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Methods of Separating Used Plastics for Recycling

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Abstract

Plastics waste constitutes approximately 23% by volume of the municipal solid waste (MSW) generated in the U.S. each year, and have slow rate of degradation in the environment. Therefore, there is a great deal of public pressure to recycle plastics, and more than 100 million people participate in the curbside recycling programs Despite the high level of public interest, only 3.5% of the plastic are recycled, which is substantially lower than the recycle rates of other materials such as paper fibers, glass, and iron. Although a large part of the reason is due to the low price of virgin polymers, which in turn is due to the low price of oil, it is possible to make the plastics recycling as a profitable business by developing advanced technologies. In this communication, various methods of separating plastics from metals and from each other are discussed.

1. Introduction

In 1993, the U.S. produced 70 billion pounds of virgin polymers. Approximately one third of the material was used for packaging and transportation, relatively short-life products, and the balance was used for construction, furniture, appliances, electrical and other longer-life products (Anon., 1994). During the same year, 16 billion pounds of plastics entered the municipal solid waste (MSW) stream, which accounted for 9.3% by weight and 23.1% by volume of the total MSW. Because of its large volume fraction, a significant part of the landfill cost is attributed to plastics. Also, the landfill of plastics raises environmental concern that the material degrades very slowly. These concerns created a significant public pressure to recycle plastics.

In 1988, there were about one thousand curbside recycling programs in the U.S. In 1994, this number grew by seven fold, involving more than 100 million people. At present, approximately 34.0% of the paper, 22.0% of glass, 26.1% of steel, 3.5% of plastics and 5.9% of rubber and leader are recycled. The low percentage of plastics recycled indicates that there are problems in making plastics recycling into a profitable business. Part of the reason is the low price of the virgin polymers, which in turn can be attributed to the low oil price. On the other hand, the cost of recycling can be reduced substantially by improving the technologies involved and building more efficient infrastructure.

There are two important factors that determine the profitability of recycling businesses, i.e., i) processing cost and ii) the quality of recyclate relative to that of the corresponding virgin material. In general, polymer recyclates are inferior to first-quality virgin polymers; therefore, the recyclates sell at 65 to 85% of the virgin polymers. The relatively small price differential is the main reason for the low level of recycling plastics. On the contrary, the recycled paper pulp sells at prices less than 20% of the virgin pulp, which is the reason that 34% of the paper in MSW is recycled. Thus, there are only two possibilities for increased recycling of plastics. Either the price of oil goes up significantly, or technological improvements are made to increase the product quality and reduce the processing cost. It is also possible to subsidize the recycling cost by legislation. which is not a desirable solution, however.

Fig. 1 shows the life-cycle of plastics beginning from virgin polymer resin (Radar and Stockel, 1995). Any pronounced difficulty in any of the steps involved in the post consumer recycling process can make recycling impractical relative to the other options, i.e., landfill and incineration. The *first step* in the post-consumer recycling process is the collection of used articles. There are several different collection options. including. i) voluntary drop-off ii) buy-back, and iii) curbside collecion. The *second step* in the recycling process is the separation, which includes sorting, shredding

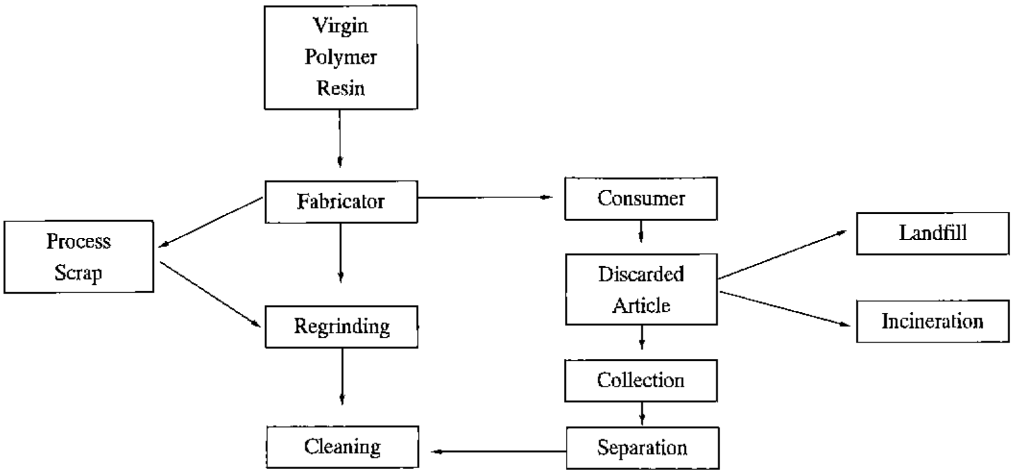

Fig. 1. The life cycle of plastics (Radar and Stockel, 1995).

