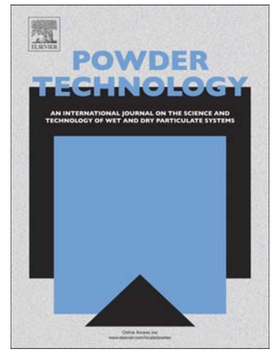

Recycling oriented vertical vibratory separation of copper and polypropylene particles

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Recycling oriented vertical vibratory separation of copper and polypropylene particles

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Abstract

Vibration has been employed in various engineering processes for material handling. The famous Brazil nut effect, large particles tend to rise to the top under vibration, initiates various research about vibration induced particle segregation. Particle size and density are two determining factors for their behaviour under vibration. Previous research in University of Nottingham proves vertical vibratory separation to be a promising environmental friendly mechanical separation method for recycling metallic fraction from shredded Waste Electric and Electronic Equipment (WEEE) stream. A pilot scale thin cell vibratory separator has been developed to investigate the potential for WEEE recycling applications. Shredded copper and polypropylene particles have been chosen to mimic metallic and non-metallic fractions in WEEE. Vibratory separation experiment with controlled environment and addition of solid lubricant are presented in this paper. The result demonstrates the effect of relative humidity and solid lubricant on improving flowability of granular system hence successful vibratory separation. The proposed mechanisms for the presence of moisture and solid lubricant are lubricant effect and elimination of static electricity.

Keyword: vibratory separation, WEEE, particle separation, particle flowability, humidity

1. Introduction

Increasing concern has revolved around the issue of Waste Electric and Electronic Equipment (WEEE) recycling around the world. It is estimated that 315 million computers has be discarded between 1997 and 2004 [1]. Global WEEE generation is estimated to be 20-25 million tonnes per year [2]. WEEE recycling has posed a great challenge to China, which is the destination for over 70% of WEEE worldwide [3, 4]. The current approach of WEEE recycling is predominately acid leaching [5-8]and open incineration in remote areas in developing countries [9, 10]. Serious environmental and health problems induced by WEEE recycling have been reported in the famous WEEE recycling town, Guiyu [3, 11]. Chemical methods such as strong acid leaching and open incineration are practiced in this town for decades for WEEE recycling, which has caused soil, water and air pollution. Nephrolith and some respiratory problem become common local diseases and no portable water could be found within 10 km from this town [12]. From resource and economic points of view, WEEE can be regarded as source of precious metals. A life cycle assessment report for metal recovery from high-grade WEEE stated the recovery of 165 kg copper and precious metal, 381 kg iron and 22 kg aluminium from 1000 kg of high-grade WEEE [5]. Widmer et al. claimed that early generation PCs each contain up to 4 g of gold and 1 g for current generation PCs [13].

Originated from 'Brazil nut effect', the phenomena of vibration-induced segregation of granular material had attracted attention from numerous researchers to investigate the behaviour pattern of particles subjected to vertical vibration [14-18]. Vibration condition, separation cell geometry and properties of particles are three major factors influencing the particle separation efficiency [19, 20]. The application of vibratory separation on waste recycling proves its potential in metal recovery from WEEE, especially Printed Wiring Boards (PWBs). The development of a novel dry separation system for WEEE recycling could significantly reduce the amount of energy and chemical consumption as well as environmental impact. Mohabuth et al. [21] developed a lab scale two-chamber partition cell and proved the capability to concentrate metal elements from waste electrical cables and PWBs in different size fractions from 105-300 μm. The system was then modified by Habib et al. [22] to T-shape separation cell for the separation of metallic fractions from shredded PWBs particles less than 1.5mm. Both systems have proved the effectiveness of vibratory separation for the recovery of metallic fraction from shredded WEEE. However, the separation processes of both systems were very slow (about 45 minutes) and limited their scale-up development for industrial application.

The research presented in this paper aims at providing experimental basis for developing a fast vertical vibratory separation system for WEEE recycling. The thin cell design used for vibratory separation of bronze and glass spheres has been reappraised[23]. Successful separation experiment presented in this study finish within two minutes, single thin cell separation cell can be expanded to multi-cell design for industrial scale-up still maintain the same separation time. Copper and polypropylene particle samples have been prepared to represent the metallic and non-metallic fractions in shredded PWBs respectively. Two sets of experiment with controlled environment and addition of solid lubricant has been designed to investigate the effect of water and glidant on separation mechanisms. Experimental results illustrate that success of separation is related to the presence of water and solid lubrication in the granular system. The outcome of this experiment improves the understanding of the influence of flowability of granular system on vibration induced particle separation and provides a possible solution for enhanced vibratory separation.

2. Experimental methodology

2.1 Vertical vibration system

To understand the separation mechanisms and investigate the optimal separation parameters (vibration intensity, frequency, separation cell geometry) for WEEE recycling oriented operation, a novel vibratory separation rig has been developed as shown in Figure 1. The vibration system in this rig consists of two carbon steel plates, the bottom plate sits on the metallic frame with poles and springs fixed at four corners, which nest to ball bearings and spring holders on the vibration plate. Vibtec-FP-95 pneumatic linear vibrator was bolted to the bottom of the vibration plate to provide vibratory force. Freescale MMA2241KEG single axis accelerometer with acceleration range of ±10g (g = gravitational acceleration) is installed on the top vibration plate to monitor the vibrational acceleration and frequency. Separation cell design from Webster [23] has been reappraised and thin depth with slopped base has been adopted to accelerate the separation process. The base block of the separation cell is made from polyoxymethylene with 15° slope and two height-adjustable weirs at both ends. Perspex plates are used for separation cell for visual observation to identify separation. The thickness of the block is 50mm and another piece of perspex can be inserted to adjust the depth of separation cell. The depth of separation cell used in this study is 10mm. The length of the separation cell is 200mm and the height can be altered via adjustable weirs between 10mm and 100mm. Silica glue is used to seal the connection among different parts.

