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Separation of mixed waste plastics via magnetic levitation

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ABSTRACT

Separation becomes a bottleneck of dealing with the enormous stream of waste plastics, as most of the extant methods can only handle binary mixtures. In this paper, a novel method that based on magnetic levitation was proposed for separating multiple mixed plastics. Six types of plastics, i.e., polypropylene (PP), acrylonitrile butadiene styrene (ABS), polyamide 6 (PA6), polycarbonate (PC), polyethylene terephthalate (PET), and polytetrafluoroethylene (PTFE), were used to simulate the mixed waste plastics. The samples were mixed and immersed into paramagnetic medium that placed into a magnetic levitation configuration with two identical NdFeB magnets with like-poles facing each other, and Fourier transform infrared (FTIR) spectroscopy was employed to verify the separation outputs. Unlike any conventional separation methods such as froth flotation and hydrocyclone, this method is not limited by particle sizes, as mixtures of different size fractions reached their respective equilibrium positions in the initial tests. The two-stage separation tests demonstrated that the plastics can be completely separated with purities reached 100%. The method has the potential to be industrialised into an economically-viable and environmentally-friendly mass production procedure, since quantitative correlations are determined, and the paramagnetic medium can be reused indefinitely.

1. Introduction

Massive global production of plastics, e.g., 322 M tonnes in 2015, has resulted in an ever-increasing stream of waste plastics (PlasticsEurope, 2016). Owning to less environmental burdens and economic feasibility, mechanical recycling of waste plastics or plastic recycling is becoming a promising practise in dealing with this particular waste stream (see Gu et al., 2014, 2016a,b, 2017a; Biganzoli et al., 2015; Wäger and Hischier, 2015; Ripa et al., 2017; Zheng et al., 2017). Recycled plastics possess comparable performance and advantageous prices to their virgin counterparts (Gu et al., 2016a), and have already been applied in the manufacturing sector (Gu et al., 2016b, 2017a). Plastic recycling is also one of the major sources of environmental benefits in waste management systems (Biganzoli et al., 2015; Wäger and Hischier, 2015; Ripa et al., 2017). However, although plastic recycling enjoys a rapid growth in recent years, most of waste plastics are still sent to landfill or incineration (PlasticsEurope, 2016). In reported cases of plastic recycling, only waste plastics of certain types and sources are recycled. For example, in the municipal solid waste (MSW) management system of Naples, only polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET) get mechanically recycled while the mix plastics are recovered as fuels or directly end up in landfill (Ripa et al., 2017). Some Chinese plastic recycler only takes sorted waste plastics from factories or dismantling sites (Gu et al., 2017a). From a brief review of the extant literature, it can be deduced that the technology of separating mixed waste plastics is highly desirable for promoting the rate of plastic recycling, as most current practises cannot handle this particular type of MSW.

Since separation of mixed plastics poses a difficult challenge to promoting mechanical recycling of plastics, the field thereby attracts a great deal of attention from academics. Froth flotation is one intensively studied plastic separation technology (see Guney et al., 2013; Wang et al., 2014, 2015, 2017a,b; Zhao et al., 2015; Censori et al., 2016; Truc and Lee, 2016, 2017; Pita and Castilho, 2017; Salerno et al., 2018; Wang and Wang, 2017). Froth flotation exploits tiny density differences between materials (Censori et al., 2016), yet, this technology primarily focuses on separating desirable types of plastics from binary mixtures, e.g., separating polyvinyl chloride (PVC) from mixtures like PVC/polystyrene

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Nomenclature

Abbreviations

ABS	acrylonitrile butadiene styrene
CHC	calcium hypochlorite
ELV	end-of-life vehicle
HDPE	high-density polyethylene
FTIR	Fourier transform infrared
LIB	lithium-ion battery
MIBC	methyl isobutyl carbinol
MSW	municipal solid waste
NBS	national Bureau of Statistics
PA	polyamide
PC	polycarbonate
PE	polyethylene
PET	polyethylene terephthalate
PMMA	polymethylmethacrylate
PP	polypropylene
PS	polystyrene
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
WEEE	waste electrical and electronic equipment

