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AIR CLASSIFICATION OF MIXED PLASTICS

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ABSTRACT

Plastics collection poses a quandary: if one wishes the easiest collection, the citizen must be given very simple instructions as to what plastics to set out; if the maximum collection of the many recyclable plastics is desired, one must accept mixed plastics. In either case, processing is necessary: in the first, to control contamination; in the second to separate the polymers. Many sophisticated technologies are being developed for mixed plastics processing: solvent extraction, melt technologies, X-ray detection, etc. These are too sophisticated for primary separation at a local MRF. This work focuses on the application of air classification to the separation of mixed plastics at the MRF level. Air classification has the advantage over hydro-cyclones of being a dry operation. The differences in densities and in shredding behavior are employed. The air classifier and methods for its analysis are those developed by Stessel. Interesting interactions have been observed between tensile strength governing shredding behavior, the resulting particle sizes, and material density. Laboratory separation data are presented and analyzed. Implications for the employment of air classifiers for separation of plastics at the MRF are discussed.

INTRODUCTION

Most modern recycling systems that include plastics are severely limited in the numbers and types of plastics that they can incorporate. These recycling systems rely on the consumer to make the initial decisions regarding types of plastics to include in a recycling system. Thus, despite uniform labelling on the under-sides of most plastic containers, it is not seen as feasible to ask homeowners to "include HDPE and PET; do not give us PVC," for example. Rather, householders are asked to include plastic milk jugs and soda bottles; this neglects great amounts of other containers made from the same polymers, such as window cleaner bottles. Worse, other polymers are entirely omitted from these recycling systems: polypropylene, polystyrene, etc. are almost never collected, although they are very recyclable [Spindler 1989].

Only co-mingled recyclable materials collection is cost-effective. However, adoption of co-mingled collection requires renewed emphasis on efficient separation. An industrial approach is required. MRFs (materials recovery facilities) at the local level would employ relatively simple unit operations. Successive processing steps contribute new levels of refinement to the product. For economic viability, automation is required [Stessel, forthcoming]; this includes automated initial separation of collected plastics.

The low bulk density of plastics continues to be a serious problem in collection and shipping of recycled polymers [Glenn, 1990]. Baling is frequently employed. Size reduction may offer significant advantages in shipping density and simplicity of operation at the MRF. Size reduction would also expose all sides of the plastic to surrounding air, as well as contributing moderate heat; in combination with subsequent air processing, significant drying of remaining foodstuffs might help mitigate odor problems.

Separation of plastics by material properties has been the subject of considerable work. Efforts at Rutgers University in New Brunswick, NJ and in Europe have shown very promising detect-and-route systems based upon electro magnetic spectra. Gannon University (Erie, PA) is using dielectric characteristics; University of Pittsburgh (PA) is using supercritical CO_2; Rennselaer Polytechnic Institute (Troy, NY) is using solvents; University of Tennessee, Knoxville is trying melt temperatures. These sophisticated and expensive advanced refining steps would operate more cost-effectively with a concentrated feed [Stessel, forthcoming]. This work sought to explore the suitability of the Active Pulsed-Flow Air Classifier (APFAC) as a preliminary processing step, suitable for implementation at a MRF.

TABLE I DENSITIES OF COMMON POLYMERS [BRANDRUP AND IMMERGUT, 1975; PERRY 1982; WEAST 1980]

Polymer	Median Tensile Strength (N/cm²)	Median Density (g/cm³)
Polyethylene Low Density	827.	0.917
High Density	2970.	0.955
Polypropylene	3380.	0.90
PVC Rigid	4830.	1.38
PET Amorphous	25000.	1.362
Polystyrene Amorphous	5170.	1.052
Crystalline		1.11
Foam		0.047 (measured)

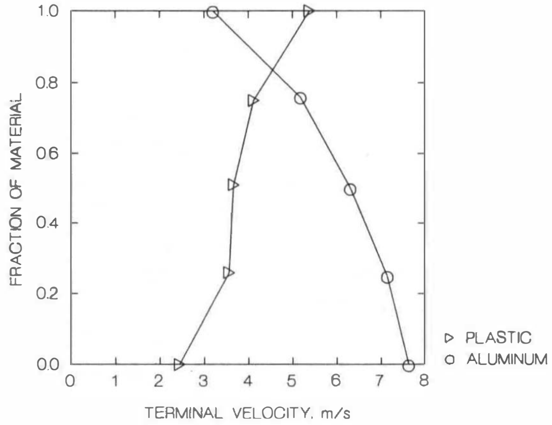

FIG. 1. TERMINAL VELOCITY PLOT SHOWING OVERLAP FOR SHREDDED MATERIAL [MCNABB, 1980]

