CIRP Annals - Manufacturing Technology 61 (2012) 35–38

Contents lists available at SciVerse ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

A novel separation process for recycling of post-consumer products

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ARTICLE INFO

Keywords:
Recycling
Sustainable development
Footwear material recycling

ABSTRACT

The use of automated product recycling based upon fragmentation and separation processes is rapidly increasing due to the high economic feasibility. Air-classifiers are key low-cost technologies employed in these processes; however their efficiency can be highly variable due to inhomogeneous particle sizes as separation largely relies upon the difference in particle terminal velocity. In this paper a pulsing air-column classifier is introduced in which particles are constantly accelerated and decelerated to provide higher separation efficiency regardless of particle sizes. Experimentation with inhomogeneous granulated leather, foam and rubber from footwear waste products demonstrates a separation improvement of 10–25% compared to existing technologies and ability to reclaim rubber with above 90% purity.

1. Introduction

Over the past decade, the increase in raw material cost, producer responsibility directives (such as WEEE: Waste Electrical and Electronic Equipment and ELV: End of Life Vehicles), and increased taxation on waste disposal has reduced the amount post-consumer waste sent to landfill in the EU [1]. In spite of this, unsustainable consumption of cheaply produced goods driven by rapidly changing consumer fashion trends has resulted in the prediction that by 2020 the EU will be generating 45% more waste, potentially offsetting the gains through improved waste management and disposal [1]. Therefore, there is a growing pressure to identify and apply the most appropriate end-of-life option for the treatment of different post-consumer waste streams. In this context, remanufacturing has been identified as the most environmental and economically feasible options for a subset of products [2]. However at present, in a large number of applications product remanufacturing is infeasible and therefore material or component recycling and reuse are often the preferred end-of-life options. The overall percentage of waste recycled varies significantly among European countries [3], due to poor waste collection, lack of appropriate regional waste treatment facilities, but more importantly due to high labour costs. Therefore, the increase use of automation within large scale recycling applications has been promoted as an economically viable solution to improve recycling rates [4].

A range of automated solutions have been investigated both for product disassembly through 'active' and 'robotic' disassembly [5], but mainly using fragmentation combined with separation technologies that exploit material properties such as electromagnetic conductivity, particle size and density [6]. The flexibility to deal with different waste streams coupled with high throughput and low operational cost has resulted in a significant increase in number of fragmentation and separation plants. The majority of these plants are based on complex multi-stage recycling processes employing a range of fragmentation processes such as shredding, granulation, impact milling and pulverisation together with a variety of separation technologies including magnetic and eddy current separators, air classifiers, dense media devices and optical sorters [7].

In recycling facilities where low-value waste streams (e.g. textile, foams, paper, and plastics) are processed, density based separation technologies i.e. liquid dense media tanks and air classifiers are among the most widely adopted processes. This is due to their simple implementation and low operational cost. However, there are inherent problems with both of these technologies: as the dense media separation often requires additional energy to dry the waste stream, and air classifiers are unable to easily deal with inhomogeneous waste particles with similar densities. Therefore, one of the key research challenges in achieving the goal of 'zero waste landfilling [8]' across various industrial sectors is to introduce new improved technologies to recycle low-value materials in an economically sustainable manner. This paper will introduce a novel air-based separation technology for materials with similar density, and will utilise the results from a set of experimental studies carried out with post-consumer footwear waste to develop bespoke separation modelling curves to validate the efficiency of this process and to make comparisons with existing technologies.

2. Air-based separation technologies

Air-based separation technologies such as cyclones, zigzag separators, and air-tables, provide high throughput low-cost solutions, and are particularly suitable for application where there is a low inherent recovery value associated with the waste materials. These processes rely predominately on the exploitation

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http://dx.doi.org/10.1016/j.cirp.2012.03.026

of particle terminal velocity which is dependent upon both the size and weight of particles. Thus, the efficiency of air classifiers can be highly variable for various fragmented waste streams in which particle sizes can be largely inhomogeneous, especially within multi-material waste streams. In such waste streams, larger lighter components will join the heavy fractions, while smaller heavier particles will enter the light fractions. This can be illustrated by application of particle terminal velocity equation (see Eq. (1)) as defined by Haider and Levenspiel [9].

