Plastic Particle Separation via Liquid-Fluidized Bed Classification

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Liquid-fluidized bed classification (LFBC) is being investigated as a potential process for the separation of complex waste plastic mixtures for recycling. Experiments were performed in a 10 cm diameter, fluidized bed apparatus that was designed to operate in both upflow *and* downflow *modes, for the separation of "heavier-than-water" (HTW) and "lighter-than-water" (LTW) plastic particle species, respectively, using water as the fluidization medium. The investigations were primarily focused on binary plastic particle mixtures of the typical industrial plastics, PVC, PET, PS PC, HDPE, LDPE, and PP. Particle segregation was obtained for all the binary mixtures studied. The effects of particle size and superficial liquid velocity were examined. It was found that low fluidization velocities favored segregation performance by minimizing particle dispersion. A limited number of experiments with ternary plastic particle mixtures demonstrated that the behavior of more complex mixtures appears to be an extension of binary mixture behavior, and that multiple plastic particle mixtures can be separated in the same column. The novel technique of selective thermal modification of particle size/density by application of a step change in temperature of the fluidizing medium was demonstrated to improve separation performance for both HTW and LTW plastic sample mixtures. This behavior was attributed primarily to differences in the thermal diffusivities of plastic particle pairs. The experimental data and conclusions reported in the current work can serve as the basis for the development of LFBC systems for waste plastics separation.*
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Introduction

Plastics are widely used in film, sheet, and container applications for packaging of food and other consumer goods. Plastics are also prevalent materials in durable goods, including automobiles, appliances, computer and business equipment, electronics, and even sporting equipment. Most plastics packaging is discarded as municipal solid waste (MSW). The U.S. Environmental Protection Agency has reported that discarded plastics have increased from 0.49 million tons in 1960 to 26.7 million tons in 2003, and it is expected that this trend will continue.[1] Waste plastics are typically land-filled or disposed of in municipal solid waste incinerators.[2] Due to more stringent regulations on soil and water contamination and on landfill capacity, the number of landfill sites available for solid waste disposal is steadily decreasing.[1]

Incineration reduces waste volume and can be used to potentially recover energy from MSW in the form of hot gases, taking advantage of the high energy values of plastics to obtain energy from waste.[3] However, the high costs of constructing and operating MSW incineration plants and their potential negative environmental impact have severely limited their use

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in waste plastics disposal. Therefore, there is an increasing need for in-process and post-consumer recycling in order to minimize the generation of solid waste. Recycling has been shown to be the most energy efficient route for plastics re-use, and usually provides the greatest environmental benefit.[4] However, for the bulk of mixed plastics, recycling techniques are limited. Before waste plastics can be recycled, the various types of plastics must be separated.[5] Separating individual plastics at high purity from a mixture containing a number of different plastic types is a challenging problem. However, there is a need to develop effective continuous sorting technologies in order to recycle plastics economically.

Although a number of other approaches have been either proposed or applied to plastics separation, none are completely satisfactory in terms of economics and/or performance.[6-10] Under liquid-fluidized conditions, particles segregate according to their density (i.e., "sorting") and/or size (i.e., "sizing").[11] It is known that "sorting" tends to predominate at high particle volume fractions, while "sizing" predominates at low particle volume fractions.[12] In the current work, particle segregation performance was dominated by differences in particle density. The "sorting" tendency was intentionally enhanced by pre-sizing the particles by sieving, as well as by operating at high particle volume fractions.

We have demonstrated that liquid-fluidized bed classification (LFBC) is an effective separation technology for coal beneficiation[13] and also for plastic "chips."[14] There are a number of potential advantages to the use of LFBC for plastics separation. It can be used to separate a number of plastic particle types simultaneously in the same device, whereas other density-based techniques, like flotation, centrifugation, air classification, hydroclones, etc., typically can only separate "lights" from "heavies." LFBC is potentially quite economical since it only requires water for both *upflow* (that is, for "heavier-than-water" (HTW) plastics) and *downflow* (that is, for "lighter-than-water" (LTW) plastics). In addition, LFBC is compatible with almost all other proposed separation and plastic identification methods, such that it can be used in conjunction with other technologies to enhance separation and improve overall process economics.

Here we present an overview of the LFBC concept, including the separation of both "heavier-than-water" (HTW) and "lighter-than-water" (LTW) plastic particles, as well as the novel technique of separation enhancement via selective thermal particle density modification induced by step changes in the fluidizing water temperature.

Experimental Procedures

Liquid-fluidized bed apparatus and experimental system

A schematic of the liquid-fluidized bed apparatus is presented in Figure 1. The liquid-fluidized bed column was fabricated from 4 inch (10 cm) I.D. PMMA tubing with PVC fittings and flanges. The liquid distributor was a fine plastic mesh with an opening size of 0.5 mm. The fluidized section of the column beyond the distributor was 1 m in height. The elimination of gross secondary flows is necessary when striving to minimize particle dispersion and maximize particle segregation. The section of the column located before the distributor serves as a homogenizing zone to provide more uniformity to the flow across the distributor cross section at the entrance of the fluidized section in order to minimize secondary flows. This section consisted of a 38 cm deep bed of 6 mm plastic spheres and a 26 cm section of bundled thin walled plastic tubes (i.e., plastic straws). In addition, the column was aligned to ensure that it was plumb. Simple flow visualization experiments with a dye tracer revealed no gross secondary flows beyond the distributor over the range of superficial liquid velocities investigated.