The vibration condition is described by two parameters: dimensionless vibration intensity parameter Γ and vibration frequency f.

$$\Gamma = A\omega^2/g$$

where A is the amplitude of vibration, angular frequency $\omega = 2\pi f$, and g is gravitational acceleration.

2.2 Sample preparation

Artificial samples have been prepared to investigate the vibration-induced separation behaviour of granular system. Copper and polypropylene were selected to represent the metallic and non-metallic fractions in WEEE respectively. To determine the optimum particle size that can be achieved under room temperature condition, two stage grinding with Fengli CSF570 hammer mill and Retsch SM2000 cutting mill (Figure 3) have been applied to process waste computer motherboards (high valuable PWBs from recycling point of view) purchased from the market. Considering the energy consumption for size reduction, the imperial particle size identified from experimental results is 850μm, smaller than which metallic fractions in shredded PWBs starts to balling and smashing rather than break down into smaller particles. Initial sample used to prepare copper and polypropylene were copper from single wiring copper cable and polypropylene pellets (EPS30R, Dushanzi, China National Petroleum Corporation) with particle size of about 2mm. Because this vibratory separation system is designed to recover metallic fractions from WEEE stream, copper and polypropylene were prepared with the same grinding process as waste computer mother boards to simulate particle characteristics of shredded WEEE sample. The shape of prepared copper and polypropylene particles is irregular and the accumulative particle size distributions are shown in Figure 4. as well as that of shredded PWBs.

To mimic the concentration of metallic and non-metallic fractions of shredded PWBs and ease visual identification of particle segregation within the bed, the bulk volume ratio of copper and polypropylene particles was 1:3 for all vibratory separation experiment. Particle bed height was designed to be 40mm based on previous experimental result. The true densities of samples were measured with Quantachrome ULTRAPYC 1200e Pycnometer, 8.76 g/cm^3 and 0.91 g/cm^3 for copper and polypropylene respectively.

2.3 Humidity control

Previous experiment illustrated that successful separation of copper and plastic particles achieved in summer can not be reproduced in winter. The hypothesis of humidity effect on successful separation has been proposed. Vibratory separation experiment has been conducted under precisely controlled temperature and relative humidity in the environmental chamber to investigate the effect of environmental condition. The experimental set-up is illustrated in Figure 5 and 6. Three air compressors (Dynamic DA5002) have been used to supply compressed air to the pneumatic piston that powers the vibration plate on the vibratory separator. 10mm diameter polyurethane tube was used to divert compressed air into the pneumatic piston and exhaust air out of the environmental chamber so that the temperature and relative humidity will not be affected.

In addition to internal temperature and humidity probe from the environmental chamber, a thermocouple and a Honeywell HIH-4000-003 humidity sensor has been positioned next to the vibratory separator cell to monitor the environmental condition of granular system during experiment. The temperature and relative humidity for vibration separation test range from 15℃ to 30℃ and 70% to 90% with increment of 5℃ and 10% respectively.

2.4 Addition of glidant

Fine talc has been added to copper and polypropylene particles to investigate the influence of glidant addition on separation efficiency.

Fine talc used in this experiment was purchased from Shanghai Liangjiang Titanium White Product Co., Ltd and sieved to select fine powders with particle size less than 38μm. The amount of fine powders added to the system for each tests are 0.1%, 0.5% and 1% (mass percentage).

3. Results and discussion

3.1 Effect of humidity

Conditions listed in Table 1 has been tested for vibratory separation of copper and polypropylene particles and successful separation has been identified at 25°C with relative humidity of 90%, dimensionless vibration intensity parameter 5 and 6. The absolute humidity of experimental conditions listed in Table 1 are shown in Table 2. Figure 6 demonstrates the successful separation process of copper and polypropylene particles at 25°C and 90% relative humidity. Vibration generated by the pneumatic piston induced global convection current within the particle bed, dominate convection of particles flowed counterclockwise, moved upwards to the higher side of the cell bed at the bottom and downwards to the lower side near the surface. Soon after vibration started, localized concentration of copper particles in random regions of the particle bed occured (30s picture in Figure 7), the localized concentrated copper particles were taken by the global convection current and accumulated at the top layer near the lower side of the separation cell afterwards, after that the movement of polypropylene layer slowed down and the particle bed stratificated into top copper layer and bottom polypropylene layer. The separation process normally finished within two minutes and the strafication status remained during 10 miuntes' experiment time.

Vibratory separation experiment in the environmental chamber suggested that suitable temperature and relative humidity is crucial for the successful vibratory separation of copper and polypropylene particles.

3.2 The effect of solid lubricant

The vibratory separation experiment carried out in the environmental chamber confirmed the effect of water in successful separation. From visual observation of the vibratory separation process, movement patterns of particles are different between successful and unsuccessful separation experiments. In successful separation processes, there were both inter-particle movement and global convection of particles within the separation cell. However, in unsuccessful separation processes, there was only global convection of particles whereas the relative position of particles remained the same throughout the process. It is suspected that the absence of relative movement of particles results from low flowability of particles. To test the hypothesis of flowability effect, talc with particle size less than 38μm has been added as solid lubricant to adjust the flowability of the copper and polypropylene particles. Figure 8 to 11 show the comparasion of vibratory separation process of copper and polypropylene particles with different talc percentage. To aviod the interference from moisture content, all samples were dried in the oven at 75°C for 4 hours prior to vibratory separation test.