APPLICABLE CHARACTERISTICS OF PLASTICS

There exist density differences between plastic polymers that can be exploited to affect separations; densities of those most often considered for recycling are shown in Table I. Sink/float separators can be used to make these distinctions, but they have the marked disadvantage of requiring that the product be dried afterwards, which usually requires a significant energy expenditure. The necessary cleaning of plastics before advanced processing must also include removal of labels, glue, etc. This might be part of an advanced processing system, particularly one using heat. At the MRF, the key requirement is initial segregation for further processing; it is not appropriate to perform advanced material cleaning at this stage. Currently, HDPE and PET are viewed as the most recyclable products. There is actually more PVC resin sold, although much of it ends up in durable products [Glenn, 1990]. PVC is a major contaminant in the collection of HDPE and PET, and certain environmental groups accuse it of contributing chlorine to the formation of chlorinated cyclic organics in waste combustors; nevertheless, it is eminently recyclable. Clearly, Table I shows that density can be used to separate PVC from HDPE.

Table I also gives tensile strength information. This is important in determining shredding behavior. Shredders, even with output grates, are not absolute sizing devices: they generate particle size distributions. The higher the tensile strength of a feed component, the larger the particles that will exit the shredder at a given feed rate [Hasselriis, 1984]. Clearly, there is a distinction among common polymers that would result in varying particle sizes even between polymers of similar densities; this could also be used to separate polymers.

AIR CLASSIFICATION

The study of air classifiers leading to the development of the APFAC has been the subject of over a decade of work. This section and the next serve as a brief summary: references to the existing literature are provided.

Air classifiers were originally employed in industries such as agriculture, where they were employed to separate, for example, wheat from chaff. This simple task requires nothing more than a rising current of air. The combined wheat and chaff are fed in the middle of a vertical pipe with rising airflow; the wheat sinks, and the chaff rises. In the early days of resource recovery, production of a fuel from solid waste led to the recognition that most combustible components had lower densities than the non-combustible. Air classifiers were taken directly from other industries and implemented. They did not work well. Fig. 1 shows why: in a simple waste characterization, it is important to separate plastics into the combustible fraction, and aluminum into the non-combustible. Due to differing particle sizes and configurations, Fig. 1 shows that a clear separation can never be achieved by steady airflow: separation occurs by aerodynamic lightness, not density.

This difficulty in separation led to the description of "confused" separation. To illustrate, one can posit four particles: small, low-density; large low-density; small, high-density; and large high-density. In a steady, rising airstream, the particles would separate by size, rather than density. Fig. 2 is a conceptual rendition of this situation. Particles can be modelled as spheres using the concept of equivalent diameters [Vesilind and Rimer, 1981]. Pulsatile (pulsing) airflow was identified as the method to more directly address density as a separation characteristic. A

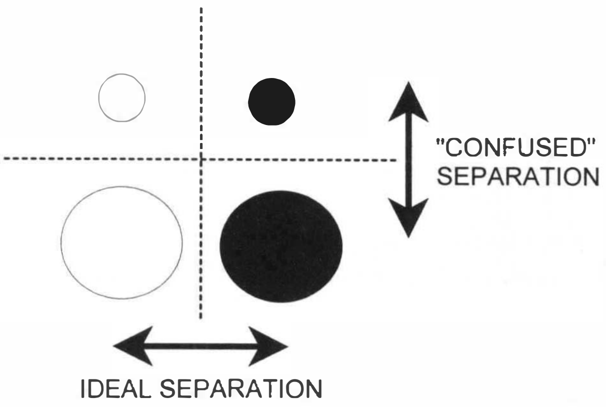

FIG. 2. REPRESENTATION OF CHARACTERISTICS OF "CONFUSED" PARTICLES

consistent difference in the particle size distribution would also affect separation, either positively or negatively. As is clear in the context of Fig. 1, considerable overlap could still exist in the particle size distributions, precluding the use of screening.