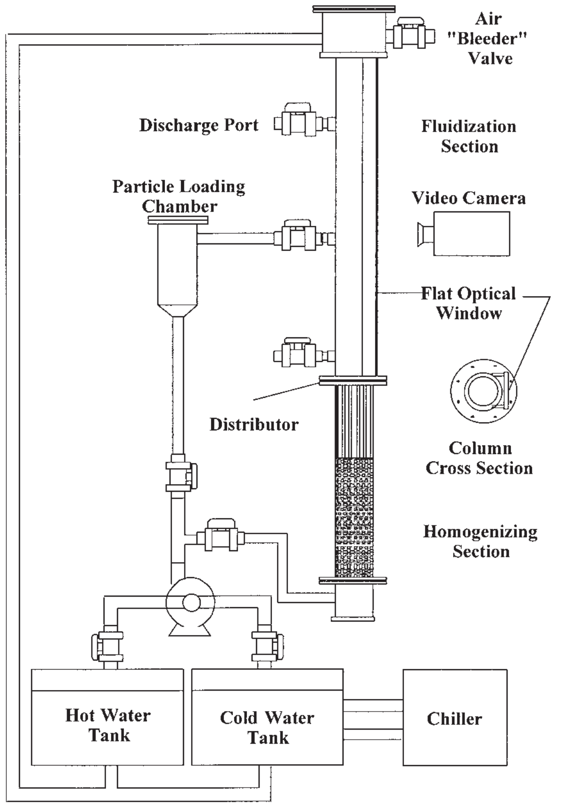

Figure 1. Liquid-fluidized bed apparatus in the *upflow* configuration.

The column was equipped with two sampling ball valves located along the length of the column with distances from the distributor of 5 and 25 cm, respectively. The distribution of water between the bypass, column inlet, and injection port inlet was controlled with a series of ball valves. This arrangement allowed for fine control of the fluidizing water flow rate. The water flow rate was measured with a flow meter (Omega FP-1005). The system employed a series of screen filters to prevent plastic particles from entering the pump, and a particle injection port that allowed for nearly continuous operation of the pump during particle charging operations. The column was constructed so as to rotate about a normal to its axis so that it could be oriented with the homogenizing section, distributor, and fluidizing water inlet located at the bottom or the top of the column to accommodate both *upflow* (for HTW plastics) and *downflow* (for LTW plastics) fluidization, respectively.

Two feed water tanks, each containing thermostatically-controlled hot or cold water, were the sources of the fluidizing water for the column. A solenoid valve switching system was used to select water from either tank. The fluidizing water was recirculated back to the two respective holding tanks.

Table 1. Physical and Fluidization Properties of the Plastic Particles in Water at 22°C

Plastic Sample† (mean size, mm)	Density (kg/m^3)	U_{mf} (mm/s)	U_t or U_r (mm/s)	$n^\dagger$
PVC(2.18)	1390	14.3	126.3	2.93
PVC(1.72)	″	8.32	102.1	3.00
PVC(1.25)	″	5.56	75.1	3.13
PET(2.18)	1250	12.5	105.3	2.96
PET(1.72)	″	6.21	84.3	3.03
PET(1.25)	″	4.47	61.5	3.18
PC(2.18)	1150	6.82	68.8	3.02
PC(1.72)	″	4.02	54.7	3.13
PC(1.25)	″	2.41	39.2	3.33
PS(2.18)	1090	5.13	49.3	3.10
PS(1.72)	″	2.72	38.7	3.23
PS(1.25)	″	1.50	27.4	3.47
HDPE(2.18)	920	*	43.5	3.04
HDPE(1.72)	″	*	33.2	3.14
HDPE(1.25)	″	*	23.0	3.31
LDPE(2.18)	900	*	51.0	2.99
LDPE(1.72)	″	*	39.0	3.09
LDPE(1.25)	″	*	27.0	3.25
PP(2.18)	880	*	58.1	2.95
PP(1.72)	″	*	44.3	3.05
PP(1.25)	″	*	30.8	3.21

†The Richardson-Zaki [16] parameter n as determined from the correlations: $5.1 - n/n - 2.8 = 0.1\ \mathrm{Re}_t^{0.65}$ (for HTW plastics); $n = (4.4 + 18\ d_p/D)\mathrm{Re}_t^{-0.1}$ (for LTW plastics) [19].

*Omitted, since unambiguous identification of a comparable "minimum fluidization velocity" is problematic for *downflow* or inverse fluidization.

Fluidization/segregation of the plastic particles was affected by the presence of air bubbles within the column. Prior to loading the particles, water was pumped into the column through the particle loading chamber, forcing trapped air out through a bleeder valve located at the top of the column. Any residual fine air bubbles that coalesced from dissolved air in the water and attached to particles were eliminated by the use of a few drops of a surfactant (3M Fluorad FC-135$^{\mathrm{TM}}$), which also served to eliminate electrostatic agglomeration of particles.

Plastic particles

The HTW plastic particle species used in the current work were: polyvinyl chloride (PVC), polyethylene terephthalate (PET), polycarbonate (PC), and polystyrene (PS); and the LTW plastic particles were: low density polyethylene (LDPE), high density polyethylene (HDPE), and polypropylene (PP); all of which are typical industrial plastics. These plastics were obtained as 1/16 inch (1.6 mm) thick sheets. The sheets were cut into two-inch (5 cm) wide strips that were then ground in a Wiley knife mill. The knife-milled particles were sieved to produce three nominal size ranges: 1.91-2.46 mm, 1.52-1.91 mm, and 0.98-1.52 mm, with mean sizes of 2.18 mm, 1.72 mm, and 1.25 mm, respectively. The final particles were irregularly-shaped, prolate "chips," with sphericity ranging from 0.2 to 0.9. The salient physical (and fluidization—see below) properties of these particles are summarized in Table 1. Except where specifically indicated otherwise, the binary particle mixtures charged to the column consisted of 200 g of particles of each type.