Figure 7 shows the vibratory separation of copper and polypropylene particles with no talc powder as lubricant, this serves as blank experiment for comparision. Particles circulated within the separation cell without any strafication effect identified in 10 minutes' experimental period. Figure 9 to 11 below illustrate separation process of copper and polyprolene particles with different weight percentage of fine talc particles as solid lubricant. Particle separation has been observed in the vibratory separation experiment with the addition of talc as solid lubricant. The duration of separation process depends on the amount of talc added into the system. For 0.1% w/w and 0.5% w/w addition of talc, the separation process last for about 2.5 and 6.5 minutes respectively, after which particles start to mix. This disappearance of concentration effect is caused by fine talc in the granular system either sink to the bottom or adhere to the cell wall due to triboelectrification effect generated from the vibration process. With addition of 1% w/w talc as solid lubricant, separation of copper and polypropylene particles has been achieved within two minutes and the stratification state remains within 10 minutes' experiment period.

3.3 Mechanisms explaining the effect of humidity and addition of glidant

Two sets of vibratory separation experiment of copper and polypropylene particles proved that suitable environmental condition and addition of solid lubricant enhance particle segregation. Different particle movement patterns have been identified between successful and unsuccessful separation. In successful vibratory separation, particles were forced to move with vibration induced global circulation within the separation cell. Copper and polypropylene particles showed different movement patterns, copper particles concentrated in certain region of the separation bed and emerged to the surface forms the top layer. On the other hand, in unsuccessful separation processes, movement pattern of copper and polypropylene particles were very similar and they circulated with global convection showing no separation effect. The global particle circulation in the separation cell results from vibration, which is forced movement of particles. Whereas the different movement patterns of particles shown in successful separations is the reflection of the ability of the granular system to flow freely – flowability[24]. The flowability of granular systems is influenced by physical-chemical properties of the particles and governed by inter-particle forces. Those properties include intrinsic characteristics of the particles like particle size, size distribution, shape, surface texture, surface energy, chemical composition and extrinsic bulk properties like moisture content, vessel geometry. ~~The predominate force that affects the flowability of granular system is inter-particle adhesion which is caused by intermolecular forces like van der Waals forces, local chemical bonds, electrostatic charges, and bridging forces.~~

Two mechanisms have been proposed to explain the effect of water and talc in vibratory separation of copper and polypropylene particles: lubrication and elimination of static electricity.

3.3.1 Lubrication effect

Lubrication effect of water has been reported in various granular systems. The flowability of distilled dried grains and rapeseed were found to increase with increasing moisture content [25, 26]. There are two mechanisms that water affects the behavior of the granular systems: capillary adhesion and lubrication. Water present in granular systems will form liquid bridges which generate capillary adhesion force [27, 28]. Moisture could have different effect on flowability of granular system under normal stress depend on the property of particles and the moisture content: Thakur et al. [29] reported reduced flowability of spray dried detergent powders with moisture content increased from 2% to 5% under high normal stress; Opalinski et al. [26] stated that moisture reduce the flowability of food powders at low normal stress and increase flowability at high normal stress with moisture content in the range of 0% to 25%. High relative humidity of experimental condition of vibratory separation experiment in the environmental chamber results in relatively high moisture content of copper and polypropylene particles. The behavior of particles is similar as food powder reported by Opalinski et al. [26]. When low normal stress being applied to the granular system, surface tension produced by capillary adhesion force dominates to hold the particles together, in other words, reduce the flowability. When the system started to vibrate, particles within the separation cell are subject to high normal stress and forced to vibrate. Under this circumstance, lubrication dominates the effect of water in granular system. Water attached on the surface of particles will form thin layers functioning as lubricant to reduce friction between particles. The behavior of copper and polypropylene particles in environmental chamber was affected by both vibration – normal stress and moisture content – capillary adhesion force. As shown in Table 2, the absolute humidity of successful separation condition - 25°C and 90% relative humidity is 20.77 g/m^3 water. It is reported that particle flowability increase with humidity to a maximum level and then start to decrease [30]. For conditions with less absolute humidity the moisture content is not enough to form thin lubricant layer between particles, on the other hand, high absolute humidity lead to strong capillary force hold particles together therefore reduce the flowability. The environmental condition provided suitable moisture content for increased particle flowability, the reason for unsuccessful separation under vibration intensity 4 is not able to provide high normal stress to suppress capillary adhesion force between particles.

Solid lubricants have been used in various engineering processes to adjust the flowability of granular systems, the most commonly used are magnesium stearate, colloidal silica and talc [31]. The addition of fine similar and dissimilar materials proves to be effective in enhancing flow properties of granular systems and the extent of lubrication depend on the physical and chemical properties of particles. Jones [32] suggested that frictional effect and separation effect explains the mechanism of solid lubricant. Fines added to the granular system adhere to the surface of particles resulting in reduction of surface asperities therefore inter-particle friction. For dissimilar materials like talc to the copper and polypropylene system, the inter-particle force can be reduced from smaller friction coefficient of talc added to the granular system. Separation effect has also been caused by the addition of fine particles to the granular system: fines adhere to particles to form aggregates with larger size and longer inter-particle distance, results in reduction of inter-particle van der Waals attraction force and capillary adhesion force. The frictional effect and separation effect caused by fines in the granular system enhances the free flow of particles.

3.3.2 Elimination of electrostatic force

Electrostatic force is another major force that affects the behavior of the granular system. In vibratory separation, particles within the separation cell are forced to vibrate, which generate particle-particle collision and mechanical attributes between particles and wall surface. Particles and the wall surface can then be charged triboelectrically result from these interactions. [33-35]. Commonly used methods to reduce triboelectrification effect in particle handling involve addition of antistatic agent, increase of relative humidity and ionization [36].

