1 and #2 divided by the supplied PVC total mass, while the cumulative extract content of PVC in bin #2 can be obtained from the ratio of PVC mass in two bins #1 and #2 divided by the mass of two bins #1 and #2 collected. PVC material can be recovered 96.1% at the extract content of 91.8% in bin #1, 98.2% at the extract content of 89.8% in two bins #1 and #2, 99% at the extract content of 86.5% in three bins #1-#3, 99.3% at the extract content 79.2% in the four bins #1-#4, and 100% at the extract content 48.7% in the five bins #1-#5. The number of collection bins for PVC recovery can be designed from the results of the cumulative yield and extract content. The higher extract con-

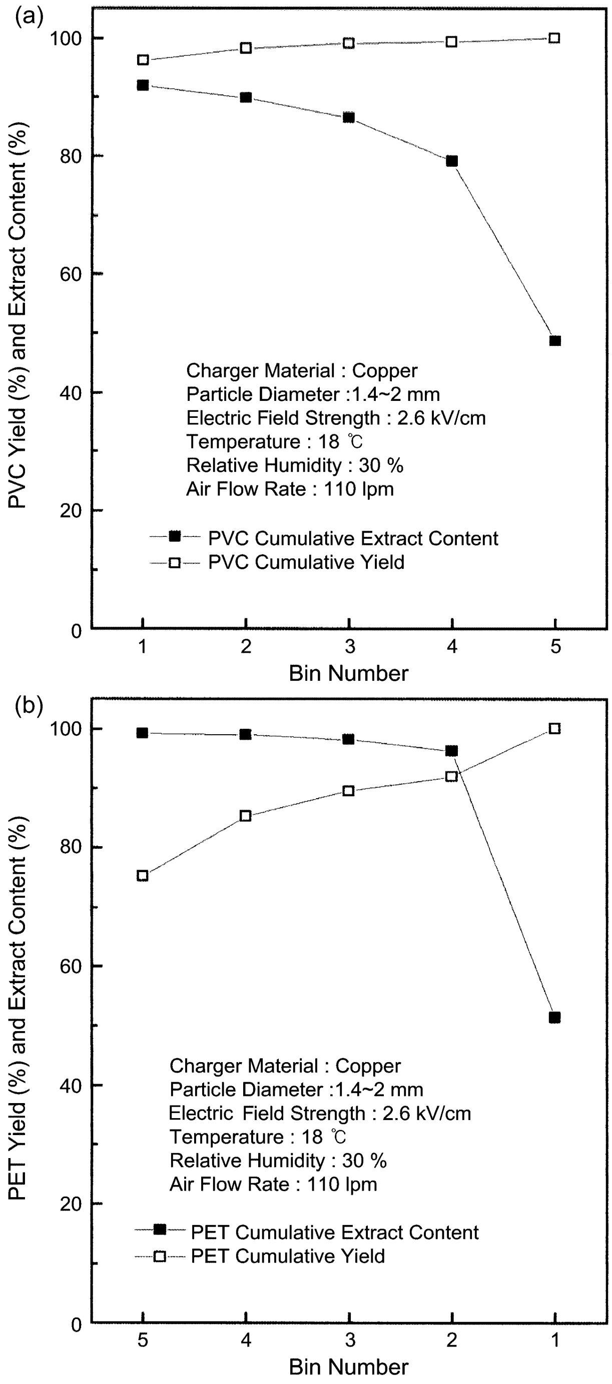


Fig. 8. The separation results of the cumulative extract content and yield for a mixture of 50% PVC and 50% PET particles [(a) PVC, (b) PET].