Most work on air classification uses stochastic methods (e.g., Senden [1978] and Henrikson [1979]). A deterministic approach models the motion of particles using a partial solution of the Navier-Stokes equation [Stessel and Peirce, 1987] results in a force balance solved for acceleration:

$$\frac{dv_p}{dt} = \frac{1}{\rho_p + \frac{1}{2}\rho_f\delta} - \rho_p g + \frac{3\rho_f(v_A - v_p)^2}{4D}C_D - \frac{\rho_f}{2}\frac{dv_A}{dt}\delta \tag{1}$$

where ρ_p = particle density; ρ_f = density of air; v_p = particle velocity; v_A = air velocity; D = particle diameter; g = the acceleration of gravity; and δ = Kronecker delta function. This equation is solved numerically to determine the fates of specific particles. Computer modelling with Eq. 1 showed that pulsing the airflow (v_A) rectifies the incorrect separation of confused particle pairs [Stessel and Peirce, 1987].

THE APFAC

The computer model implementing Eq. 1 was used to study the types of pulsing airflow that would best enhance separation. It was found that, for the distinction between plastic and aluminum, produced by a shredder identical to that used in this work, a sawtooth (asymmetric) pulse of approximately 1 s wavelength was best. Variations of the APFAC have been built in the laboratory for testing. Fig. 3 is a sketch showing the recommended configuration of the APFAC. That used for this work employed a 15 cm (6 in) cylindrical throat 2.25 m (8 ft) tall. A 5.6 kW (7.5 hp) blower was used. The pulsing valve employed an 25.4 cm (10 in) boiler damper valve powered by a pneumatic cylinder controlled by a pair of solenoid valves triggered by reed switches. Pulse waveform was controlled with diaphragm valves [Stessel 1992]. The *drum feeder*, as shown in Fig. 3, gives significant operational advantages: better feeding and lessened disruption of airflow [Stessel, 1990].

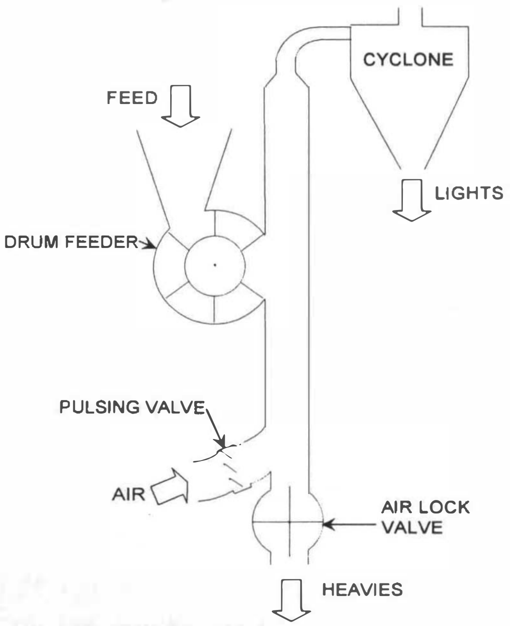

FIG. 3. THE ACTIVE PULSED-FLOW AIR CLASSIFIER (APFAC)

Laboratory studies with the APFAC (e.g. Stessel and Peirce [1985]) have shown a marked improvement in efficiency by comparison to straight and zigzag air classifiers. Experiments with pairs of spheres showed a statistically significant reversal of improper separation with pulsing. Various simulated wastes were then tried, also showing improved separation. In the case of simulated wastes, the exact reason for which pulsing improved separation could not be determined. This results from an additional advantage obtained from pulsed flow: the pulsing action breaks up clumps that would otherwise sweep the throat. Further, pulsing may act to improve separation between particles that, theoretically, would separate properly in a more traditional type of air classifier.

This work studied the application of the APFAC to the separation of some of the most important plastics in recycling.