Guardiola et al. [37] had conducted a series of experiment with particles belong to Geldart's group B classification to investigate the influence of relative humidity of fluidizing air on particle electrification. The results illustrate that when relative humidity is higher than a critical value, triboelectrification effect is not observed in the granular systems. The critical relative humidity varies from 45% to 70% for different samples. In humid environment, water molecules will accumulate on the surface of particles to form water droplet or thin layer, which serves as conductor for electrons to travel and neutralize in the system. Experiment illustrates that elimination of static electricity generate similar effect on enhancing the flowability of granular system as the addition of solid lubricant [31]. Revel et al. [36] reported that addition of small proportion of fines to granular system leads to the splitting of agglomerates and disappearance of particulate attached on the walls, which indicate the elimination of static electricity. This effect is found to be independent of electric nature of the added fine material [38]. The proposed theories for explaining the static electricity elimination effect are reduction of particle-particle collision and charge carrier function of the fine particles. In granular system with 1 vol% fines, the probability of direct particle-particle contact and fine-fine contact are of the order of magnitude of 10^{-3}-10^{-4}, therefore the electric forces in it is estimated to be 8-12 orders of magnitude smaller than that in system of pure particles. Fines in the granular system may also acts as charge carriers within the system and cause neutralization process to reduce the inter-particle electrostatic force [38, 39].

4. Conclusion

The separation of copper and polypropylene particles is found to be affected by the flowability of the granular system. Experiments have been carried out to investigate the effect of relative humidity and addition of talc as solid lubricant on separation. Environmental condition at 25°C, relative humidity of 90% proves to stimulate the separation process with dimensionless vibration intensity parameter 5 and 6. Experiment of adding glidant to the granular system illustrates that separation can be facilitated with the addition of fine talc as solid lubricant. Successful separation of copper and polypropylene particles has been achieved with the addition of 1 mass % of fine talc powder. Two mechanisms have been proposed to explain the effect of relative humidity and solid lubricant on separation: lubricant effect and elimination of static electricity, which enhanced the flowability of the granular system. Future work will be focused on two aspects: the development of a method to quantify the dynamic flowability of granular systems thereafter establishing the relationship between dynamic flowability of granular systems with its behaviour in vibratory separation, and the development of process to control or adjust the flowability of granular systems.

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References:

1. Realff, M.J., M. Raymond, and J.C. Ammons, *E-waste: An opportunity.* Materials Today, 2004. **7**(1): p. 40-45.
2. Robinson, B.H., *E-waste: An assessment of global production and environmental impacts.* Science of The Total Environment, 2009. **408**(2): p. 183-191.
3. Hicks, C., R. Dietmar, and M. Eugster, *The recycling and disposal of electrical and electronic waste in China—legislative and market responses.* Environmental Impact Assessment Review, 2005. **25**(5): p. 459-471.
4. Puckett, J., et al., *Exporting Harm: The High-Tech Trashing of Asia*, 2002, The Basel Action Network & Silicon Valley Toxics Coalition: Seattle.
5. Bigum, M., L. Brogaard, and T.H. Christensen, *Metal recovery from high-grade WEEE: A life cycle assessment.* Journal of Hazardous Materials, 2012. **207–208**(0): p. 8-14.
6. Bas, A.D., H. Deveci, and E.Y. Yazici, *Treatment of manufacturing scrap TV boards by nitric acid leaching.* Separation and Purification Technology, 2014. **130**(0): p. 151-159.
7. Petter, P.M.H., H.M. Veit, and A.M. Bernardes, *Evaluation of gold and silver leaching from printed circuit board of cellphones.* Waste Management, 2014. **34**(2): p. 475-482.
8. Havlik, T., et al., *Leaching of copper and tin from used printed circuit boards after thermal treatment.* Journal of Hazardous Materials, 2010. **183**(1–3): p. 866-873.
9. Townsend, T.G., *Environmental Issues and Management Strategies for Waste Electronic and Electrical Equipment.* Journal of the Air & Waste Management Association, 2011. **61**(6): p. 587-610.
10. Onwughara, N.I., et al., *Disposal Methods and Heavy Metals Released from Certain Electrical and Electronic Equipment Wastes in Nigeria: Adoption of Environmental Sound Recycling System.* International Journal of Environmental Science and Development, 2010. **1**(4).
11. Sepúlveda, A., et al., *A review of the environmental fate and effects of hazardous substances released from electrical and electronic equipments*

during recycling: Examples from China and India. Environmental Impact Assessment Review, 2010. **30**(1): p. 28-41.

12. Lai, Y. and S. Lu, *Anthropological survey report on e-waste dismantling in Guiyu. Shantou*, Y. Lai and S. Lu, Editors. 2003, Anthropology Department of Zhongshan University, Greenpeace China: Guangzhou.
13. Widmer, R., et al., *Global perspectives on e-waste.* Environmental Impact Assessment Review, 2005. **25**(5): p. 436-458.
14. Chung, Y.C., H.H. Liao, and S.S. Hsiau, *Convection behavior of non-spherical particles in a vibrating bed: Discrete element modeling and experimental validation.* Powder Technology, 2013. **237**(0): p. 53-66.
15. Xu, C. and J. Zhu, *Parametric study of fine particle fluidization under mechanical vibration.* Powder Technology, 2006. **161**(2): p. 135-144.
16. An, X.Z., et al., *Effect of vibration condition and inter-particle frictions on the packing of uniform spheres.* Powder Technology, 2008. **188**(2): p. 102-109.
17. Rémond, S., *Compaction of confined mono-sized spherical particle systems under symmetric vibration: a suspension model.* Physica A: Statistical Mechanics and its Applications, 2004. **337**(3–4): p. 411-427.
18. Mawatari, Y., et al., *Effect of particle diameter on fluidization under vibration.* Powder Technology, 2002. **123**(1): p. 69-74.
19. Williams, J.C. and G. Shields, *The segregation of granules in a vibrated bed.* Powder Technology, 1967. **1**(3): p. 134-142.
20. Ahmad, K. and I.J. Smalley, *Observation of particle segregation in vibrated granular systems.* Powder Technology, 1973. **8**(1–2): p. 69-75.
21. Mohabuth, N., P. Hall, and N. Miles, *Investigating the use of vertical vibration to recover metal from electrical and electronic waste.* Minerals Engineering, 2007. **20**(9): p. 926-932.
22. Habib, M., N.J. Miles, and P. Hall, *Recovering metallic fractions from waste electrical and electronic equipment by a novel vibration system.* Waste Management, 2013. **33**(3): p. 722-729.
23. Webster, H.E.C., *Developing a Vertically-Vibrated Separator for Fine Granular Mixtures*, in *Department of Chemical and Environmental Engineering*2009, University of Nottingham.