$$u_t = u_t^* \left[\frac{\mu(\rho_s - \rho_g)g}{\rho_g^2} \right]^{1/3} \quad (1)$$

where ρ_s is particle density (kg/m^3); p_g is density of air (1.29 kg/m^3); g is gravity (9.81 m/s^2); μ is absolute viscosity of air (1.8×10^{-5} Pa s); u_t^* is particle shape characteristics, and finally u_t is the terminal velocity of the particle. For example in a mixed post-consumer waste stream (such as footwear products) largely consisting of foam and rubber materials with particle sizes of less than 4 mm, the terminal velocity (calculated using Eq. (1)) for a foam particle with density of 0.6 g/cm^3 and particle size of 5 mm would be very similar to that of a rubber particle with density of 1.1 g/cm^3 and particle size of 1 mm, resulting in a poor separation rate within the existing air classifiers.

In an attempt to overcome this shortcoming, commercial recycling facilities will often use a screening device to separate the waste stream into different sizes and utilise multiple air-classifiers to process materials with similar particle sizes. However due to inherent inefficiencies in these screening processes, inhomogeneous particles will still exist within many waste streams, and implementation of such multi-stage screening and separation processes adds extra complexity and cost to the recycling process. In addition, previous studies have indicated that due to these process inefficiencies, a minimum density difference of 0.45 g/cm^3 is required for the effective separation of materials using commercially available air separation technologies [10]. This clearly highlights the need for investigating new separation technologies for inhomogeneous fragmented waste streams such as footwear waste in which materials have very small density differences e.g. leather (0.7–0.8 g/cm^3), foam (0.4–0.65 g/cm^3) and rubber (0.9–1.4 g/cm^3).

2.1. Air-pulse separators

In commercial applications of air column separation, such as zigzag separators, a constant air stream is applied from specific directions in order to redirect the light particles travelling above their terminal velocity away from the heavy particles that are falling subject to gravity, as illustrated in Fig. 1a. However in the air-pulse separators, particles are subjected to an air pulsation (generated by opening and closing an inlet air valve based on an adjustable frequency) rather than a constant air stream (see Fig. 1b). In this approach, the particles are constantly accelerating and decelerating towards their terminal velocity resulting in complex aerodynamic forces acting on the particles, and thus providing an improved density dominated separation for non-uniformly sized particles.

A number of such air-pulse separators have been designed and prototyped largely for 'pre-consumer' industrial waste which have more predictable material properties and tend to be more homogeneous in size [11]. A number of air-pulse configurations are also described by Stessel and Peirce [12]. This includes a 'passive' configuration based on varying column size and shape and an 'active' configuration based on the use of an inline mechanical valve to generate the air-pulse. However, the application of such technologies for separation of 'post-consumer' waste streams which provides greater challenges due to unpredictable material properties and particle sizes, have received limited attention. An active air-pulse separator has been developed for inhomogeneous fragmented low-value

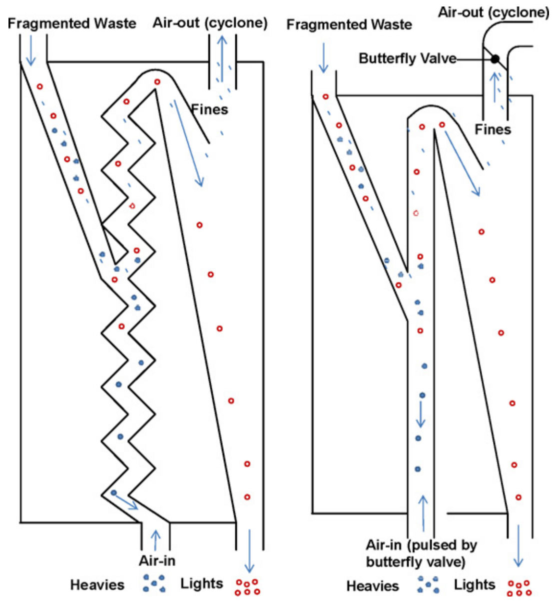

Fig. 1. (a) Zigzag separator and (b) air-pulse separator.

post-consumer waste such as those in end-of-life footwear products. This separator (see Fig. 2) contains an air column of 1.5 m long, 0.15 m depth and 0.1 m width, utilises a mechanical air valve to generate pulse frequencies between 2 and 7 Hz, and is capable of varying air speed of 2–10 m/s.