INITIAL LABORATORY PREPARATION AND ANALYSIS

Given the plastics characteristics discussed in connection with Table I, combined with probable ancillary unit operations that would be considered suitable for a MRF, it

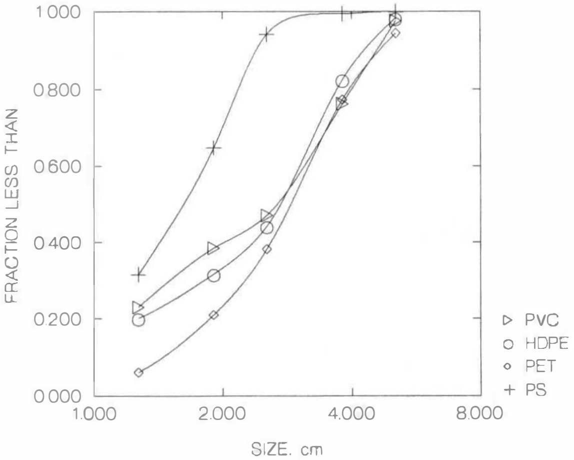

FIG. 4. PSD OF SHREDDED PLASTICS

was decided to begin by shredding the plastics. PET and HDPE containers were collected, washed, and saved by the writers. Reject consumer PVC bottles were donated by a local molder, as was PS sheet.

Using hammermill shredder, one might expect to achieve a difference in particle size and shape due to material strength parameters shown in Table I. This would combine with the difference in densities to produce varied behaviors of the particles in airflow. The particles were shredded using a small 3.7 kW (5 hp) hammermill in the Solid Waste Processing Laboratory, shredding through a 1.9 cm (3/4 in) grate. The particle size distribution obtained is shown in Fig. 4. The mean particle size is far greater than the grate size, as would be expected for such flexible materials.

Differences in the appearance of the shredded particles were also noted. To determine the effect of particle size, density, and configuration on aerodynamic behavior, one employs the *method of equivalent diameters* [Vesilind and Rimer, 1981]. A glass cone was connected to a laboratory blower, with the wide mouth open to the ceiling. Six particles of the median particle size identified during the particle size distribution were, separately, placed in the cone. Airflow was adjusted so as to hold the particle suspended in the cone. The particle was then removed and air velocity sampled using a hot-film anemometry system. The hot-film system was connected to an analog-to-digital conversion system in a microcomputer. Data-gathering software linearized and temperature-compensated the signal, producing a mean air velocity and pulse frequency.

The mass of each particle was measured on an analytical balance. The terminal velocity, v_T found in the laboratory was in the turbulent regime. Finding the equivalent diameter, d, required solving the cubic:

$$\frac{4}{3}\frac{g}{C_D}d^3 + v_T^2 d^2 - \frac{8gM_s}{\pi C_D \rho_f} = 0 \qquad (2)$$

TABLE II RESULTS OF EQUIVALENT DIAMETER ANALYSIS

PLASTIC	SIZE INTERVAL (cm)	MASS (g)		TERMINAL VELOCITY (m/s)		EQUIVALENT DIAMETER (cm)	
		MEAN	SD	MEAN	SD	MEAN	SD
PET	2.5>x<3.8	2.74	0.91	8.2	2.6	4.7	0.0062
PVC	2.5>x<3.8	2.00	0.44	6.3	0.8	5.0	0.0021
PS	1.3>x<1.9	0.470	0.112	4.0	1.1	3.8	0.0041
HDPE	2.5>x<3.8	1.55	0.73	6.1	0.9	4.4	0.0070

where g = the acceleration of gravity, C_D = the drag coefficient, and M_s is the mass of the particle.

Results of the equivalent diameter analysis are shown in Table II. Great irregularity among individual particles, even within one size interval, led to fairly high standard deviations in the direct measurements of mass and terminal velocity. The largest standard deviations were for PET, which may be due to the obvious difficulty in shredding a material with a significantly higher tensile strength. The mass and the terminal velocity are dependent: a greater mass results in a greater terminal velocity. When Eq. 2 was solved using terminal velocity/mass pairs, the error in the resultant equivalent diameter was thus reduced. Different equivalent diameters were obtained for different plastics, even those whose mean sizes were the same, and whose densities were virtually identical. PET and HDPE had virtually identical equivalent diameters, although their terminal velocities differed by a greater percentage. It is most critical to remove PVC from other plastics because even small contaminations damage the melts. In comparing PVC with HDPE, the terminal velocities were very close, and the equivalent diameters the closest after the PET/HDPE pair. The APFAC's abilities to ameliorate these separation problems were investigated. These data were used in a modeling effort to attempt to predict operating parameters and performance of the APFAC.