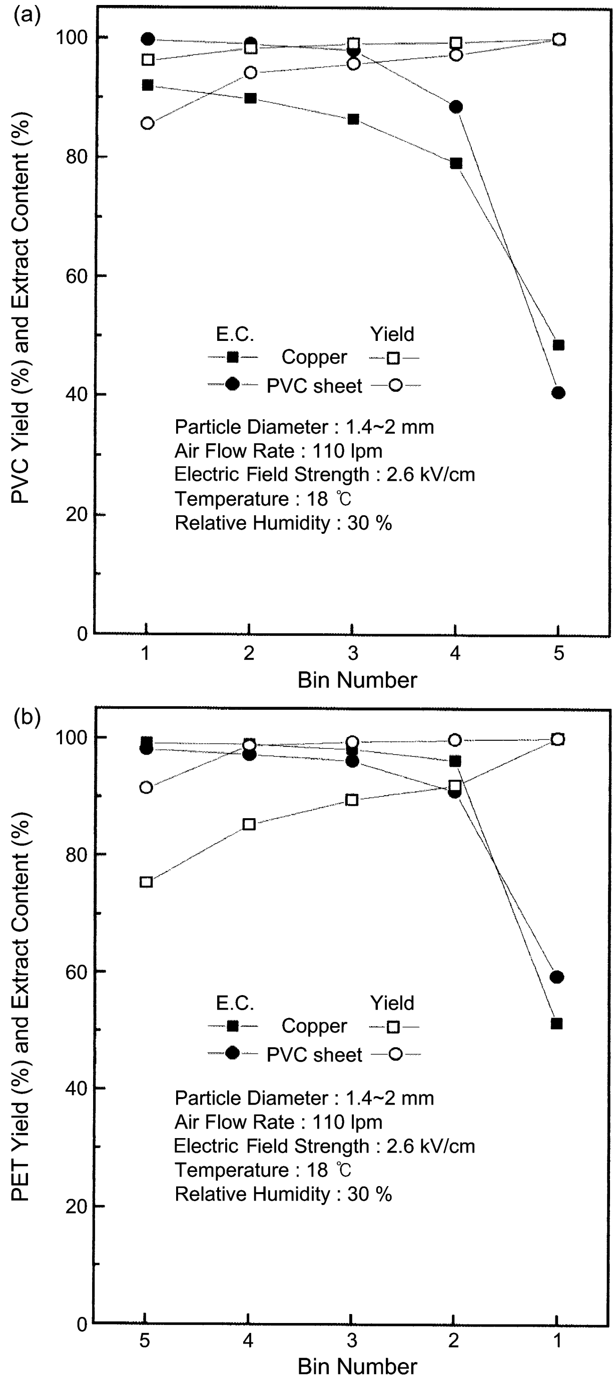


Fig. 9. Extract content and yield of PVC/PET as function of tribocharger materials [(a) Copper, (b) PVC sheet].

tent of PVC gets, the lower yield produces. In Fig. 8(b), the cumulative extract content and yield of PET can be calculated from the starting bin #5 of the negative electrode which collects most PET particles. PET material can be recovered 75.2% at the extract content of 99.1% in bin #5, 85.3% at the extract content of 98.9% in two bins #5 and #4, and 100% at the extract content 51.3% in the five bins #1-#5. In summary, for a single stage of processing and by combining the contents of the two bins closest to the each electrode, it is possible to recover 98.2% of the PVC at the extract content of 89.8% and 85.3% of the PET with the extract content of 98.9%.