Most of the plastics were available in white, which required dyeing some of them for identification/image analysis purposes: The PVC was charcoal in color; HDPE and PET were used in their original (white) state; PC and LDPE were dyed red; and PS and PP particles were dyed green.

Particle volume fraction data

An in situ method, based on processing of digital images, was used to measure particle volume fractions. Images were taken with a digital camera through a flat window, fitted along the entire length of the fluidization section, and filled with water in order to minimize optical distortion due to column curvature. Several frames of digital images at the same location and operating conditions were averaged, and IPLab Spectrum$^{\mathrm{TM}}$ image analysis software was used to extract particle volume fractions. In order to account for the possibility that particle volume fraction profiles obtained from the 2D images were not the same as the actual radially-averaged values at a particular height in the column, a calibration procedure was developed comparing the results from the images to actual mean measured volume fractions in single component beds of each plastic type at the same fluidization velocities.

From the calibration experiments, it was found that the particle volume fraction profiles obtained from analysis of the 2D images were quite close to the actual measured mean values in the 3D bed. It was experimentally established that this relationship was not affected by the type of plastic particles, fluid velocity, and particle loading, within the experimental ranges used in the current work. It was found, however, that the empirical relationships thus established varied somewhat with respect to particle size. Thus, a similar calibration was performed for each particle size range. The calibration results indicated that the 2D images of beds with larger particles tended to exhibit slightly better agreement with the actual 3D bed data. For a more detailed description of the procedure and the calibration process, the reader is referred to [15].

Fluidization characteristics of the plastic particles

The individual plastic particle samples were also characterized with respect to their standard liquid-fluidization characteristics over a range of superficial velocities. This included the settling velocities and the exponent n for the Richardson and Zaki correlation:[16]

$$\frac{U_0}{U_t} = \varepsilon^n \tag{1}$$

Experimental values of the parameter n were fit to the expression:

$$\frac{5.1 - n}{n - 2.8} = 0.1 \times \mathrm{Re}_t^{0.65} \tag{2}$$

which is similar in form to a correlation proposed by Garside and Al-Dibouni.[17] (The values of n reported in Table 1 were determined from Eq. 2.) The single-particle terminal velocity data were well described by[18]:

$$U_t = \left[\frac{4gd_p(\rho_p - \rho)}{3c_D\mu\rho}\right]^{0.5} \tag{3}$$

In the current work, Re is in the transition region, $1 < Re < 10^3$, and $c_D \approx 18\text{Re}^{-0.6}$.[18] It was found that the Richardson-Zaki correlation describes the behavior of the HTW plastic particles used in current work very well, even though they are neither spherical nor regularly-shaped.

Characterization of the fluidization behavior of the LTW plastic particles in *downflow* or *inverse fluidization* is somewhat more problematic. This will be the subject of another publication. For the current purposes, suffice it to say that for sufficiently low liquid superficial velocities, the Richardson-Zaki correlation was found to provide an accurate representation. This conclusion agrees with that of Karamanev and Nikolov,[19,20] who reported that LTW particles with $\rho_p > 900$ kg/m^3 and $Re_r < 130$ can still be well described by "free-settling." This conclusion is applicable to the current work, where the specific gravities of the three LTW plastics investigated lie between 0.88 and 0.92.

A summary of the fundamental fluidization characteristics determined for all the plastic particle samples is presented in Table 1.

Characterization of separation performance

The extent or degree of segregation can be determined from the measured volume fraction profiles by defining a segregation coefficient, or "figure of merit," *S,* as[21]:

$$S = \frac{|\bar{C}_B - \bar{C}_T|}{\bar{C}_B + \bar{C}_T} \times 100(\%) \qquad (4)$$

where $\bar{C}_B$ and $\bar{C}_T$ are the average particle volume fractions of the particular material of interest in the bottom and top zones of the bed, respectively. These values were determined by integrating the particle volume fraction profile with respect to bed height, from each end of the column to the point where the two volume fraction profiles cross in the mixing zone. With this definition, S can assume values ranging from 0 to 100%, corresponding to perfect mixing and perfect segregation, respectively.

Results and Discussion

Separation performance was measured over a range of fluidization velocities between the minimum fluidization velocity of the lighter particle (approximated for *downflow fluidization*) to the point of significant particle entrainment. HTW plastics mixtures were separated in *upflow,* in which the fluidization medium, water, entered the column at the bottom and exited at the top. LTW plastics mixtures were separated in *downflow,* in which the water entered the column at the top and exited at the bottom.

Complete segregation

Complete segregation (i.e., absence of a *mixing zone*) was obtained for the PVC/PC, PET/PS, and PVC/PS binary mixtures for all three particle sizes at almost every operating velocity. Particle volume fraction profiles for three of these mixtures are presented in Figure 2. The corresponding segregation coefficients, *S,* for these mixtures are *ca.* 100%, reflecting complete segregation. A sample image of a PVC/PC mixture is presented in Figure 3, in which the black particles are PVC and the white are PC. The interface between the two pure plastic regions is clearly evident.