Symbols

g	gravitational acceleration
V	volume of the object
$\vec{B}$	magnetic flux density
χ	magnetic permeability
ρ	specific density

Subscripts

G	gravitation
f	buoyancy
m	paramagnetic medium
s	sample

(PS) (Salerno et al., 2018), PVC/PET (Guney et al., 2013), PVC/acrylonitrile butadiene styrene (ABS) (Wang et al., 2017b; Wang and Wang, 2017), PVC/polycarbonate (PC) or PVC/polymethylmethacrylate (PMMA) (Wang et al., 2017a), or separating PS from PS/PMMA, PS/PET, and PS/PVC (Pita and Castilho, 2017). Introduction of frothers such as methyl isobutyl carbinol (MIBC) (Truc and Lee, 2016; Salerno et al., 2018; Wang et al., 2017a) or terpineol (Wang et al., 2015) significantly improves selective floatability of target materials, but also would bring extra costs and environmental burdens of these processes. Surface treatments like boiling treatment (Wang et al., 2014), calcium hypochlorite (CHC) treatment (Wang et al., 2017a), Fenton treatment (Wang et al., 2017b; Wang and Wang, 2017), microwave and/or mild-heat treatment (Truc and Lee, 2016, 2017) have been proved to be effective in promoting recovery rates and purity, and shortening process time. However, considering the massive stream of waste plastics which shows no sign of stopping increasing, these pre-treatments might not be practicably and economically feasible. The sizes of plastics play important roles in froth floatation (Wang et al., 2014, 2017a; Pita and Castilho, 2017). To achieve such narrow size distribution as that used in the extant works (Truc and Lee, 2016; Salerno et al., 2018) could lead to huge energy consumption, and shredding poses significant environmental impacts to the overall lifecycle performance of mechanical recycling of waste plastics (Gu et al., 2017a). Similarly, hydrocyclone is only competent of separating binary plastics, and uses plenty of density medium which has a density in between the two types of plastics (Manidool, 1997; Richard et al., 2011; Yuan et al., 2015). Using a specific designed channel, hydraulic separation is a promising alternative in plastic separation (Lupo et al., 2016; Moroni et al., 2017). Still, this process can only handle binary plastic mixtures, and is also affected by particle sizes.

In this study, a technology denoted as "magnetic levitation" or "MagLev", which is based on a simple configuration of two identical square magnets are at precise alignment with like-poles facing each other, is applied and investigated for separating mixed waste plastics. Combining with the conventional Archimedes method, the magnetic levitation employs a much simpler, cheaper and more convenient configuration than the magneto-Archimedes levitation which uses delicate and expensive superconducting magnets of high magnetic flux density, which is up to 12 T (Ando et al., 2015) or 17 T (Liu et al., 2014a,b). Owning to the capacity of distinguishing minor differences in densities, that is, up to 0.0002 g cm^{-3} (Mirica et al., 2009), a level that can reflect the changes in molecular structures (Atkinson et al., 2013), this technology has been applied in density-based applications such as density measurement (see Mirica et al., 2010; Nemiroski et al., 2016a,b; Xie et al., 2016; Xia et al., 2017), forensic analysis (see Lockett et al., 2013), particle manipulation (see Mirica et al., 2011; Subramaniam et al., 2014), and quality control (see Hennek et al., 2015). However, according to the brief review, there is no reported application of this technology can be found in the arena of environmental engineering, or more precisely in waste management. Furthermore, very limited attention has been paid on applying the magnetic levitation method on particle separation, and the only relevant publication is about extracting desirable type from binary mixtures (Atkinson et al., 2013). To address the conundrum of separating mixed waste plastics more than two types, this work can extend the literature of applying magnetic levitation to solve engineering problems. Multiple commonly-used thermoplastics were used to simulate the mixed waste plastics more than binary, and were then applied to the proposed separation methods. The contribution of this study is threefold. First, the application of the magnetic levitation, a process is still in its early development, has been extended to the field of waste management, for separating and recycling resources from multiple mixtures. Second, a novel plastic separation process that based on magnetic levitation is developed, in which is multiple plastics can be separated based on their tiny density differences and without constrained by the particle sizes or in need of any exterior energy supply, as froth floatation and hydrocyclone do. Third, mathematical correlation between magnetic field, material density and levitated height is discussed for scaling up the experimental configuration. Currently, all the reported MagLev methods are employing standards for curve fitting (see Mirica et al., 2010; Nemiroski et al., 2016a,b; Xie et al., 2016; Xia et al., 2017), and the absence of such correlation could limit the further development of this process. Clarification of this mathematical correlation would provide tremendous implications for future research and potential industrialisation of the magnetic levitation technology.