2. Effect of Tribocharger Materials

Fig. 9 shows the separation results of the cumulative extract content and yield as a function of tribocharger materials. Copper vessels without or with the PVC sheet added plasticizers and softeners inside the vessel are used. Triboseries of copper and PVC sheet is shown in Fig. 2. A mixture of 50% PVC and 50% PET particles is measured in each of the individual collection bins #1 to #5. Particle diameter and the electric field strength are 1.4-2.0 mm and 2.6 kV/cm, respectively. In bin #1 of Fig. 9(a), the yields of PVC particles for the vessel material without and with PVC sheets are 96.1 and 85.6%, respectively, while the extract contents are 91.9 and 99.6% respectively. And, in bin #5 of the Fig. 9(b), the yield of PET particles for the vessel material without and with PVC sheets is 75.2 and 91.4%, respectively, while the extract contents are 99.1 and 98%, respectively. The vessel material with PVC sheets added plasticizers and softeners enhances the yield of PET particles and the extract content of PVC particles. The tribocharger material is undoubtedly important because the difference in the triboseries determines the polarity and magnitude of the charge. When PVC and PET particles in the copper surface of the fluidized-bed tribocharger come into contact with one another, the PVC becomes negative and the PET positive for the case of the particle-to-particle contact, while the PVC and PET become negative for the case of the particle-to-wall contact. On the other hand, when PVC and PET particles inside the PVC sheet surface of the fluidized-bed tribocharger come into contact with one another, the PVC becomes negative and the PET positive for all cases. It is important to select the optimum tribocharger material according to materials of the mixed plastics for separating. The choice of the optimum material for the walls of the

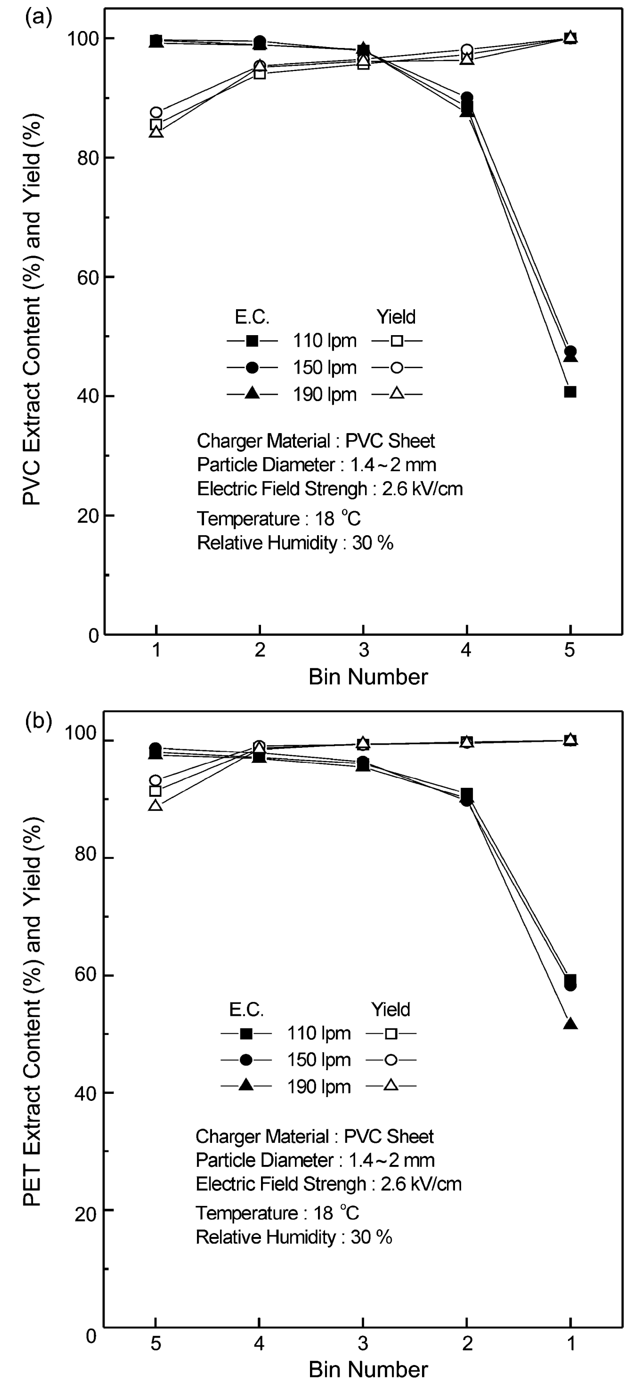


Fig. 10. Extract content and yield of PVC/PET as function of air flow rate [(a) PVC, (b) PET].