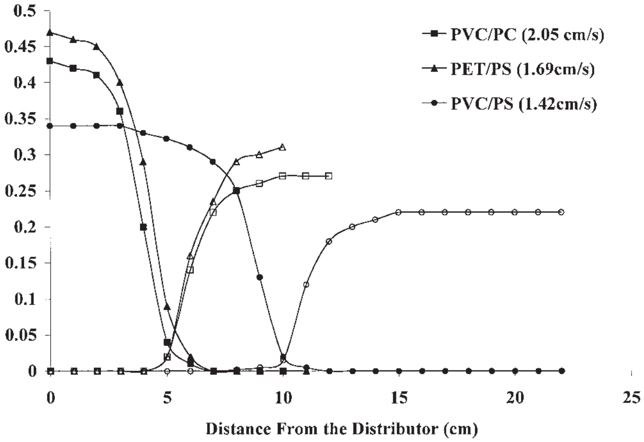

Figure 2. Particle volume fraction profiles for HTW binary mixtures PVC/PC (d_p = 2.18 mm; 200 g of each), PET/PS (d_p = 2.18 mm; 200 g of each), and PVC/PS (d_p = 1.25 mm; 200 g of each).

The PVC/PS mixture exhibited the best separation performance, forming two practically pure plastic regions, due to the large difference in the settling velocities of the two plastic types, caused by the relatively large difference in densities between the two species. In the current work, complete segregation was obtained when the density ratio exceeded about 1.2 for binary mixtures of the same particle size, differing only in density. For the cases where complete segregation occurred, the superficial liquid velocity, particle size, and the amounts of particles charged to the column had relatively little effect on segregation performance.

Partial segregation

For all the other binary mixtures, a mixing layer of significant extent formed between the two different plastic layers, which is indicative of partial segregation. For such systems, the separation performance is more dependent on particle characteristics and operating parameters.

Effect of Fluidization Velocity. Particle volume fraction profiles for PET/PC and PVC/PET, and PP/LDPE and LDPE/HDPE mixtures are presented in Figures 4 and 5 as a function of superficial liquid velocity. As shown, partial segregation is evident in each case. Also, the particle volume fraction curves become more stretched and flatter with increasing superficial liquid velocity. This trend is also evident in the corresponding segregation coefficients that are also included in these Figures. This behavior is qualitatively similar for both the HTW mixtures (Figure 4) and the LTW mixtures (Figure 5). It is noted, however, that the superficial liquid velocities required for the LTW plastics are significantly less than for the HTW particles. Also, the segregation performance of the LTW binary mixtures particles in *downflow* is particularly good, especially considering that the specific gravities of the three polyolefins are only 0.002 apart.

These data indicate that the degree of mixing increases and segregation decreases with increasing superficial liquid veloc-

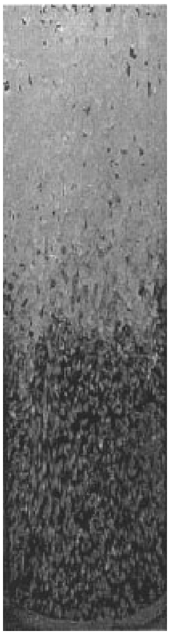

Figure 3. Image of a completely segregated bed for a binary PVC/PC mixture.

d_p = 2.18mm; U_0 = 2.05 cm/s; 200 g of each.

ity. This is due to the fact that for the particle sizes and fluidization parameters used, the particle dispersion coefficient increases with liquid superficial velocity to a power greater than unity.[22-24] Consequently, mixing increases to a greater degree than segregation with increasing liquid superficial velocity.

Effect of Particle Size. Both the particle dispersion coefficient and the difference between the settling velocities of the two particle species increase with particle size. The former promotes mixing, while the latter promotes segregation. The net effect of these two counteracting tendencies determines the net segregation achieved in the bed. For the operating conditions in the current work, it was found that the mixtures with the larger plastic particles exhibited better segregation performance than those with smaller particles. For example, as shown in Table 2 for the ambient temperature segregation results, the 2.18 mm PVC/PET mixture exhibited a larger segregation coefficient (S = 83%) than that for the 1.72 mm mixture (S = 72%) at the same superficial liquid velocity of 2.23 cm/s. This is also evident at the greater superficial velocity of 3.04 cm/s, although the overall segregation is slightly reduced due to the higher velocity, as discussed above. Similar results are presented in Table 2 for the LDPE/PP mixtures; i.e., at 1.53 cm/s, the 2.18 mm mixture (S = 72%) exhibited much better separation performance than the 1.72 mm mixture (S = 57%).

These results, however, do not necessarily mean that larger particles than those used will yield even better performance. The fluidization behavior of very large particles is generally less satisfactory than smaller ones.[25] In addition, the particle dispersion coefficient is a function of particle size raised to a power greater than unity,[22] while classification velocity increases almost linearly with particle size. Therefore, beyond some point, mixing will become the predominant factor,[23,24] such that increasing particle size beyond that point can only cause increased mixing and less segregation.

Effect of Particle Loading. A limited number of experiments varying the loadings of the different particle types in the binary mixtures by factors of two greater and less than the standard 200 g loading used, showed that segregation performance was relatively independent of the absolute amounts of particles, at least over this range of variation. The only major effect observed was increased/decreased bed height with the addition/removal of particles at the same superficial velocity. However, it stands to reason that relative loadings would have a much more dramatic effect on separation performance when the loading of one particle type is reduced to the order of the amount that would otherwise be present in the mixing zone, for example.