24. Traina, K., et al., *Flow abilities of powders and granular materials evidenced from dynamical tap density measurement.* Powder Technology, 2013. **235**(0): p. 842-852.
25. Ganesan, V., K. Muthukumarappan, and K.A. Rosentrater, *Flow properties of DDGS with varying soluble and moisture contents using jenike shear testing.* Powder Technology, 2008. **187**(2): p. 130-137.
26. Opaliński, I., M. Chutkowski, and M. Stasiak, *Characterizing moist food-powder flowability using a Jenike shear-tester.* Journal of Food Engineering, 2012. **108**(1): p. 51-58.
27. Dhanalakshmi, K., S. Ghosal, and S. Bhattacharya, *Agglomeration of food powder and applications.* Critical Reviews in Food Science and Nutrition, 2011. **51**(5): p. 432-441.
28. York, P., *Particle–Particle Adhesion in Pharmaceutical Powder Handling, Fridrun Podczeck, Imperial College Press, 1998. ISBN 1-86094-112-5.* International Journal of Pharmaceutics, 2000. **206**(1–2): p. 105.
29. Thakur, S.C., et al., *An experimental and numerical study of packing, compression, and caking behaviour of detergent powders.* Particuology, 2014. **12**: p. 2-12.
30. Sandler, N., et al., *Effect of Moisture on Powder Flow Properties of Theophylline.* Pharmaceutics, 2010. **2**(3): p. 275.
31. Pingali, K.C., et al., *Use of a static eliminator to improve powder flow.* International Journal of Pharmaceutics, 2009. **369**(1–2): p. 2-4.
32. Jones, T.M., *The effect of glidant addition on the flowability of bulk particulate solids.* Journal of The Society of Cosmetic Chemists, 1970. **21**: p. 18.
33. Ireland, P.M., *Triboelectrification of particulate flows on surfaces: Part I — Experiments.* Powder Technology, 2010. **198**(2): p. 189-198.
34. Forward, K.M., D.J. Lacks, and R. Mohan Sankaran, *Methodology for studying particle–particle triboelectrification in granular materials.* Journal of Electrostatics, 2009. **67**(2–3): p. 178-183.
35. Mehrani, P., H.T. Bi, and J.R. Grace, *Electrostatic charge generation in gas–solid fluidized beds.* Journal of Electrostatics, 2005. **63**(2): p. 165-173.
36. Revel, J., et al., *Generation of static electricity during fluidisation of*

polyethylene and its elimination by air ionisation. Powder Technology, 2003. **135–136**(0): p. 192-200.

37. Guardiola, J., V. Rojo, and G. Ramos, *Influence of particle size, fluidization velocity and relative humidity on fluidized bed electrostatics.* Journal of Electrostatics, 1996. **37**(1–2): p. 1-20.

38. Wolny, A. and I. Opaliǹ ski, *Electric charge neutralization by addition of fines to a fluidized bed composed of coarse dielectric particles.* Journal of Electrostatics, 1983. **14**(3): p. 279-289.

39. Donsi, G., S. Moser, and L. Massimilla, *Solid—solid interaction between particles of a fluid bed catalyst.* Chemical Engineering Science, 1975. **30**(12): p. 1533-1535.

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Figures:

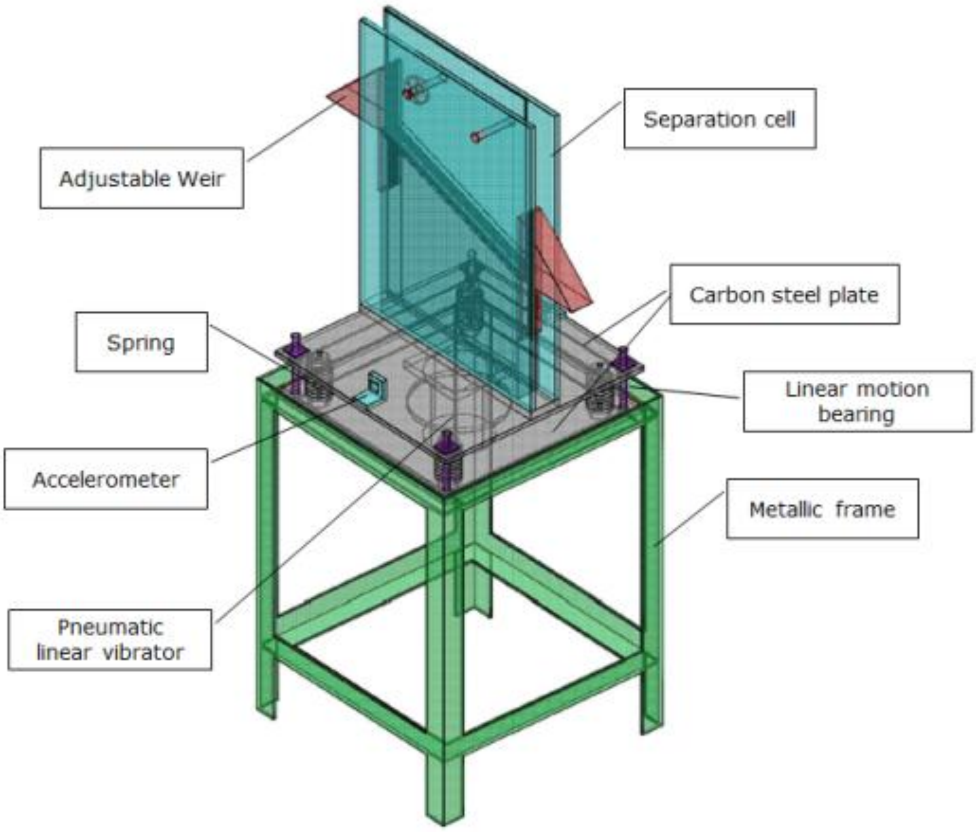


Figure 1. The design of a novel vibratory separator

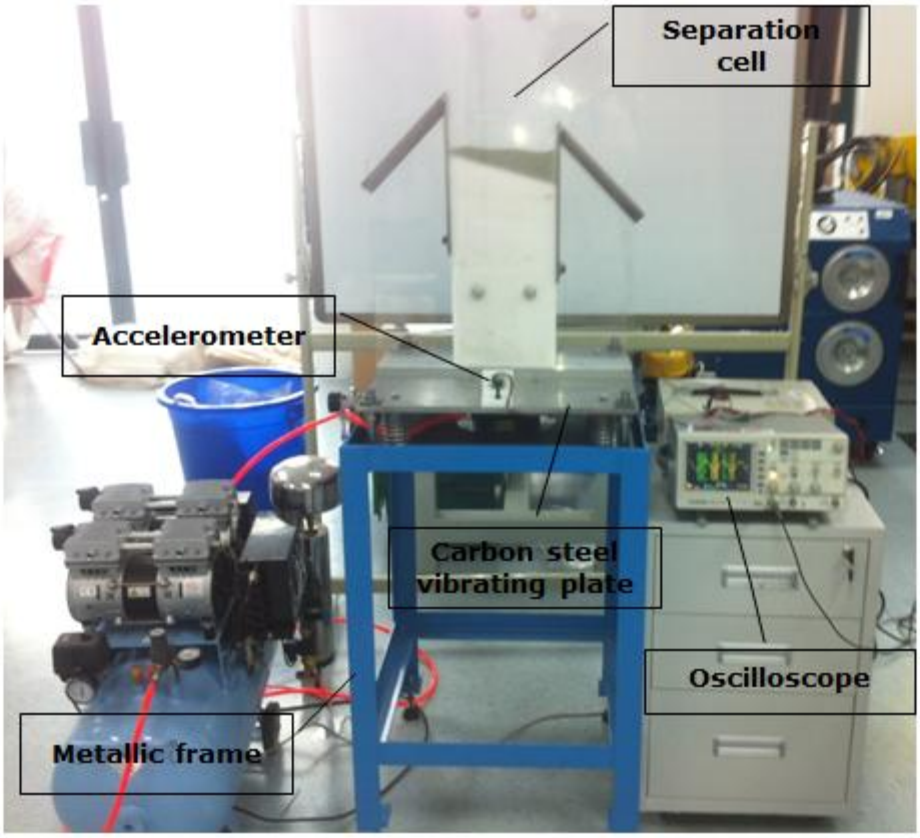


Figure 2. The novel vibratory separator

Figure 3. Instrument for size reduction

(left: Retsch SM 2000; right: Fengli CSF570)