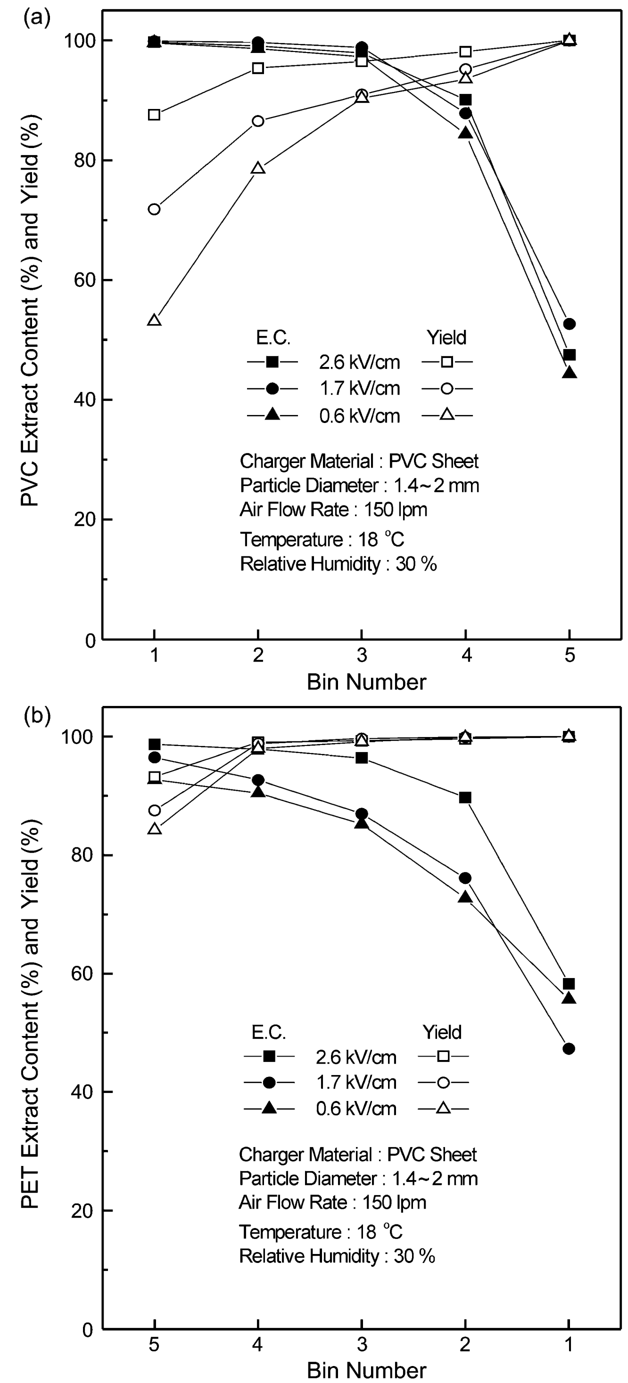


Fig. 11. Extract content and yield of PVC/PET as function of electric field strength [(a) PVC, (b) PET].

tribocharger must be such as to enhance the desired triboelectrification.

3. Effect of Air Flow Rates

Fig. 10 shows the separation results of the cumulative extract content and yield as a function of air flow rate through the fluidized-bed tribocharger. A mixture of 50% PVC and 50% PET particles is measured in each of the individual collection bin #1 to #5. Particle diameter and the electric field strength are 1.4-2.0 mm and 2.6 kV/cm, respectively. The air flow rates are 110, 150 and 190 lpm. For the air flow rate of 110 lpm being indicative of minimum fluidizing air flow rate, PVC material can be recovered 94.1% at the extract content of 99.0% in two bins #1, #2 and PET material recovered 98.7% at the extract content of 97.1% in two bins #4, #5. For the air flow rate of 150 and 190 lpm, the cumulative extract content and yield of PVC and PET particles is similar to that of 110 lpm. Air flow rate more than minimum fluidizing flow rate does not play an important role on the yield and the extract content of PVC and PET particles. During fluidization and transport, PVC and PET particles acquire electrostatic charge due to the particle-to-particle and particle-to-wall contacts. Particles reach to the maximum