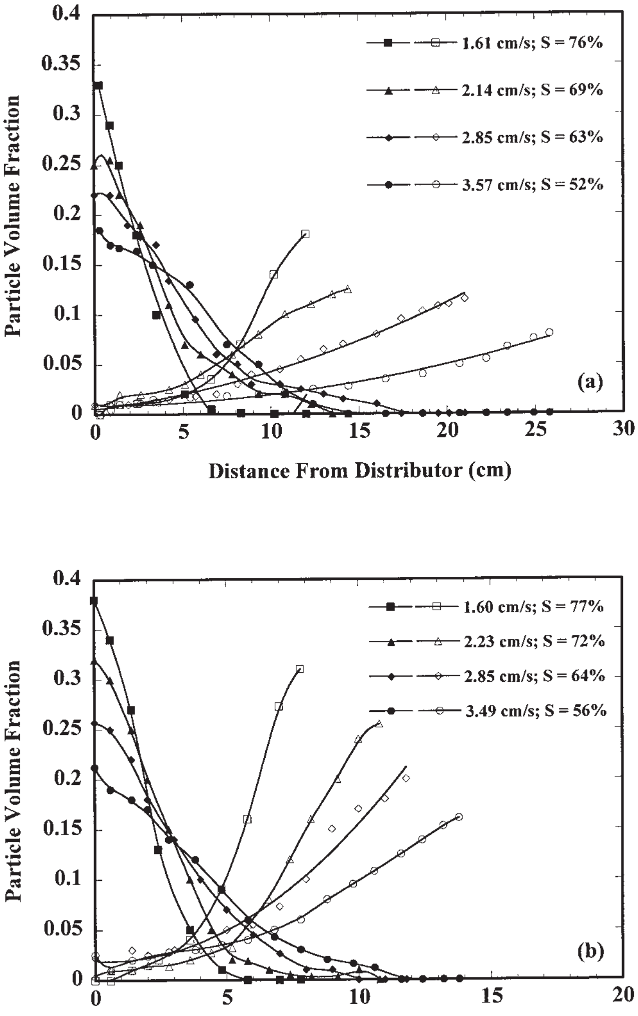

Figure 4. Particle volume fraction profiles as a function of liquid superficial velocity for two, 1.72 mm particle HTW binary mixtures.

The solid data symbols indicate the heavier species, and the open symbols the lighter species (listed second): (a) PET/PC, and (b) PVC/PET. The corresponding segregation coefficient (S, %) is listed in the legend for each binary mixture.

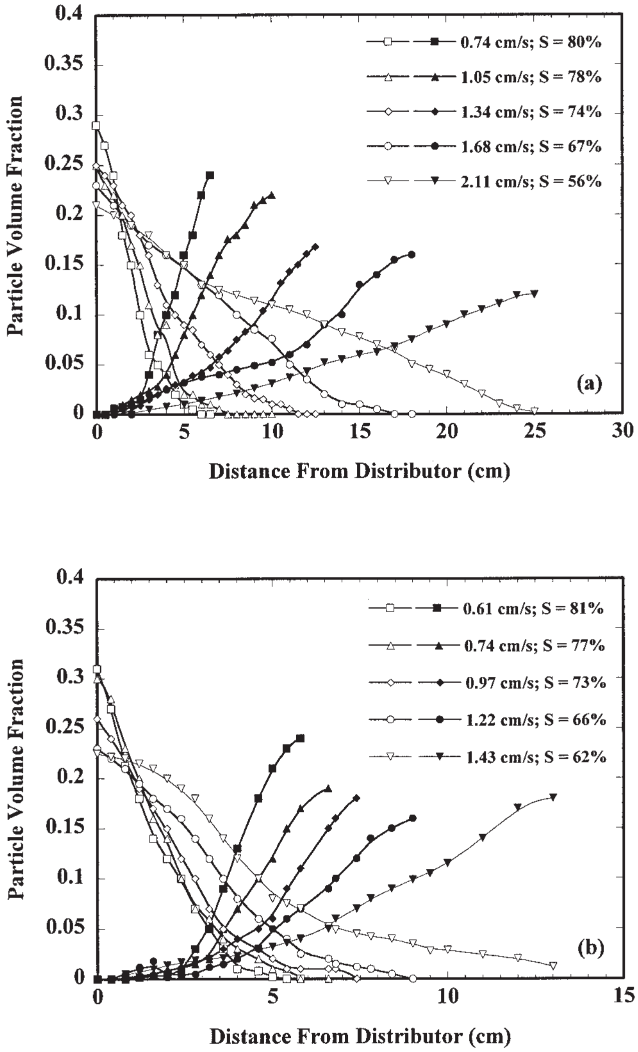

Figure 5. Particle volume fraction profiles as a function of liquid superficial velocity for two, 2.18 mm particle LTW binary mixtures.

The solid data symbols indicate the heavier species, and the open symbols the lighter species (listed second): (a) LDPE/PP, and (b) HDPE/LDPE. The corresponding segregation coefficient (S, %) is listed in the legend for each binary mixture.

It was also found that significant segregation was obtained when the volume fraction of plastic particles in the column was relatively high. Under these conditions, "sorting" was the dominant mechanism rather than "sizing."

Thermal enhancement of separation performance

Partial segregation based solely on intrinsic density differences between different plastic types represents a limitation on the purity of the various plastic fractions that can be obtained. However, there are other physical property differences among plastics that can be exploited to enhance separation performance in LFBC. Relevant thermal properties of the plastic particles investigated here are presented in Table 3. From these data, it is evident that there are significant differences among the thermal diffusivity values of the various plastics, especially above and below the glass transition temperatures of the HTW plastics, as well as the values of the glass transition temperatures themselves; differences in the linear expansivities, β, are significantly less.