(and grinding), separation, and cleaning. The cleaned recyclate is dewatered, reground and used for fabricating new products. It is the purpose of the present communication to review the current post-consumer recycling processes for plastics, with an emphasis on the review of separation processes.

2. Separation Methods

2.1. Sorting

Collected materials are delivered to materials recovery facilities (MRF), which are usually built at 100 to 500 tons per day capacity. On arrival at an MRF, commingled materials are dumped onto the "tipping floor," where containers are manually separated from news papers and then pushed with a front-end loader onto a conveyer belt. The various containers on the belt are separated according to the flowsheet shown in Fig. 2 (Saba and Pearson, 1995). The steel cans are removed from glass and plastics by magnetic separators. while aluminum cans are removed by eddy current separators. After removing glass containers by exploiting the differences in specific gravities (SG), the plastics are hand-sorted into different types of plastic bottles, i.e., PET soda, HDPE milk, water and juice, HDPE detergent, PVC water and PP ketchup. etc. The separated plastics are then baled and shipped to reclaimers.

The hand-sorting is, however, is labor-intensive and costly. Therefore. many different types of automatic sorting machines have been developed recently (Dinger, 1992). Fig. 3 illustrates the operating principle of typical automatic sorting devices. A feed passes over a plate which is equipped with a sensor or a series of sensors to identify different objects. The signal is processed by a computer, which in turn sends a signal to the solenoid that can actuate the air jet to remove the identified object from the feed stream.

The Center for Plastics Recycling Research, at the State University of New Jersey, Rutgers. developed a system to separate PET, unpigmented HDPE, and pigmented containers using the light transmission properties of the resins. It is based on a single station, multidetector system with

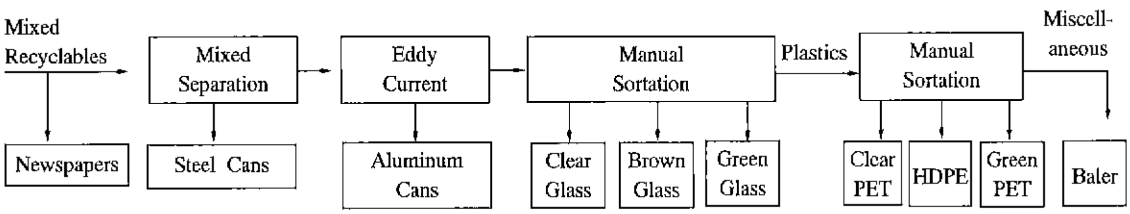

Fig. 2. Flowsheet at a typical materials recovery facility (Saba and Pearson. 1995).

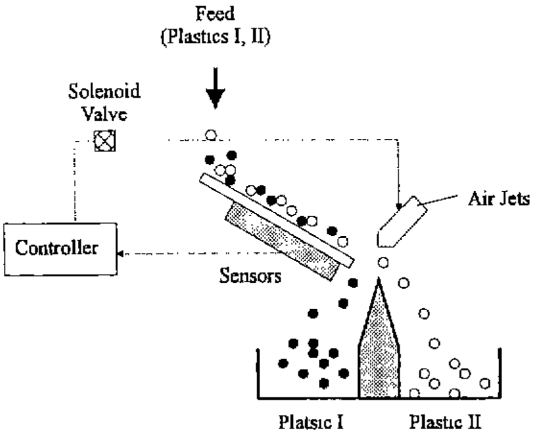

Fig. 3. The layout of a typical automatic sorting system.

computer software to tract the containers and eject them by resin and color into separate downstream containers.

Asoma Instruments, Inc., Austin, Texas, developed an automatic sorter that can detect PVC using an X-ray fluorescence (XRF) analyzer and eject them from PET. Because of the chlorine, PVC responds to X-ray. The first unit was sold in 1989. The new model, Asoma VS-2, can identify PVC bottles traveling in single file anywhere in one foot wide channel at a speed of 10 feet per second, with a miss rate of one bottle per 100,000. Several units can be installed side by side to cover wider channels and increase the throughput.