Implementation of this air-pulse separator as part of a footwear recycling system has been utilised to test the efficiency of this separator. The complete separation of footwear materials is a multi-stage process [13]. The air-pulse separator is designed and implemented specifically for the recovery of rubber from leather and foam, as will be described in the following section. For each recovered shoe materials there are potential applications including surfacing, insulation and underlay products [13]. However, one of the goals of this research is to create high purity rubber that could be used in the manufacture of new footwear products.

3. Experimental studies

The primary objectives of the experimental studies have been (a) to compare the yield and purity for the separation of post-consumer waste materials based on the design of a commercially available zigzag separator and the new air-pulse separator, and (b) to further analyse the particle separation behaviour of the two

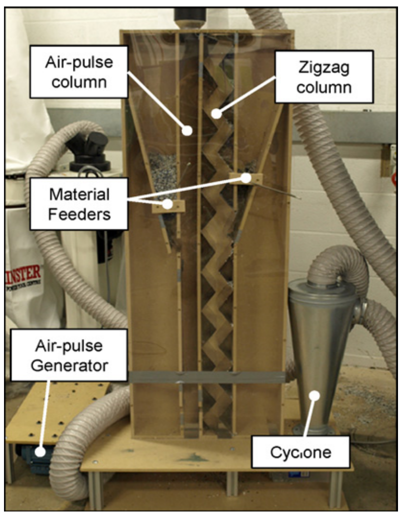

Fig. 2. Air separation test rig – zigzag and air-pulse.

Fig. 3. Separated footwear waste materials streams.

systems. More specifically, the separation purity and yield of rubber from two specific footwear waste material samples has been investigated, namely from (a) men's leather shoes containing rubber with a density range of 1.0–1.2 g/cm^3 and leather with 0.7–0.8 g/cm^3, and (b) sports shoes containing rubber with a density range of 0.9–1.4 g/cm^3 and PU/EVA foam with 0.4–0.65 g/cm^3.

These waste streams are fragmented using a granulator with a 5 mm screen, giving a nominal particle size in range of 3–4 mm in both scenarios (see Fig. 3). Previous experimental studies have shown that this is the optimal size for liberation of footwear materials, as larger particle sizes will include a significant proportion of mixed material (interconnected), while producing smaller particles will significantly reduce the throughput [13].

To measure material separation efficiency, sample sizes of 10 kg of shoes for each waste stream (i.e. leather and sport shoes) were prepared for experimentation. Purity has been calculated as the percentage of the target material (rubber) by weight in the corresponding processed waste stream, and yield was calculated as the amount of target material (rubber) collected as a percentage of the overall weight of the rubber in the waste stream. Visual inspection has been used for measurement of purity and yield, i.e. 10 samples of 50 g each (collected at random from heavy and light fractions after separation process) are visually inspected and sorted to calculate the process efficiencies. The airflow rate has also been varied in each experiment to demonstrate the predominant effects on yield and purity. Feed rate is kept constant for all trials at approximately 30 kg/hr, and finally air-pulse frequency of 3 Hz has been used for air-pulse separation trials.

3.1. Yield and purity results

The results from the experiments are summarised in Table 1 for zigzag separation and in Table 2 for air-pulse separation. The experiments 1–3 for sports and leather shoes were repeated four times, and the yield and purity figures in Tables 1 and 2 represent the mean values. The individual repetition values for each experiment are plotted in Fig. 4.