The thermal conductivities of the plastics of interest here are all relatively low.[26,27] Consequently, the Biot number for heat transfer between plastic particles and water ($Bi = hd_P/k$, where h is the interphase heat transfer coefficient and k the particle thermal conductivity) at typical liquid fluidized bed conditions is considerably greater than unity (e.g., $Bi \sim 14$ for 2 mm LDPE particles fluidized in water at 25°C, for $U_0 = 1.5$ cm/s). Therefore, heat transfer is internally controlled by the particle thermal diffusivity, α ($\alpha = k/\rho C_P$, where ρC_P is the total heat capacity of the particle). In the case of the HTW plastics, differences in α values can be considerably increased by making use of temperatures that lie between the T_g values of HTW plastic pairs. Although the same cannot be done using water for the LTW polyolefins (because of their subambient T_g values—see below), differences in α at ambient temperatures are already relatively large for these plastics.

α is a transport or kinetic property, while β is a steady-state, or more rigorously, an equilibrium property. It is actually the differences in α that account for most of the observed enhancement in separation performance. Upon a step change in temperature, the particles with the smaller time constant (i.e., the larger α value) rapidly change density, while the particles with the larger time constant (i.e., the lower α value) remain close to their original density for a time. The resultant, induced transient difference in classification velocities causes the particles to move to different heights in the bed. Once the particles move to their new locations, under conditions of low particle dispersion, at which the system must operate, they tend to remain there even when the system has completely accommodated to the final temperature after a few minutes. This explanation is supported by data that show that some degree of the improved particle segregation achieved upon a step change in temperature, remains even after the entire system is allowed to relax back to ambient temperature. In other words, there is some "memory" of the temperature step change response in the system.

Thus, even if there were no difference in β values between plastics, differences in α would still produce separation enhancement. This fact is demonstrated by the behavior of the HDPE/LDPE mixtures. As shown in Table 3, the α values of these two plastics differ by an order of magnitude, whereas their β values are practically the same. Thus, if it is only the β values that control the thermal separation enhancement process, there should be little or no separation enhancement for these mixtures. In point of fact, however, these mixtures exhibited some of the largest enhancements in separation following a step change in temperature. The relatively large differences in α values account for this behavior. It is noted, however, that differences in β values can also contribute to the effect by serving to reinforce or preserve the separation enhancement achieved during the transient following the step change in temperature at steady-state. This occurs when the species with the larger α value (smaller time constant) exhibits the larger β value as well.

Thermal enhancement of particle segregation in either *upflow* or *downflow* is invariably accompanied by bed expansion. For the HTW plastics, this can be accomplished by *decreasing*

Table 2. Comparison of Segregation Coefficients Under Ambient Conditions and Following the Indicated Step Change in Temperature of the Fluidizing Water

Binary Mixture	Average Particle Size, d_P (mm)	Superficial Liquid Velocity, U_0 (cm/s)	$S(\%)$ @ Ambient Temperature	Temperature Step Change (°C)	$S(\%)$ After Temperature Step Change
PVC/PET	2.18	2.23	83	–	–
	1.72	2.23	72	–	–
	2.18	3.04	81	5–80	88
	2.18	3.04	81	0–80	88
	1.72	3.04	68	0–80	80
PET/PC		1.34	82		92
	1.72	2.14	69	0–75	76
		2.85	63		67
PC/PS	2.18	1.46	68	5–80	88
HDPE/PP	1.25	0.91	72	80–0	80
HDPE/LDPE		1.21	75		87
	1.72	1.67	64	80–0	74
		2.11	52		58
LDPE/PP	2.18		72		79
	1.72		57		70

the density of one of the plastics by particle *expansion* accompanying an *increase* in temperature. That is, the mixture was first exposed to cold water until steady-state was attained. Upon switching the fluidizing medium to hot water at a temperature selected to lie between the T_g values of the pair of plastics (to enhance the differences in thermal diffusivities), the two types of particles expand at significantly different rates. This will cause the particles with the smaller ("faster") time constant (d_P^2/α) to move to a higher level in the bed than the particles with the larger time constant, causing separation enhancement. This behavior is schematized in Figure 6a.

In Figure 7 are presented images of a PVC/PET particle mixture for a step change in fluidizing water temperature from 0°C to 80°C. These images show that the extent of the mixing layer is decreased and that the interface between the two plastic layers becomes more distinct following the step change in temperature.

For the LTW plastics, thermal bed expansion is accomplished by preferentially *increasing* the density of one of the plastics in comparison to the other in a transient manner by particle *contraction* accompanying a *decrease* in temperature. From the data in Table 3, it is apparent that for downflow fluidization in water, all the LTW plastic types will be above their glass transition temperatures at ambient temperatures. However, the thermal diffusivities of the LTW polyolefins are already significantly different under these conditions. Thus, for LTW binary particle mixtures in downflow fluidization, a step *decrease* in temperature, taking advantage of different particle *contraction* rates, will move the targeted particles (i.e., the species with the higher thermal diffusivity) further down the bed, away from the distributor, thereby causing thermal bed expansion and improving separation. This behavior is schematized in Figure 6b.

A summary of segregation coefficient values obtained at ambient conditions, as well as after a step change in temperature, are presented in Table 2. As shown, in all cases, the step change in temperature improved segregation performance over that attained under comparable ambient temperature conditions - considerably in some cases. Also, the improvement in separation performance is significantly influenced by the superficial liquid velocity and particle size. In all cases, the separation performance improvement at lower liquid velocities was better than that at higher velocities, just as was found at ambient temperatures. For example, for the HDPE/LDPE mixtures, the separation improvement at 1.21 cm/s ($S = 75\% \rightarrow 87\%$) was greater than that at 2.11 cm/s ($S = 52\% \rightarrow 58\%$).