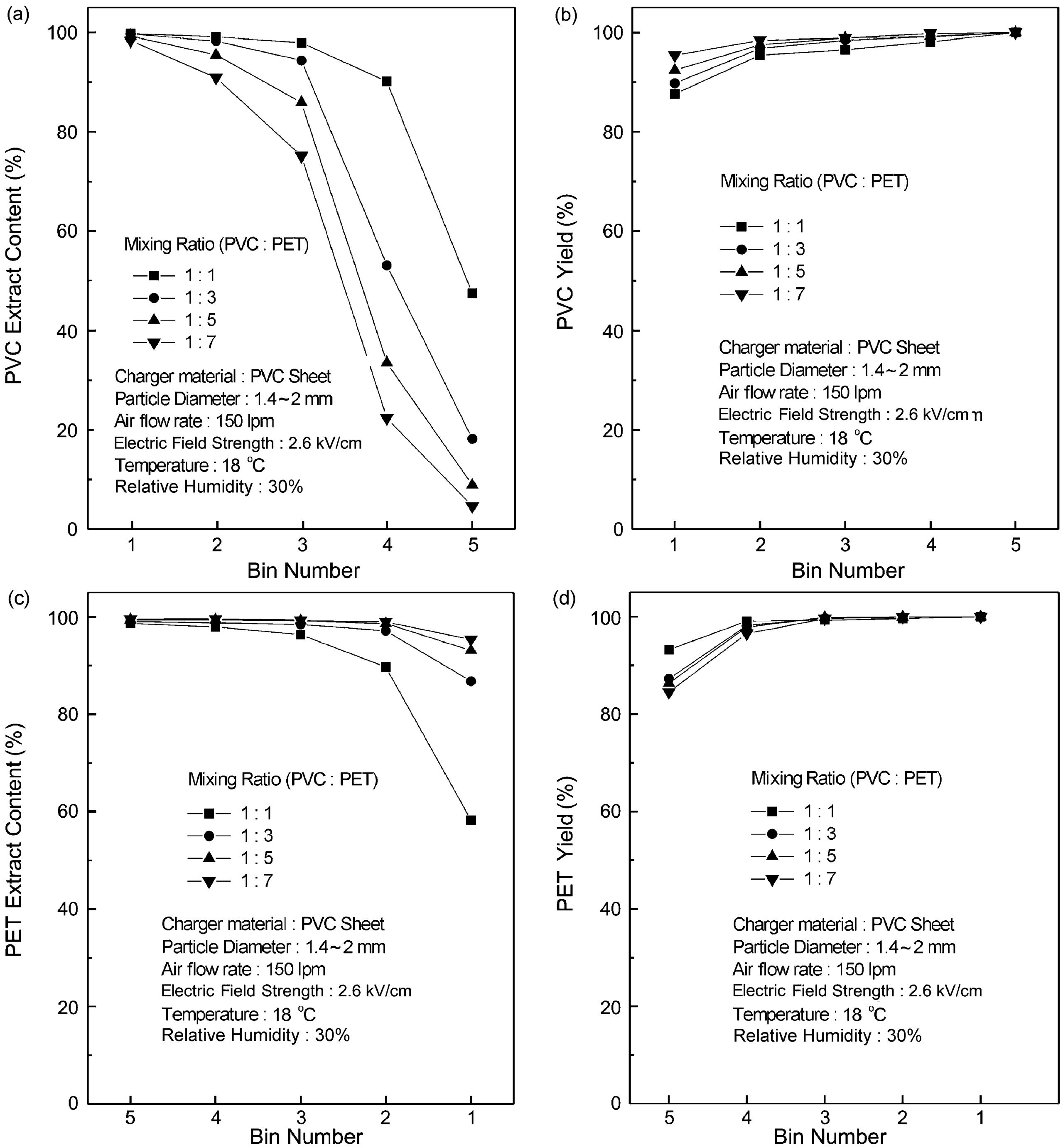


Fig. 12. Extract content and yield of PVC/PET as function of particle mixing ratio [(a) PVC extract content, (b) PVC yield, (c) PET extract content, (d) PET yield].