The *Vinyl Cycle* developed by National Recovery Technologies, Inc., Nashville, Tennessee, also uses an XRF sensor to dientify PVC. The system works on whole or crushed bottles, and does not require that the containers be delivered single file. Vinyl Cycle consists of a row of detectors beneath the width of a conveyer belt. The computer tracks a PVC bottle and ejects it by an air jet. Other containers in the vicinity of a PVC bottle can also be ejected. Thus. the reject stream contains bottles other than PVC, but the main stream is essentially PVC-free. The throughput is in the range of 2,000 to 5,000 pounds per hour

Magnetic Separation System, Nashville, Tennessee, developed an integrated high-speed sorting system, which is capable of separating four of the most common plastics, i.e., PET, PVC, HDPE, and PP. The MSS *Bottlesort* employs a primary detector system to separate bottles into three streams :

- PE and PVC,
- Unpigmented HDPE and PP, and
- mixed color opaque

Each product stream can be further processed to separate i) PVC from PE, ii) green and amber PET from clear PET, iii) unpigmented HDPE from unpigmented PP, and iv) mixed color opaque into seven individual colors or combinations of colors. The primary system is capable of handling 1,250 pounds per hour (pph).

Automation Industrial Control, Baltimore, Maryland, developed a system using a pair of detectors at a single station, one for determining resin type, and another for identifying color. It is capable of separating all of the common packaging resins, i.e., PET. HDPE, LDPE, PVC, PP, PS, and PC. The throughput is 1,500 pph, or three bottles per second

Many companies are considering marking either the container or the resin for easy detection and separation. Quantum Corporation, Cincinnati. Ohio. is considering adding fluorescent compounds, and Eastman Chemical Company announced the development of a molecular marker that can identify not only the type but also the grade of resins.

2.2. Size reduction

Once the plastic containers have been sorted out by kind, they are shredded into flakes to liberate impurities, such as aluminum, dirt, oils, etc., from plastics This process is akin to the crushing and grinding of ores to liberate valuable minerals from impurities before separaion. There are various types of shredders that are used to size-reduce plastics before separation. Shredders are available with two or four cutting shafts, and it is important that the cutters have separate drivers running at widely different speeds (Mustafa and Hansman, 1993). For handling bulky products, such as sacks and foam parts, rotating screw shafts can be used. Guillotines are used when it is essential to separate large waste parts that have fused or meshed together.

After plastics have been separated and washed, they are granulated to $\frac{1}{8}$- to $\frac{1}{4}$-inches. Wet-milling is often used to prevent the clogging of screens and the degradation of plastics that can be caused by frictional heat. If powdered material is needed, plastics can be pulverized in a cryogenic grinding mill (Anon , 1977)

2.3. Gravity Separation

Various techniques are used for separating minerals and coal based on their SG differences. For example, coal (SG$\approx$ 1 4) is separated from non-combustible mineral matter (SG $\approx$2.5) in a dense-medium whose SG is in between the two The same technique is used for separating plastics from

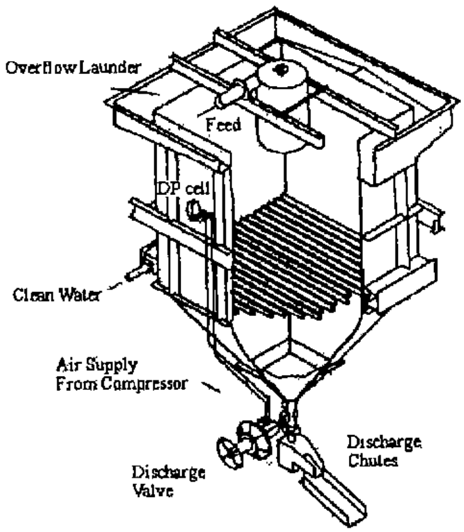

Fig. 4. The flotex density separator.

heavier materials such as copper, aluminum and ferrous metals Because of the large differences in SGs between plastic and metals, the separation can be very efficient. It is more difficult to separate various plastics from each other using gravity separation techniques; however, many investigators showed that it can be done.

Fig. 4 shows a Flotex density separator, which is marketed by Carpco Inc. in the U.S. for the chopped wire recycling industry. The feed to this separator consists of the rejects from air tables and electrodynamic separators, and contains less than 2% by weight of metallic copper, plastic insulation, broken glass, rocks. organic debris, etc. In order to improve the segregation (or liberation) of these materials from each other, the feed is scrubbed in a series of attritors which contains 55 to 60% sands. The scrubber discharge is fed along with the sand to the top of the separator, which is equipped with a series of perforated water spray pipes located at the bottom to provide a uniform current of water flowing upward. This water current keeps the narrowly-sized sand particles in suspension. The water flowrates are adjusted in such a way that the sand particles neither float nor sink, thereby creating a fluidized bed which serves effectively as a dense medium. The effective SG of the sand bed (also referred to as 'teeter bed') lies in the range of 1.2 to 1.7, so that the plastics (GS<1.4) can be readily separated from the metals (SG>7) present in the feed. The pilot-scale test results reported by Mankosa and Carber (1995) show that wire products containing greater than 96% metallics can be obtained with recoveries in excess of 99%.