Modelling. The computer model discussed above was further developed to study the effect of pulse frequency. It stepped through frequencies from 0 hz (no pulse) to 5 hz, in increments of 0.2 hz. 5 hz was selected as the maximum because experience indicated that it was difficult to achieve higher frequencies in practice. The model determined the separation achieved after 4 s residence time. It has been shown that separation increases monotonically with time; 4 s was chosen to allow time for sufficient repetitions of low-frequency pulses. In each case, the modeled airflow was adjusted so as to produce separation centered about the point of injection.

Table III presents modeling results on the left. Key data were the maximum separation achieved: the PS/PET combination yielded the greatest separation; HDPE/PVC yielded the smallest; the rest were very similar. To compare desirable frequencies for all the plastic pairs, the dis-

TABLE III KEY MODEL AND LABORATORY RESULTS

PLASTIC PAIR	MODEL		LABORATORY		
	MAXIMUM SEP. (m)	MEAN AIR VELOCITY (m/s)	MEAN AIR VELOCITY (m/s)	MAXIMUM ϵ	r^2
HDPE/PVC	1.1	5.3	3.8	0.69	0.99
HDPE/PS	8.9	4.2	2.4	0.80	1.0
HDPE/PET	8.8	5.9	3.1	0.99	0.94
PS/PVC	9.9	4.3	2.6	0.95	0.96
PS/PET	16.9	5.0	2.1	0.88	N/A
PVC/PET	7.8	6.0	4.1	0.65	N/A

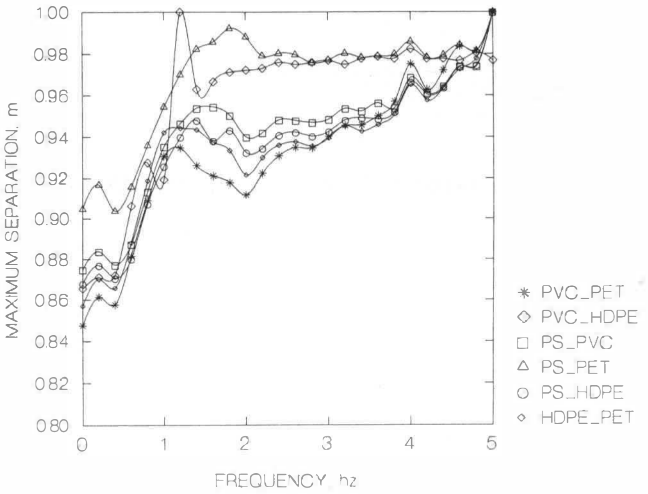

FIG. 5. PULSE FREQUENCY VERSUS NORMALIZED SEPARATION FROM THE MODEL

parate separations were normalized. The resulting graph is shown in Fig. 5. In all cases, pulsing significantly improved separation. Maximum separation was achieved with the maximum modelled frequency in all but the case of HDPE/PVC. Yet, all the plastics pairs seemed to exhibit a local maximum between 1 and 2 hz. This is in agreement with previous results [Stessel and Peirce, 1984]. The most reasonable practical conclusion was that separation was equally benefited by any pulse over 1 hz. Table III also shows the air velocities at which this optimum separation was shown. The mean air velocities were half the total amplitude for the pulsed airflow; these were all quite similar. On the basis of the modeling, the HDPE/PVC split gave the most cause for concern, particularly given the importance of removing PVC. Yet this split was where pulsing seemed most quickly to demonstrate a benefit.

LABORATORY AIR CLASSIFICATION

The laboratory APFAC was used to test separation of the plastic pairs discussed above. Consistency between these modeling results and prior work already referenced led to the decision to restrict laboratory APFAC testing to determining separations achieved with pulsing. Limitations of funding and time further contributed to this restriction.