Although larger particles provided better separation performance than smaller ones at ambient temperatures in the current work, this was not the case for the temperature step change results. For example, as shown in Table 2 for the PVC/PET mixtures, the *segregation enhancement* for the 1.72 mm particles ($S = 68\% \rightarrow 80\%$) was better than for the 2.18 mm particles ($S = 81\% \rightarrow 88\%$). This same trend is evident for both the HTW and LTW plastic particles. This behavior is attributed to

Table 3. Thermal Properties of the Plastic Particle Species [26, 27]

Plastic	T_g (°C)	α (m^2/s)† $<T_g$	α (m^2/s)† $>T_g$	β (K^{-1}) $<T_g$	β (K^{-1}) $>T_g$
PVC	84*	1.2×10^{-8}	7.0×10^{-7}	6.6×10^{-5}	–
PET	69*	9.3×10^{-8}	8.2×10^{-7}	1.71×10^{-4}	3.94×10^{-4}
PC	142*	1.6×10^{-8}	–	6.8×10^{-5}	–
PS	80*	8.5×10^{-8}	1.1×10^{-7}	1.7×10^{-4}	5.1×10^{-4}
HDPE	−90	2.1×10^{-6}		13×10^{-5}	
LDPE	−120	1.6×10^{-7}		10×10^{-5}	
PP	−18	6.7×10^{-8}		$8.1–10 \times 10^{-5}$	

Measured with a Dupont Model 2910 differential scanning calorimeter (DSC).

†Thermal diffusivity, $\alpha = k/\rho C_P$, m^2/s, where k is the thermal conductivity, J/s/m/K, and ρC_P the total heat capacity, J/K/m^3, of the plastic sample.

‡Linear expansivity, $\beta = (1/D)(\partial D/\partial T)_P$, K^{-1}, where D is a particle diameter.

the better thermal performance of the smaller particles (primarily the species with the "faster" (smaller) time constant) that expand/contract more rapidly than the larger particles, resulting in better separation performance.[15]

For the HTW plastics, experiments were conducted starting at different temperatures from −5°C (achieved with added ethylene glycol) to room temperature. However, the experimental results showed that there was very little difference in separation performance between using −5°C to room temperature as the "cold" temperature. This is a useful result since it indicates that the additional energy required to cool the water to the lowest temperature possible is unnecessary (as is the additional cost of additives to lower the freezing point of water).

For the HTW plastics it was also found that the degree of separation performance enhancement did not vary very much as long as the temperature of the hot water was selected to lie between the glass transition temperatures of the two plastic species. For the LTW plastics, however, it was found that separation performance enhancement was somewhat more sensitive to the "hot" (initial) temperature. That is, there was some small, but discernible, improvement in separation performance as the "hot" (initial) temperature of the step was increased from 40°C to 80°C.

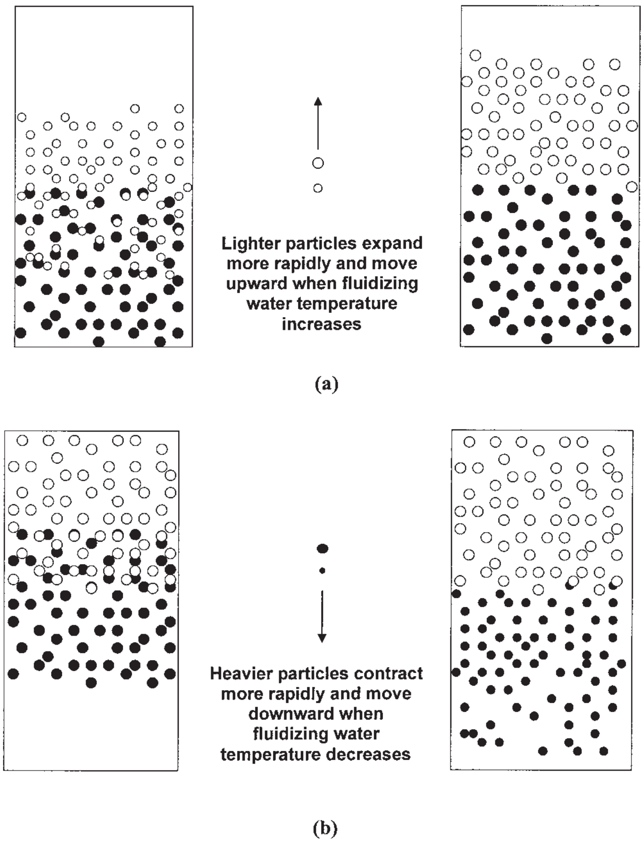

Figure 6. Particle species behavior upon a step change in temperature of the fluidizing water.

(a) From low to high temperature in *upflow* fluidization of HTW plastics, and (b) from high to low temperature in *downflow* fluidization of LTW plastics.

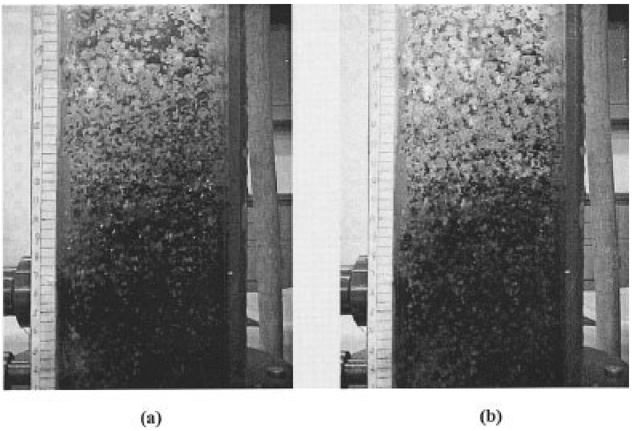

Figure 7. Comparison of images of segregation of a PVC/PET particle mixture (U_o = 4.32 cm/s; d_p = 2.18mm; 200 g of each).