Table 1 shows the SG values of some of the plastics that are important in recycling. Despite the small differences in SG values, it has been shown that plastics can be separated using appropriate gravity separation techniques. Fig. 5 shows a flowsheet in which a series of dense-medium baths (or float-sink separators) are used to separate different types of plastics from one another (Holman, *et al*, 1974). The dense media with different SGs are prepared by mixing water, alcohol and/or salt.

Fig 6 shows another method of separating plastics by gravity (Holman, *et al*., 1974). A mixture of chopped plastics is fed into the sink-float separator where polyolefins are floated off and the other components sink. The heavy frac-

Table 1. Properties of various plastics

Plastics	Specific Gravity[1]	Tensile Strength (N/cm^2)[2]	Softening or Melting Temperature (°C)[1]
Polypropylene (PP)	0.85~0.92	3380	160~160
low-density polyethylene (LDPE)	0.89~0.93	827	100
high-density polyethylene (HDPE)	0.94~0.98	2970	130
acrylonitrile-butadiene-styrene (ABS)	1.04~1.06		
polystyrene (PS)	1.04~1.08	5170	70~115
nylone, nylone 6,6	1.12~1 16		
cellulose acetobutyrate	1.15~1.25		
polymethyl methacrylate	1.16~1 20		120~160
plasticized PVC	1.19~1.35		75~90
polycarbonate	1.20~1.22		220~230
polyethylene terephthalate (PET)	1.38~1.14	25000	250~260
rigid PVC	1.38~1.41	4830	

[1]Gnatowski (1993) ; [2]Stessel and Peltz (1994)

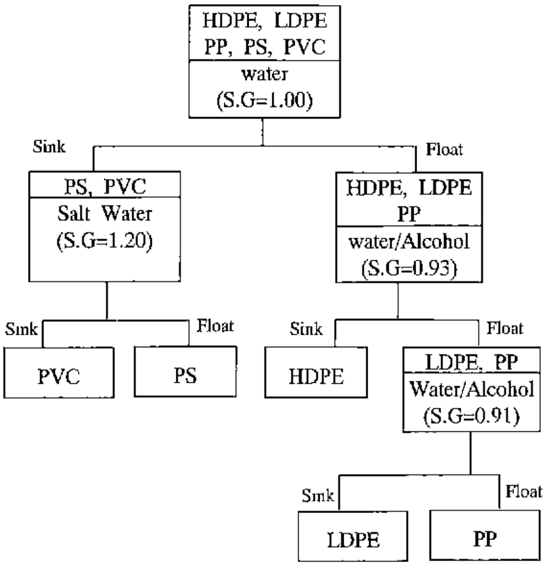

Fig. 5. A four-stage folat-sing scheme for separating waste plastic mixtures (Holman *et al*, 1974).

tion is transported to the elutriation column, where PS is carried with the water current and heavier PVC sinks. The PVC collected at the bottom of the elutriation column is lifted to a collection chamber. All of the products are collected on a screen so that the screen under flow (mostly water) can be recycled. In one test, a feed containing 14% plastic was subjected to this hydraulic separation process The three products were analyzed by laboratory float-sink tests to determine the product quality. As shown in Table 2, the PO and PS products were relatively uncontaminated as compared to the PVC product.

Table 2. Float-sink analysis of the products obtained using the flowsheet shown in Fig. 6

Products		% wt in S.G. Fractions			
	% wt	<1.0	1.0~1.2	1.2~1.5	>1.5
PO	48	97.0	3		
PS	33	0.5	95	4.5	
PVC	19		28	40	32

The gravity separation techniques described in the foregoing paragraphs are wet-processes. A disadvantage is that the product needs to be dried, which is a costly step. Therefore, it would be advantageous to separate plastics using a dry process, if possible. One of the more commonly used dry separation technique is the zigzag air separator shown in Fig 7. A trommel discharge is fed to the separator by means of a rotary feeder. The light plastics are entrained by the upward air current created by the air injected at the bottom section by means of a fan. The heavy materials such as aluminum and steel fall to the bottom and are separated by means of a magnetic separator. The light fraction is discharged through a cyclone and sent to a secondary shredder.