The objective was to conduct efficiency determinations. These involve holding conditions as constant as possible, and varying velocities. The linearized efficiency, ϵ, was employed:

$$\epsilon = \sqrt{\left(\frac{x_{1,1}}{x_{1,0}}\right)\left(\frac{x_{2,2}}{x_{2,0}}\right)} \tag{3}$$

The first term is the recovery of material 1 through product stream 1; the second is the recovery of material 2 from product stream 2. With air classification of shredded materials, it is understood that aerodynamic behavior governing separation in the airstream is a function of the shredding that gives the particles their aerodynamic behavior. Particle size distributions in shredder output are most often characterized with the Two-Parameter Weibull distribution, employed as the Rosin-Rammler distribution in shredding. Thus, an efficiency expression can be derived for air classification based upon particle terminal velocities and air velocities:

$$\epsilon = \sqrt{[1 - e^{-|v/V_{c1}|^{2n}}][e^{-|v/V_{c2}|^{2n}}]} \tag{4}$$

where v is the air velocity; v_{c1} is the terminal velocity corresponding to the critical size in the Rosin-Rammler distribution for the material to be recovered in stream 1; v_{c2} is the corresponding parameter for the second material; n is the Rosin-Rammler exponent. This work is discussed in an ASTM paper on efficiencies [Stessel, 1989].

Two liter volumes of sample were fed into the feed hopper. This constituted the volume of the 2 kg samples of simulated solid waste that had been found to give reliable results in previous tests; these simulated wastes comprised plastics, aluminum, paper, and steel used in pilot systems of very similar scale to the APFAC used here [Stessel and Peirce, 1985]. The low bulk densities of the plastics made it necessary to base feed sample on volume. Five air velocities were used, going up to the maximum velocity of which the blower was capable. Efficiencies were then calculated for each airflow, using Eq. 3. These efficiencies were then curve-fit, where possible, to Eq. 4, using the Simplex estimation method, producing r^2 as a measure of goodness-of-fit. The curve was used to identify the peak possible efficiency, which, in all likelihood, would occur between points at which experiments were actually run. The literature on efficiency [Stessel, 1989] provides a full explanation of the rationale behind this method.

Two example efficiency curves are shown. In Fig. 6, all parameters were curve-fit by the computer. The peak

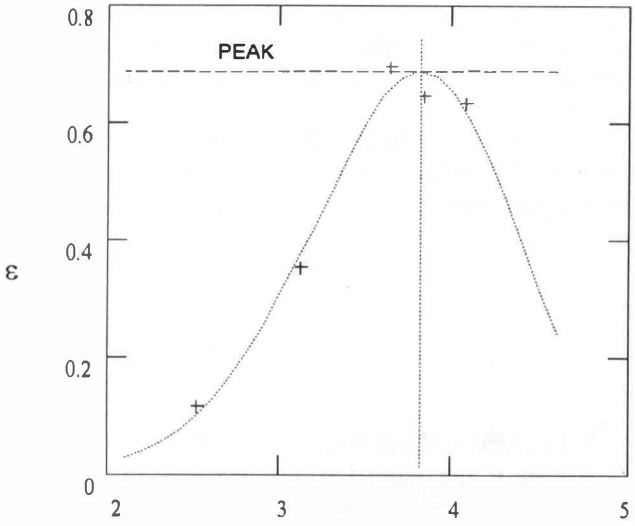

FIG. 6. EFFICIENCY CURVE FOR HDPE/PVC

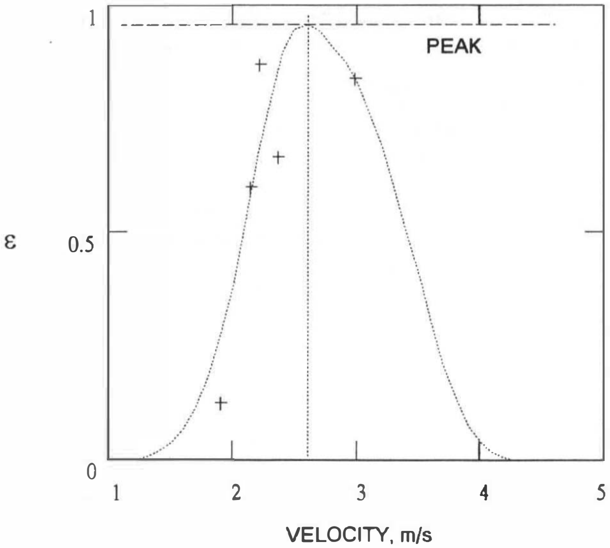

FIG. 7. EFFICIENCY CURVE FOR PS/PVC

efficiency shown is actually slightly less than the maximum test datum. Note that one might be tempted to fit a straight line, which would imply, however, efficiencies greater than one by 5 m/s; no such thing exists. In Fig. 7, the initial velocity was set by hand because Eq. 4 has multiple zeroes: if the curve-fit is not actually plotted, automated curve fitting can produce an excellent r2 by placing a zero somewhere within the experimental velocities; this has no physical meaning. Although forcing a physically-reasonable zero reduced the quality of the fit, it is more physically reasonable. An r^2 of 0.94 is still good.