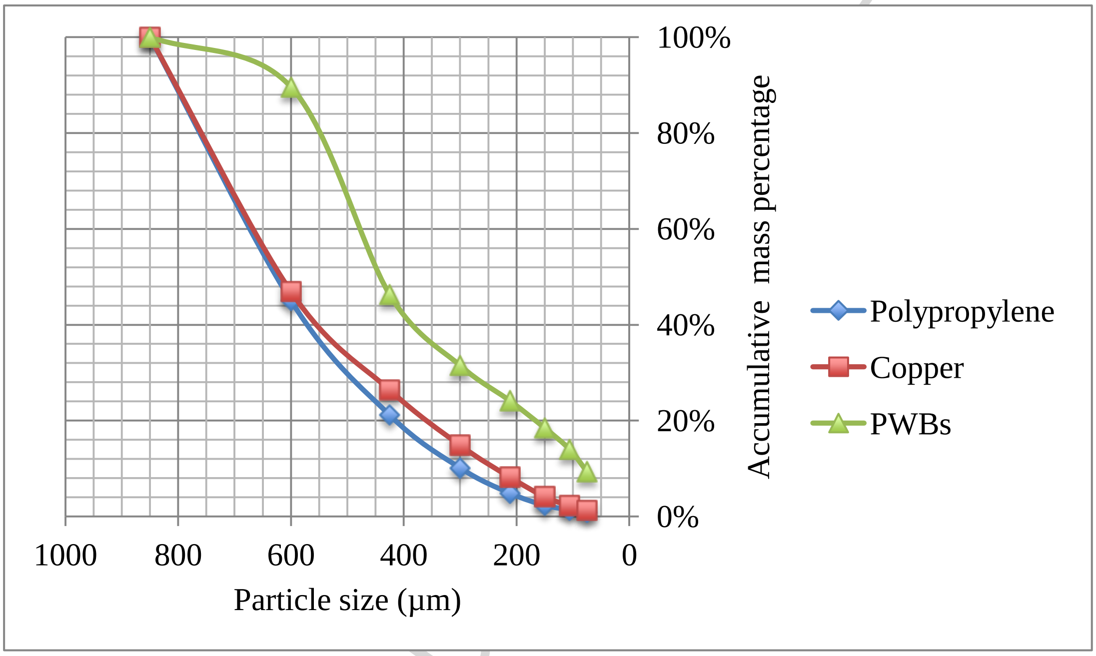


Figure 4. Sample accumulative particle size distribution

Figure 5 Experimental set-up with Edeson EWR-30S-A Environmental chamber

Figure 6 Vibratory separator in Edeson EWR-30S-A Environmental chamber

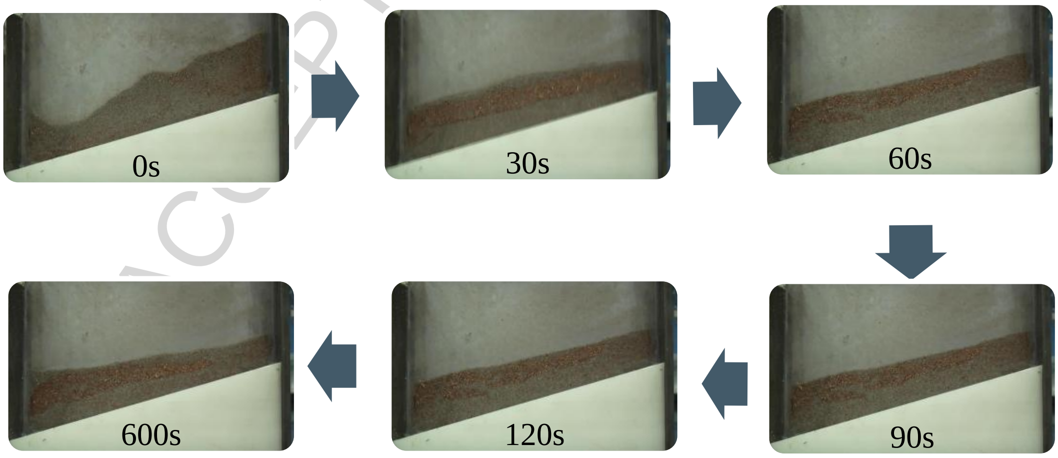


Figure 7. Vibratory separation of copper and polypropylene particles (temperature = 25°C, relative humidity = 90%, bed height = 40mm, slope = 15°; Γ=6.0, f= 32.8 Hz)

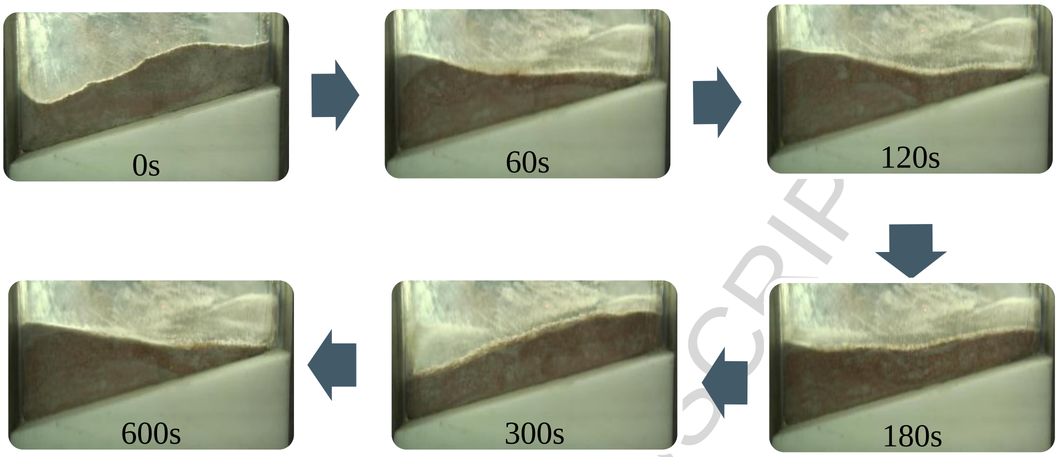


Figure 8. Vibratory separation of copper and polypropylene particles (0% w/w talc , bed height = 40mm, slope = 15°; Γ=5.0, f= 31.2 Hz)

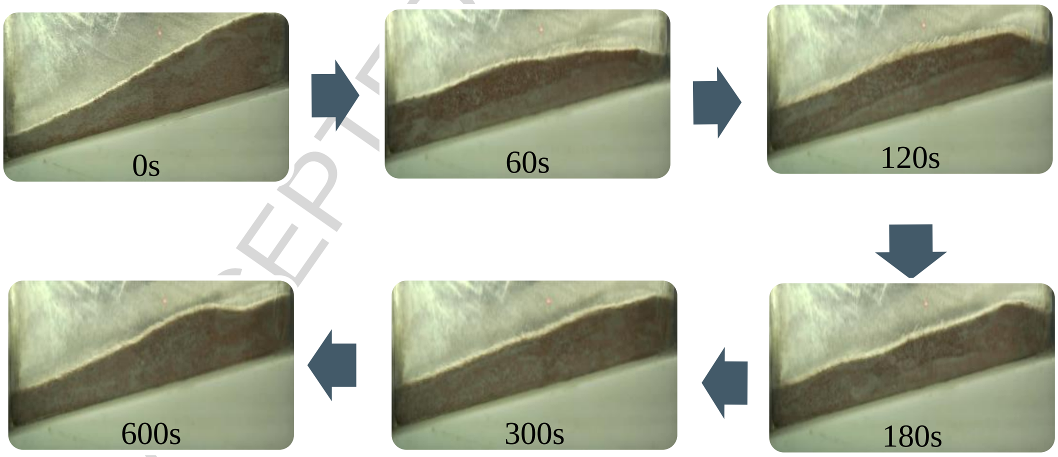


Figure 9. Vibratory separation of copper and polypropylene particles (0.1% w/w talc as lubricant, bed height = 40mm, slope = 15°; Γ=5.0, f= 31.2 Hz)