Most gravity separators, including the zigzag air classifier. separate materials based on both SG and size. Therefore, it would be difficult to separate different plastics from each other unless the feed to a separator is narrowly sized. It is difficult, however. to produce narrowly sized shredder products because different plastics have different tensile strengths as shown in Table 1. For these reasons, the zigzag air classifiers are used for separating materials with large

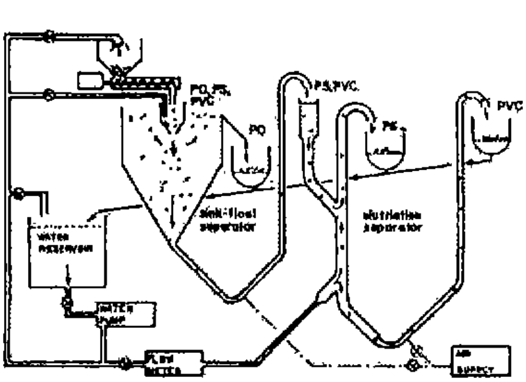

Fig. 6. Hydraulic separation of plastics (Holman. *et al.*, 1974).

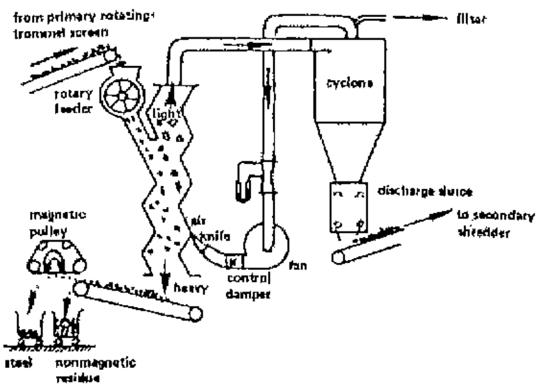

Fig. 7. A zigzag air classifier in close circuit with a cyclone (Jackson, 1975).

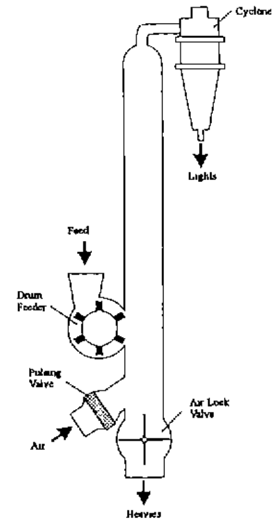

Fig. 8. The active pulsed-flow air classifier (APFAC) (Stessel and Peltz, 1994).

differences SG and size, e.g., metals from plastics and paper. In order to be able to separate plastics from each other, Stessel and Pezel (1994) developed a new air classifier designed to achieve separation substantially according to SG alone. This new separatorm, which is named Active Pulsed-Flow Air Classifier (APFAC), is shown schematically in Fig. 8. The basic operating principles are the same as those of the zigzag air classifier except that the separator is constructed from straight cylinder and that the upward air flow is pulsed. The latter arrangement minimizes the size effect so that plastic particles are separated according to specific gravity. This method is similar in principle to the mechanism of jigging in mineral separation. A pilot-scale APFAC unit was tested by Stessel and Pezel on a shredder discharge containing various plastics with wide size distributions. The best separation efficiencies were obtained between PS and PET, while the separation between HDPE and PVC proved to be more difficult.

2.4. Electrostatic separation

There are several different electrostatic separation methods used for separating granulated mineral particles. These include : i) true electrostatic separation, ii) electro-dynamic separation, and iii) triboelectrostatic separation The true electrostatic separators (Fig. 9) rely on the inductive charging mechanism, in which particles to be separated are brought to an electric field (i.e., to the vicinity of a negative

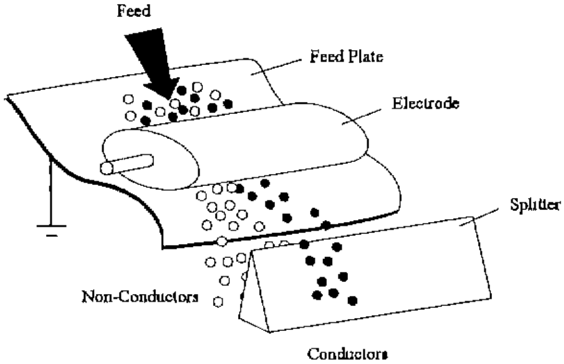

Fig. 9. True Electrostatic Separator.

electrode) where they are inductively polarized. When this happens while the particles are sliding on a grounded feed plate, conducting particles lose the electrons to the plate and become not positively charged, while non-conducting particles remain uncharged. The charged conducting particles are then *lifted* by the electrode, while the non-conducting particles are *pinned* and continue to slide on the plate, thereby achieving separation.