(a) "Before" at 5°C, and (b) following a step change to 80°C.

Separation of a Ternary Mixture. As indicated in the Introduction, it should be possible to separate a number of plastic particle species simultaneously in an LFBC column. Although the current work primarily addressed the separation of binary plastic mixtures, some experiments with ternary mixtures were also performed. Separation of a ternary PVC/PET/PC mixture into three separate layers is presented in Figure 8. The image in Figure 8a shows good separation between the three different plastics. The corresponding particle volume fraction profiles in Figure 8b indicate that there are actually five identifiable regions in this system. From bottom to top, in turn, are a pure PVC layer, a PVC/PET mixed layer, a pure PET layer, a PET/PC mixed layer, and a pure PC layer. These results suggest that the effective separation of multiple plastic types in the same column is indeed attainable.

Conclusions

Segregation of different plastic particles occurred upon fluidization of every binary plastics mixture investigated, for both HTW particles in *upflow* and LTW particles in *downflow*. If the difference in settling velocities between the two plastics species is sufficiently large, complete segregation is obtained; otherwise, partial segregation occurs, as characterized by the formation of pure plastic particle regions above and below a mixing zone composed of the two plastic types. Under the conditions investigated in the current work, at constant (ambient) fluidizing water temperatures, segregation performance increased with particle size and decreased with superficial liquid velocity. The latter is attributed to the behavior of the particle dispersion coefficient, which increases with superficial liquid velocity. Some ternary plastic particle mixtures were also investigated. These experiments demonstrated that ternary mixture behavior is a simple extension of binary mixture behavior, and that more complex plastic particle mixtures could be separated in the same column.

Application of particle size/density modification via step changes in temperature of the fluidizing medium was shown to significantly improve segregation performance. This behavior was attributed to differences in the thermal diffusivities, α,

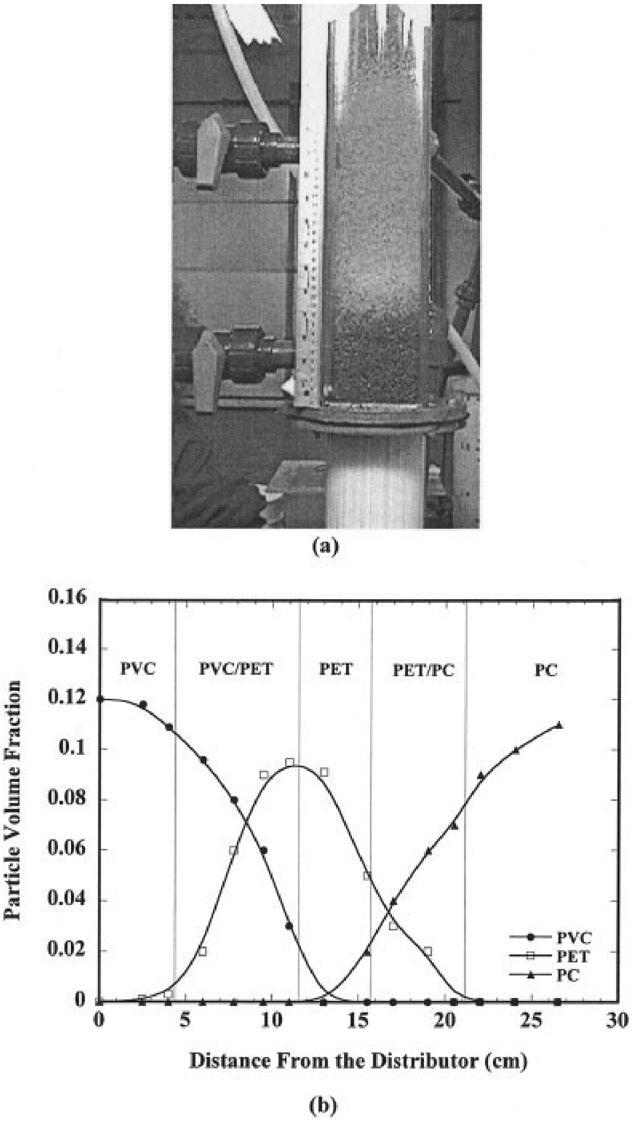

Figure 8. Particle segregation in liquid fluidization of a ternary PVC(charcoal—dark gray fraction at bottom in image)/PET(white—middle fraction)/PC(red—light gray fraction at top in image) particle mixture (U_o = 2.00 cm/s; d_p = 2.18 mm; 200 g of each).

(a) Image, and (b) particle volume fraction profiles ($S_{\mathrm{PVC/PET}}$ = 68%; $S_{\mathrm{PET/PC}}$ = 71%).

between plastic types. For the HTW plastic mixtures, the applied step change in temperature was from cold to hot. Differences in α are enhanced when the hot temperature is selected to lie between the glass transition temperatures of the plastic particle pair. For the LTW plastic mixtures, the applied step change in temperature was from hot to cold, taking advantage of the different particle contraction rates of the plastic particle pair. For all the binary plastic mixtures investigated, thermal enhancement of separation performance was favored by low fluidization velocities and smaller particle sizes. The latter behavior was different from that observed for ambient temperature segregation, for which the larger particles exhibited better performance. The improved performance of smaller particles upon temperature step changes was attributed to the more rapid expansion/contraction of smaller particles, thereby enhancing the induced differences in density.

From the work presented here, it can be concluded that liquid fluidized bed classification (LFBC) can be used for the separation of granular mixtures of plastic particles, and perhaps other materials as well. Selective particle size/density modification has been shown to be a novel, simple, and potentially low-cost method to enhance the LFBC separation performance of plastic particle mixtures.

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