The paper is organised as follows. Section 2 describes the device configuration, experimental design and procedure that used in this study. In Section 3, results of a series of experiments are presented and discussed, in which effects of sizes are studied and different plastic separation methods are compared. The conclusive marks and directions of future works are given in Section 4.

2. Experiment

2.1. Experimental configuration

The plastic separation configuration that based on magnetic levitation is shown in Fig. 1, which is similar to the devices employed in the previous literature (Xie et al., 2016; Xia et al., 2017). The magnets used in this device are N45 NdFeB magnets of 50 mm × 50 mm × 25 mm with $\overrightarrow{B_0}$ = 0.425 T, and they are strictly aligned with like-poles facing each other at a separation distance (d). Based on the comparative results of the previous research (Xie et al., 2016; Xia et al., 2017), d = 60 mm is selected to enlarge the operational space for a better presentation of plastic separation. The vessels that contain the paramagnetic medium are placed in between the two magnets. The levitated height of the submerged object is denoted as z_h, which is obtained via a photographic method of proportionally matching the pixels to d.

2.2. Materials and preparation

In this study, the waste plastic mixtures were simulated using six types of plastics, including PP, ABS, polyamide 6 (PA6), PC, PET, and polytetrafluoroethylene (PTFE). The plastics were purchased from online shops in *Taobao* (www.taobao.com) and *Tmall* (www.tmall.com), and were obtained in forms of various plastic products such as plates, containers, and bottles. The selection of these types of plastics is based on production and consumption statistics of China (NBS, 2017) and EU (PlasticsEurope, 2016), as these materials consist of over 70 wt% of the total figures. In addition, the reason of using these plastics is attributed to limited source availability, since current industrialised practises tend to focus on single-source recycling (Gu et al., 2017a). It worth noting that products of different colours were bought for distinguishing different types of plastics: yellow for PP, hoar for ABS, transparent for PA6, black for PC, red for PET, and white for PTFE. These plastic products were shredded utilising a plastic cutting machine, washed with tap water, dried at 60 °C in an oven thoroughly for 12 h, and then screened into different size fractions. The particle sizes of samples used in this study were 0.70–1.40, 1.40–2.36, and 2.36–4.00 mm. For correlating, the densities of these plastic samples were measured using a Quantachrome Ultra PYC 1200e pycnometer, tested in a sample cell of 5 ml with 99.99% N_2 as purge gas in accordance with ISO1183, at an ambient condition of 23 °C and 50% R.H.

Instead of using toxic methanol solution that utilised in the previous literature (Xie et al., 2016; Xia et al., 2017), manganese(II) chloride ($MnCl_2$) aqueous solution and $MnCl_2$ ethanol solution were employed as the paramagnetic medium. $MnCl_2$ and ethanol with purities of analytical reagent level were purchased from Sinopharm Chemical Reagent Co., Ltd, and deionised water was used to prepare the solution.