Trials 2-S (for sports shoes) and trials 2-L (for leather shoes) have resulted in the optimum balance of yield and purity for both separators, indicating that the optimal air-speeds for the zigzag separation in these trials is 4.4 m/s and for air-pulse separator is 3.1 m/s, i.e. less energy is required for air-pulse separation. It should also be noted that although an increase in air speed (in trials 3-S and 3-L) will improve the purity, the overall yield will be reduced. More importantly, the experimental results have clearly shown that the air-pulse separator is able to produce both higher yield and purity than the zigzag separator, as depicted in Fig. 4. In fact, the comparison of the results for experiments 2-S and 2-L in Tables 1 and 2 shows an improvement of 13% in yield and 18% in purity for waste sports shoes, and 12% in yield and 23% for purity for waste leather shoes. However, it should be noted that due to the nature of footwear waste, with its wide ranging material mix and densities, it is expected that experimental results may differ slightly between varying batches of shoes. This highlights the need for additional experimentation with larger quantities of waste to further validate these preliminary results.

Table 1
Footwear material zigzag separation results.

Trial	Air-flow (m/s)	Materials	Yield (rubber)	Purity (rubber)
1-S	3.3	Rubber, foam	88	69
1-L	3.3	Rubber, leather	87	65
2-S	4.4	Rubber, foam	84	78
2-L	4.4	Rubber, leather	79	74
3-S	5.1	Rubber, foam	69	85
3-L	5.1	Rubber, leather	68	82

Table 2
Footwear material air-pulse separation results.

Trial	Air-flow (m/s)	Materials	Yield (rubber)	Purity (rubber)
1-S	2.3	Rubber, foam	97	87
1-L	2.3	Rubber, leather	96	82
2-S	3.1	Rubber, foam	95	92
2-L	3.1	Rubber, leather	93	91
3-S	3.5	Rubber, foam	88	94
3-L	3.5	Rubber, leather	87	93

3.2. Particle separation behaviour

The experimental results have highlighted the potential benefits that can be obtained from air-pulse separation technology. However, a more detailed analysis of the particle separation behaviour needs to be undertaken before large scale application of these technologies within commercial recycling facilities. In this context, a computerised model of this separation process is required to enable wide ranging experimentations with various material types and waste streams. Modelling the behaviour of real-world separation processes and their interactions within a recycling facility is a very challenging problem due to a large number of factors such as inhomogeneous material mix and size, particle entanglement and interconnectedness, inter-particle collision, and other process inefficiencies.

A common method of measuring the separation efficiency of air classifiers is Tromp curves [14], which is based upon a graphical analysis of the separation efficiency across various parameters, and represents the percentages of the waste streams that end up in the wrong waste fractions. This is known as the *partition coefficient* and is generated based on two main parameters, namely the cut-point (X_{50}) and the probable error of separation (E_p). The cut-point

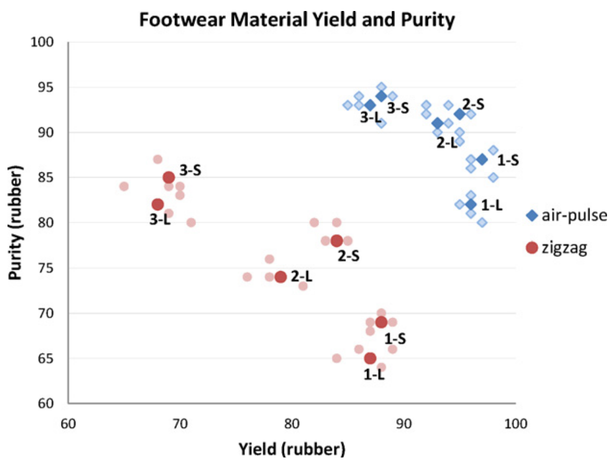

Fig. 4. Yield and purity rates for rubber in footwear materials.