charge values at the air flow rate of minimum fluidizing air flow rate. It is necessary to maintain the minimum fluidizing air flow rate for the fluidization of each particle.

4. Effect of Electric Field Strength

Fig. 11 shows the separation results of the cumulative extract content and yield as a function of electric field strength for a mixture of 50% PVC and 50% PET particles measured in each of the individual collection bins #1 to #5. The electric field strength is controlled by high voltage power supply from 0.6 to 2.6 kV/cm. The stronger the field strength is, the higher the separation efficiency is. The electric field strength has an influence on the electric force to charged particles in the electric field. An increase of the electric filed strength caused electric force to act on charged particles with their charge level and polarity. In the optimal conditions (150 lpm, 2.6 kV/cm), PVC material can be recovered 95.4% at the extract content of 99.1% in two bins #1 and #2, and PET material can be recovered 99.1% at the extract content of 97.9% in two bins #5 and #4 for a single stage of processing.

5. Effect of Particle Mixing Ratio

Fig. 12 shows the separation results of the cumulative extract content and yield as a function of particle mixing ratio for a mixture of PVC and PET particles measured in each of the individual collection bin #1 to #5. The mixing ratio of PET to PVC particles ranges from 1 to 7. The particle mixing ratio has an influence on the charging mechanism between particles inside the fluidized-bed tribocharger. In bins #1, #2 of Fig. 12(a) and (b), the extract content of PVC particle is decreased from 99.1% to 90.9%, but the yield is increased from 95.4% to 98.4% as the particle mixing ratio is increased. And, in bins #4, #5 of Fig. 12(c) and (d), the extract content of PET particles is >98%, but the yield is decreased from 99.1% to 96.5%. This result means that some of the PET particles become negatively charged by the triboelectrification between PET particles as the mixing ratio of PET to PVC particle is increased in the fluidized-bed tribocharger.

In the optimal conditions with PVC sheet tribocharger material, 150 lpm air flow rate, 2.6 kV/cm electric field strength and 1 : 1 particle mixing ratio, PVC material can be recovered 95.4% at the extract content of 99.1% in two bins #1 and #2, and PET material can be recovered 99.1% at the extract content of 97.9% in two bins #5 and #4 for a single stage of processing. Therefore, in the practical application of the triboelectrostatic separation system using the fluidized-bed tribocharger, the mixing ratio of the mixed plastic particles should be investigated according to the ratio of the waste plastic generation.

CONCLUSIONS

We have investigated the triboelectrostatic separator using the fluidized-bed for the optimal conditions for maximizing the separation efficiency from mixed PVC and PET plastics. Experimental results show that separation efficiency is strongly dependent on the tribocharger material, electric field strength and particle mixing ratio. In the optimum conditions of PVC tribocharger material, 150 *l*/m air flow rate, and 2.6 kV/cm electric field strength, highly purified PVC (99.1%) can be recovered with a yield of about 95.4% from the mixture of PVC and PET materials in a single stage of processing. The triboelectrostatic separation system using the fluidized-bed tribocharger shows the potential to be an effective method for removing PVC from mixed plastics for waste plastic recycling.

ACKNOWLEDGMENT

This study is supported financially by Pusan National University Research Grant and the Korea Science and Engineering Foundation through the Institute for Environmental Technology and Industry (IETI), Pusan National University, Korea (Project number: 99-10-04-01-A-3). The authors gratefully acknowledge the financial support.

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