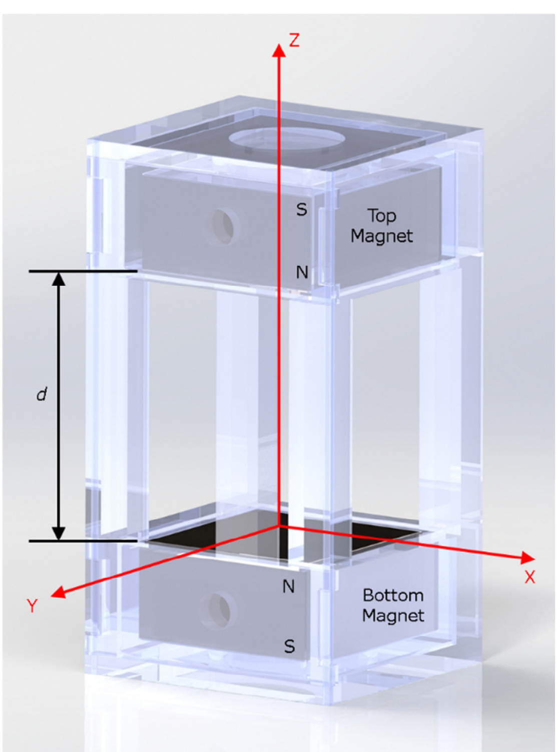

Fig. 1. Configuration of the plastic separation device that based on magnetic levitation.

2.3. Separation experiments

The experimental separation was consisted of two segments: (1) an initial separation aims at proving the concept of applying magnetic separation, and (2) a two-stage separation that shows the potential of industrialisation.

The above brief review of literature suggests that the particle size is one of the most influential factors in affecting the outputs of the extant plastic separation methods. Therefore, the first segment of the experimental work, the initial separation, is to investigate the impacts of particle sizes on the performance of the magnetic levitation. In the previous research (Xie et al., 2016; Xia et al., 2017), it has been proved that the magnetic levitation device of the same configuration can be used for measuring densities of plastic pellets, yet only specimens of similar sizes were employed. In the initial separation experiments, all the six types of plastics of the three size fractions were mixed and then tested. The paramagnetic medium was 2.5 M $MnCl_2$ solution based on 80 vol% water and 20 vol% ethanol, and its magnetic permeability $\chi_m = 4.56 \times 10^{-4}$, specific density $\rho_m = 1.216\ \text{g cm}^{-3}$.

The two-stage separation was proposed to investigate the route of potential industrialisation. Based on the results of the initial separation, one size fraction of mixed plastics was selected and tested. The separation was carried out in a similar sequence to the work of Wang et al. (2017a): the specimens were clustered in the first stage, and then fully separated in the later stage. Different from the work of Wang et al. (2017a), no extra treatment was required, and the second stage of this separation was still targeting multiple plastic mixtures instead of binary plastics. Another type of paramagnetic medium was involved in the two-stage separation, that is, 1.0 M $MnCl_2$ aqueous solution with $\chi_m = 1.77 \times 10^{-4}$, specific density $\rho_m = 1.094\ \text{g cm}^{-3}$.

Before and after the separation tests, the types of plastic specimens were verified by a handheld Fourier transform infrared (FTIR) spectroscopy, model TruDefender FT, Thermo Scientific Co., Ltd., USA.

3. Results and discussion

3.1. Initial separation

The plastic samples used in the initial separation are shown in Fig. 2, and they were arranged in the same manner as Fig. 2(a).

The mixtures of different were submerged into a tube that filled with 2.5 M $MnCl_2$ solution based on 80 vol% water and 20 vol% ethanol, and then were put into the device. A digital camera (model