In electrodynamic separation, granulated particles are fed on a grounded metal roll and bombarded with corona charges as shown in Fig. 10. The corona charges are produced by ionizing the gaseous molecules in the vicinity of the sharply pointed electrode placed near the roll. Con-

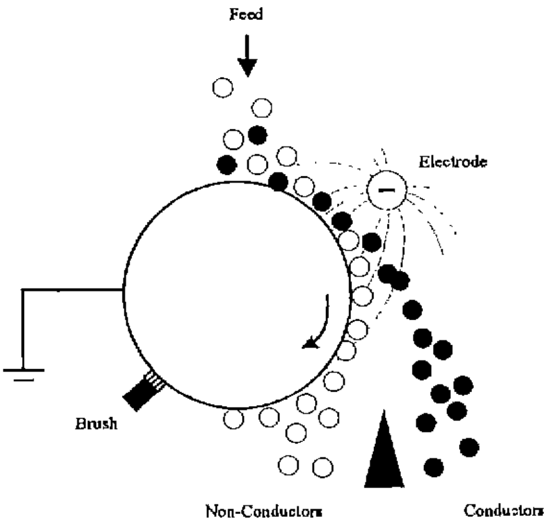

Fig. 10. Electrodynamic separator.

Table 3. Work Functions (W_a) of Common Plastics (Inculet and Castle, 1991)

Plastics	Work Function (eV)
Acrylic	2.9
Nylon	3.6
PVC	6.5
PE	7.2

ducting particles quickly lose the charge to the ground and are *thrown* off the roll, while non-conductor particles retain the charge and are held to the roll surface. The non-conducting particles are brushed-off the roll and collected separately. Thus, both the true electrostatic and electrodynamic separators rely on the difference in conductivity of the particles to be separated. The electrodynamic separation technique has been tested in Russia for recovering noble and non-ferrous metals from electronic scraps (Mesenyashin, 1995). High purity (>99 5%) metal concentrates were obtained with a 98% recovery The same technique was also used for recovering copper from telephone cable scraps. Typically, the feed contained 18 to 67% Cu by weight, and the product assayed 90 to 94% Cu at a recovery of 85 to 95%.

It is well known that charges are generated when materials of different work functions are contacted and separated. Table 3 shows the work functions of a few common plastics. This is known as tribocharging mechanism and serves as the basis of the triboelectrostatic separation process. Fig. 11 shows one embodiment of this technique, in which particles to be separated are contacting each other in a fluidized bed charger (Inculet and Castle, 1991). The charged particles exiting the fluidized bed enter the chamber where two electrodes are located to provide an electric field for separation. Table 4 shows the results obtained with binary artificial mixtures of different plastics. More recently, Inculet *et al* (1993) developed a different method of charging plastic particles In this method, particles are charged by passing them through a rotating tube whose work function is in between those of the to plastics to be separated. It appears that the fluidized bed charger relies on particle-particle contact, while the tube charger relies on wall-particle contact. At Virginia Tech. a triboelectrostatic separator of different design is being developed under the sponsorship of the U.S. Department of Energy

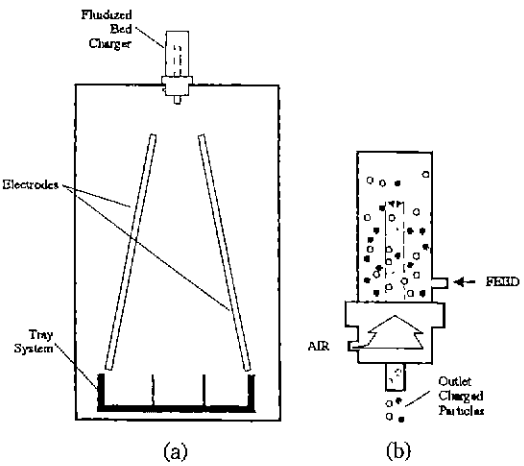

Fig. 11. Triboelectrostatic separator (Inculet and Castle, 1991).