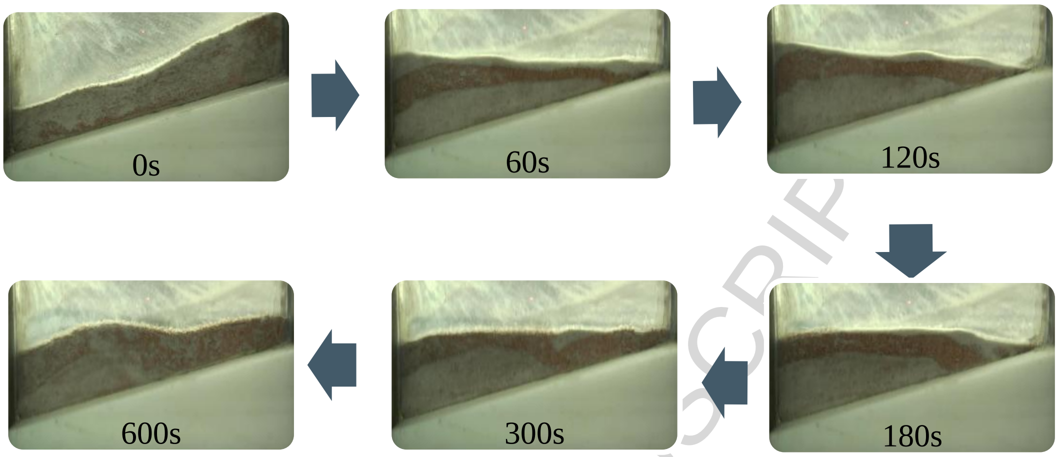


Figure 10. Vibratory separation of copper and polypropylene particles (0.5% w/w talc as lubricant, bed height = 40mm, slope = 15°; Γ=5.0, f= 31.2 Hz)

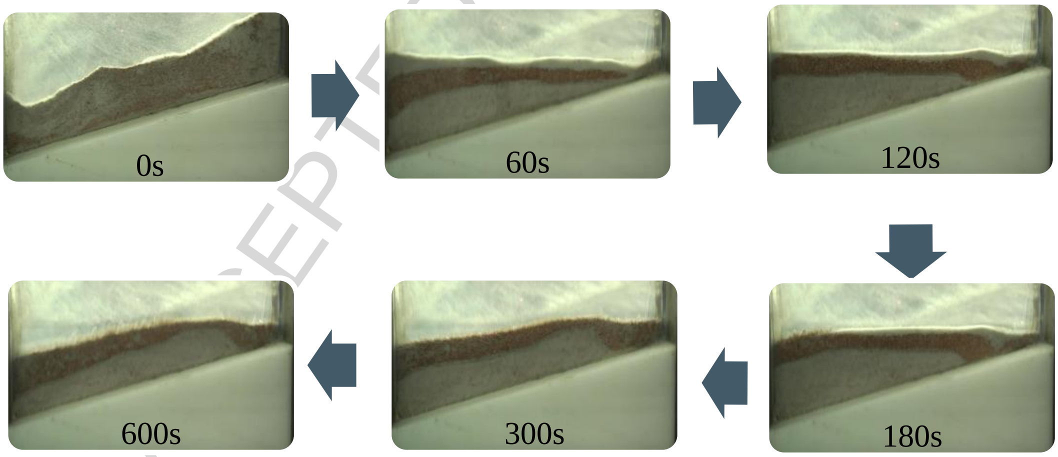


Figure 11. Vibratory separation of copper and polypropylene particles (1.0% w/w talc as lubricant, bed height = 40mm, slope = 15°; Γ=5.0, f= 31.2 Hz)

Title: Recycling oriented vertical vibratory separation of copper and polypropylene particles

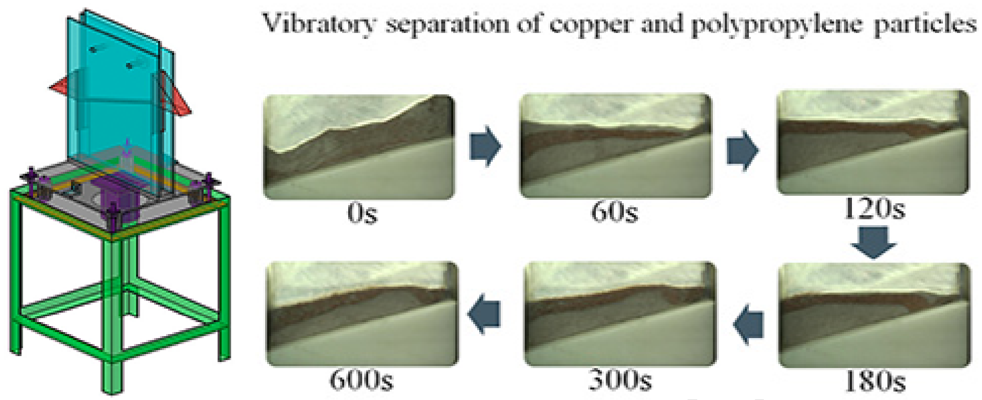
Tables:

Table 1 Vibratory separation results of copper and polypropylene particles in the environmental chamber (×= No Separation and √ = Separation.)

	Relative humidity (%)								
	70			80			90		
	Dimensionless vibration intensity parameter								
Temperature (°C)	4	5	6	4	5	6	4	5	6
15	×	×	×	×	×	×	×	×	×
20	×	×	×	×	×	×	×	×	×
25	×	×	×	×	×	×	×	√	√
30	×	×	×	×	×	×	×	×	×

Table 2 Absolute humidity for vibratory separation experiment in the environmental chamber

Absolute humidity (g/m^3 water)			
Temperature (°C)	Relative humidity (%)		
	70	80	90
15	9.00	10.29	11.57
20	12.13	13.86	15.59
25	16.15	18.46	20.77
30	21.28	24.32	27.36



Graphical abstract

Highlights

- A novel thin cell vibratory separator is developed for WEEE recycling.
- Relative humidity and addition of solid lubricant affect vibratory separation.
- The presence of moisture and solid lubricant provide lubricant effect.
- The presence of moisture and solid lubricant eliminates static electricity.