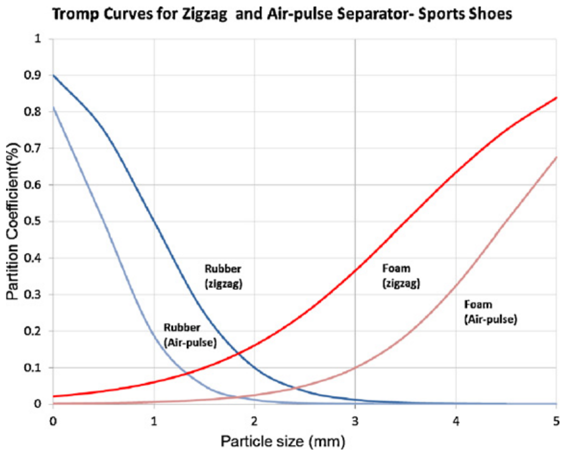

Fig. 5. Tromp curves for zigzag and air-pulse separations.

represents the value of a specific parameter (in this case particle size) at which 50% of waste will end up in the wrong fraction. The E_p is calculated using Eq. (2) where A represents the particle size at which 75% of the waste ends up in the wrong fraction and B is the particle size for which 25% of waste reports to wrong fraction. Based on the definition of these parameters, Eq. (3) is used to calculate the partition coefficient (Y) at various particle sizes and develop the Tromp curves as depicted in Fig. 5. It should be noted that the majority of separation processes follow an inverse exponential function [14], as shown in Eq. (3). These equations can be used to describe the separator behaviour for development of computerised recycling process models.

$$E_p = \frac{A - B}{2} \tag{2}$$

$$Y = \frac{1}{1 + \exp(1.099 \times ((X50 - X)/E_p))} \tag{3}$$

The values for X_{50}, A and B in this study were obtained empirically. The separated waste fractions from the experiments outlined in Tables 1 and 2 were sieved into a range of particle sizes and analysed in order to find the particle size at which 75% (A), 50% (X_{50}) and 25% (B) of the materials report to the wrong fraction. It must be noted that analysis of overall purity and yield is not the main focus of Tromp curves. These curves allow a more detailed analysis of separation behaviour for various materials at different particle sizes. However, the potential yield and purity of recovered materials is clearly impacted by the partition coefficients in the curves. An example Tromp curve for the waste sports shoe materials for the zigzag and air-pulse separators is illustrated in Fig. 5. The comparison of these curves shows that with the zigzag separator larger percentages of rubber will report to the wrong fraction. For example in Fig. 5, 1 mm rubber particles have the probability of 50% to end up in wrong fraction with lighter foam particles using zigzag separation. However, with the air-pulse separator only 18% of 1 mm rubber particles will end up in the wrong fraction. This improved separation of smaller rubber particles is the reason why the overall rubber yield is higher for the air-pulse separator. In addition, the purity of rubber is clearly affected by the amount of foam reporting to the wrong (rubber) fraction. From the curves in Fig. 5 it is apparent that a greater amount of larger foam particles (greater than 4 mm) are likely to report to the rubber fraction using the zigzag separator when compared with the air-pulse separator. In conclusion, the Tromp curves have highlighted that the separation behaviour of the two processes considered in this study is not only dependent on density of waste materials, but also as predicted, significantly influenced by the aerodynamic properties of particles within the waste stream.

At the same time, this modelling has clearly demonstrated that the air-pulse separation is less sensitive to the irregular size range of fragmented waste.

4. Conclusions

There has been a rapid growth in recycling of products and materials over the past two decades, in particular in applications where post-consumer waste streams contain highly valuable materials. However, it is argued that one of the major barriers in achieving 'closed-loop manufacturing' and eliminating the need for waste to landfill is to develop economically sustainable recycling solutions in particular for waste containing low-value materials. The air-pulse separation process presented in this paper shows an improvement of 10–25% in purity and yield when compared to a conventional separation technology like zigzag separator. It should be noted that any such small improvement in material purity could significantly influence the range of material reuse applications and may even facilitate a 'closed-loop recycling' approach. However, the commercial deployment of such separation technology will still require further investigation into energy consumption, throughput speed, scalability, cost, etc. Due to cost and time constraints in undertaking real world experimentation, there is a need to develop computerised recycling process models. The Tromp curves developed for waste footwear materials show great potential to support both the operational optimisation and the design of recycling facilities. The future work will develop further Tromp curves based on various materials and waste streams, and will implement the use of such curves within a 'computer-aided material recycling simulation model' to support design and operation of the next generation of fully automated recycling facilities.

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