Table 4. Results of Triboelectrostatic Separation

Plastics		ΔW_a*	Recovery (%)		Extract Content	
A	B	(eV)	A	B	A	B
Acrylic	Nylon	0.7	97.2	64.1	81.0	98.9
PVC	PE	0.7	98.9	98 7	99.4	100
Nylon	PVC	2.9	92.5	97.8	99.8	98.0
Acrylic	PCV	3 6	93.4	97.2	99.8	96.5
Nylon	PE	3 6	68.0	98.6	99.4	83.6
Acrylic	PE	4.3	96.4	98.2	99.9	99.5

*differences in Work function

2.5. Flotation

Froth flotation is the most widely used separation method for separating mineral particles in the mining industry. In this process, suitable reagents known as collectors (usually surfactants) are added to an aqueous slurry containing mineral particles to be separated. Collector molecules adsorb on only one type of mineral to render it hydrophobic, while others are left hydrophilic Air bubbles are then introduced to the bottom of the tank containing the slurry, so that they can collect only the hydrophobized mineral particles and rise to the top of the flotation cell, leaving the hydrophilic minerals behind This process can also be used for plastics recycling. Unlike mineral flotation, however, it is not necessary to use collectors to float plastics, because they are inherently hydrophobic. On the other hand, the fact that all plastics are hydrophobic poses a challenge in separating one

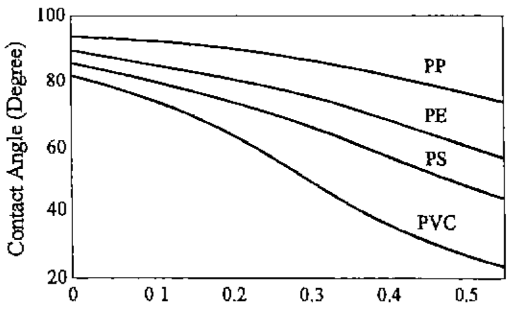

Fig. 12. Effect of wetting agent (sodium lignosulfonate) on the contact angle of various plastics (Saito *et al.*, 1976)

type of plastics from another.

Fig. 12 shows the contact angles of water on the surface of various plastics, i.e., PP, PE, PS, PVC, measured in the absence and presence of sodium lignosulfonate by Saito et al (1976). In pure water, all plastics show contact angles greater than 80°, indicating that they are very hydrophobic (or non-wetting). The difference between them are so small that it is difficult to achieve separation by flotation. As the concentration of the wetting agent increases, however, the contact angles are reduced substantially and the difference between them becomes magnified. These findings provide a basis of separating plastics by flotation. Table 5 shows some of the flotation results obtained by Siato et al (1976) using sodium lignosulfonate as wetting agent.

Sisson (1992) developed a different method of controlling the hydrophobicity of plastics for separation by flotation. He found that conditioning a mixture of PET and PVC in an aqueous solution, containing 2 to 15% NaOH (or KOH) and 0.005 and 0.1% non-ionic surfactant, decreased the contact angle of the former to below 25° while that of the latter remained above 45° Table 6 shows the results obtained after conditioning a 1:1 mixture with 5% NaOH solution and 0.05% NEODOL®91-6. These results represent 93.5% PVC recovery and 97 5% PET recovery.

Table 5. Results of Flotation Tests Conducted on Binary Mixtures of Plastics Using Lignosulfonate as Wetting Agent

Feed		Float		Sink	
Plastics	Composition (%)	Grade (%)	Recovery (%)	Grade (%)	Recovery (%)
PS	50		98.4		
PVC	50			96.5	98.4
PP	50		98.8		
PVC	50			97.8	98.8
PP	47	97.0	98.9		
PS	53			99.9	97 4
PP	50	98.8	97.3		
PE	50			97.3	98.0

Table 6. Results of flotation separation of PET and PVC

	Amount Added	Float	Residue
PET	7.92 g	0.53 g	7.39 g
PVC	7.78 g	7.59 g	0.19 g

The alkaline conditioning technique of Sisson was used by Buchan and Yarar (1995) to control the hydrophobicity of PET relative to that of PVC; however, these investigators used the γ-flotation technique in which the surface tension of the flotation liquor is reduced substantially by adding a large amount (27.9%) of methanol.