The right part of Table III shows significant results of the laboratory air classification. The last two tests did not achieve a downturn in the efficiency curve. This is due to inadequate blower power. While an excellent fit with Eq. 4 is possible, it is meaningless. The peak laboratory efficiencies are reported in this case. The mean laboratory air velocities were all less than calculated velocities. This was because the laboratory valve did not produce a perfect ramp wave, although detailed analysis shows that significant pulse asymmetry is present in waveforms produced by this method [Stessel, 1992]. Fig. 8 shows the theoretical and actual velocities used to separate HDPE and PET, together with the means shown in Table III. For the top four cases, where the blower was adequately powerful, the predicted and experimental velocities varied together.

The need for more basic research is most clearly shown here. The pulsing system must be improved as suggested in the literature on valve design [Stessel, 1992]. The method of equivalent diameters must be refined to understand the scale-up from laboratory measurement of terminal velocity to behavior in the throat. The model does not incorporate particle-to-particle interactions, which can be a significant cause of increased particle tumbling, altering terminal velocity behavior. Only expanding the model to include multiple particles will allow theoretical exploration of loading rates, which are likely to have also affected these laboratory results. A more powerful blower, the production of additional measures of confidence through replications, and a wider range of separations must all be investigated.

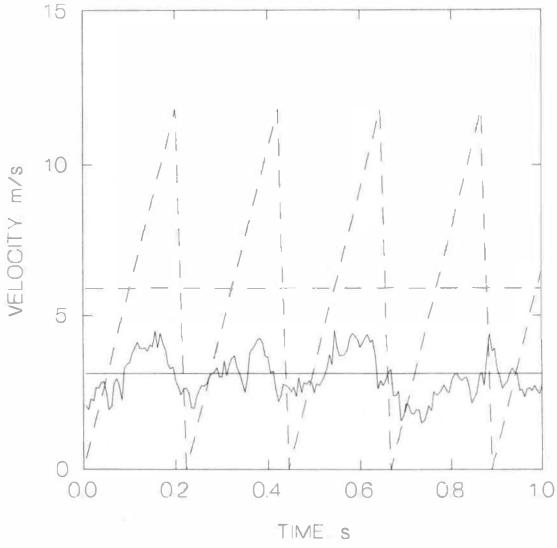

FIG. 8. THEORETICAL (DASHED) AND ACTUAL (SOLID) PULSES EMPLOYED FOR THE HDPE/PET SEPARATION, TOGETHER WITH THEIR MEAN VALUES

Of most importance is the production of good efficiencies in all cases, particularly given the preliminary nature of this work. The weakest instances were the separation of PVC, the contaminant of greatest concern, from the two plastics of greatest current interest in recycling programs: HDPE and PET. Nevertheless, the efficiencies are respectable for the intended use of the APFAC in plastics recovery.

CONCLUSIONS

The most important conclusion is that air classification, and the Active Pulsed-Flow Air Classifier in particular, could have a very worthwhile application separating commingled plastics. Collection of plastics could then occur in the only cost-effective manner conceivable: mixed. An initial separation could take place at the MRF, shredding the feed and using air classification. The shredding would reduce shipping volume, obviating the need for baling. The separate streams could then be shipped, from several MRFs, to more centralized intermediate processing facilities for further refinement, using more specialized, elaborate, and expensive equipment, albeit now in a more cost effective manner.

As this work was conducted under severe cost constraints, it cannot be said to have constituted optimization of air classification for plastics separation. In addition to more basic research into the APFAC, several options in implementation must be investigated. Certainly multiple air classifiers would be needed; sequenced operation would result in the extraction of individual plastics at various points. Many options should be tried: initial separation into two streams of two plastics each, sequential extractions of single polymers, air classification or air knife separation prior to shredding, etc. Screening may also prove useful, given the differences in shredding behavior.

The scope of this work was limited to proving the potential of air classification in plastics recycling. A return to this type of research could save significant costs in recycling systems, while recovering more useful materials for industry.

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