Bahr and Vogt (1983) compared various methods of separating plastics, e.g., PET, PVC, Polystyrene, etd., and showed that flotation is the best

2.6. Thermal treatment

Heating plastics changes their properties. Table 1 shows the softening or melting temperatures of various plastics Leidner (1981) described a method of separating plastics from others after a thermal treatment. His separator, shown in Fig 13, consists of an electrically heated cylinder en-

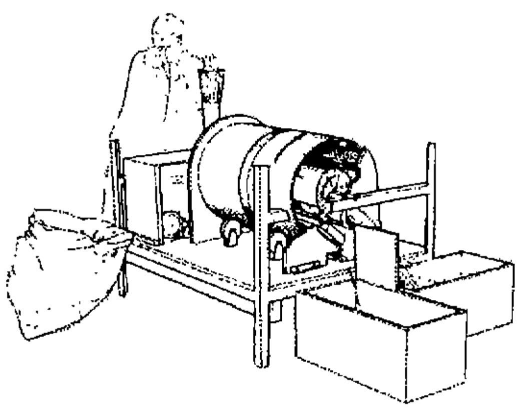

Fig. 13. Hot "Cylinder" separation method (Leidner, 1981).

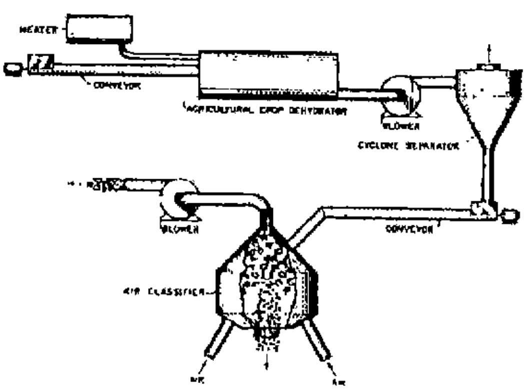

Fig. 14. Separation of plastics and paper by thermal treatment followed by air classification (Laundrie, 1972).

closed within a hollow rotating tube fitted with vanes to ensure a tumbling action about the heated cylinder. The drum and the heated cylinder rotate in opposite directions The plastics melting on the heated cylinder is removed by a doctor blade, and then discharge through a trough. Tests conducted with a mixure of plastics and paper showed that over 90% of the plastics can be removed by this process and the product contains less than 1% paper

Fig. 14 shows another method of separating plastics by thermal treatment (Laundrie, 1972). In this method, a mixture of plastics and paper is fed into a heating device (an agricultural crop dehydrator), where thermoplastic films contract and reduce their surface area. The heater discharge is fed to a cyclone and then to an air classifier to separate paper (overflow) from the plastics (underflow). The separation is almost complete

2.7. Solvent extraction

It is possible to separate plastics by selctive dissolution. Nauman et al (1992) showed that many of the common plastics are soluble in xylene,but their solubilities in this solvent vary with temperature which serves as the basis of separation. In this process, a mixture of plastics, which consists of PS, LDPE, HDPE and PP, is placed in xylene whose temperature is regulated At 25°C, only PS is dissolved and removed from the rest At 75°C, LDPE is dissolved and removed, while HDPE is dissolved and removed at 105°C. At 120°C, PP is dissolved, and separated form PET and PVC. The latter two are dissolved in another solvent at different temperatures, and separated from each other. Each polymer solution is let into a flash evaporator, where most of the solvent is evaporated and recovered. The polymers separated in this manner are melted in extruders to produce pellets. Molgaard (1995) calculated the energy and materials balances of the process.

3. Summary and Conclusion

Various techniques that can be used for separating plastics have been reviewed. It appears that the most significant technological advancement has been made during the last 5 to 7 years in the area of automatic sorting. An important element of this technology is the development of appropriate sensors that can discriminate various plastics from one another. Availability of advanced sorting machines makes it possible to produce various products from commingled plastics. Triboelectrostatic separation technique also showed promising results for separating plastics. Advantages of this technique are that dry products are obtained and that its energy consumption is low. When it is desired to remove conducting materials from plastics, electrodynamic and true electrostatic separation tehniques may give higher separation efficiencies than the triboelectrostaic technique. Various gravity separation techniques are used for separating plastics from heavier materials. A new air classifier employing pulsed air flow allows plastics to be separated from each other according to their specific gravities. with minimum interference from size effect The forth flotation technique that are used extensively in minerals industry can also be used for separating shredded and pulverized plastics. The inherent hydrophobicity of plastics can be controlled by using appropriate wetting agents and alkalis, which makes it possible to separate various plastics by flotation. It has also been shown that plastics can be separated by thermal treatment and by solvent extraction. Further development of the various separation techniques described in the present communication can increase the efficiency of plastics recycling substantially and contribute to making the business more profitable.

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