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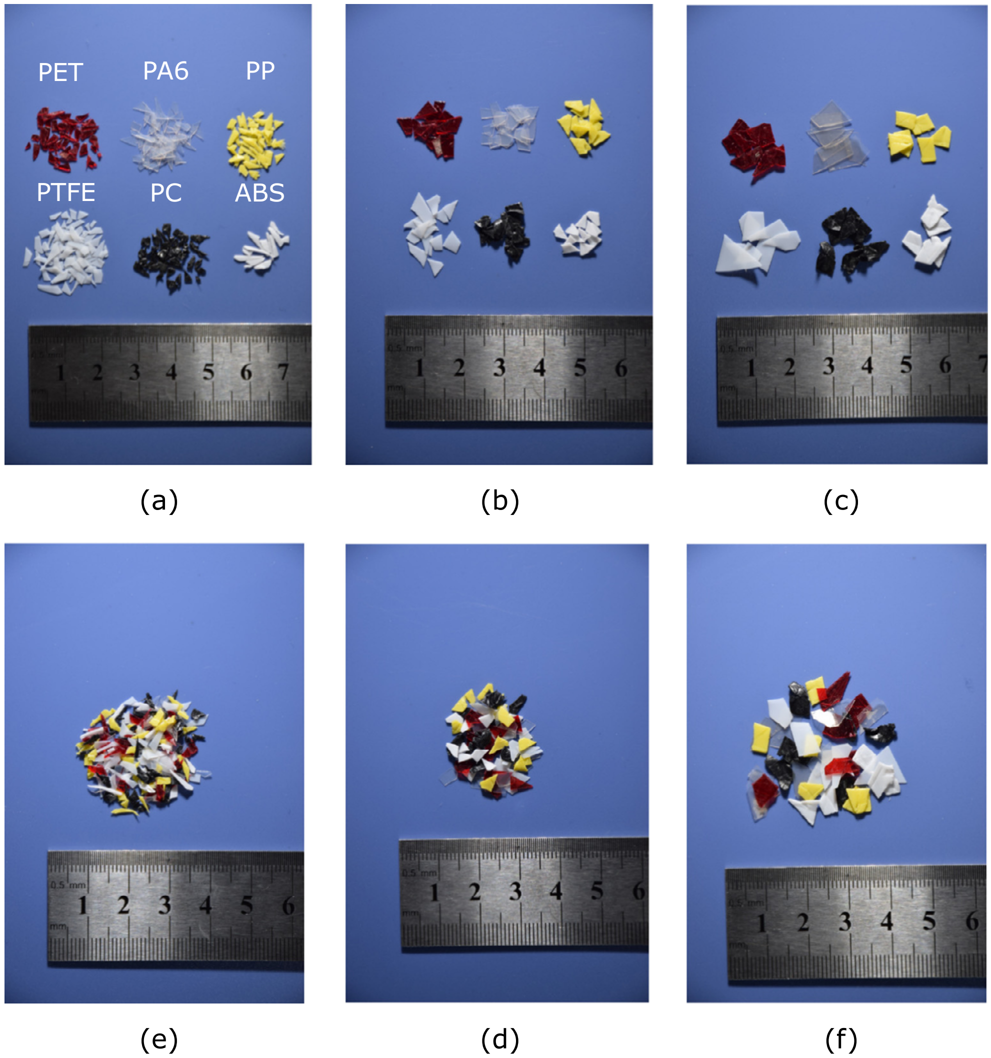

Fig. 2. Specimens of the initial separation experiments: the upper part shows the separated plastic flakes of (a) small size fraction, (b) medium size fraction, and (c) large size fraction; the lower part displays the mixed samples of (e) small size fraction, (d) medium size fraction, and (f) large size fraction.

D810, Nikon, Japan) was utilised to record the positions of the specimens in the tube during the whole experimental procedure, starting from the tube contacted the device (the time zero), and the sampling frequency was set at 0.33 s^{-1}.

Fig. 3 shows the snapshots of the mixed plastic flakes of the three size fractions taken at 0 s, 5 s and 15 s, and the changes in the heights of each type of plastics are shown in Fig. 4. At the time zero, i.e., the moment that the tube entered the separation device, the plastic mixtures are clustered with regard to their relative densities to the medium. The plastics have lower densities than the medium were floated at the surface, i.e., PP (ρ = 0.903 g m^{-3}), ABS (ρ = 1.053 g m^{-3}) and PA6 (ρ = 1.126 g m^{-3}), whereas the heavier plastics were sit at the bottom of the tube, i.e., PC (ρ = 1.232 g m^{-3}), PET (ρ = 1.338 g m^{-3}) and PTFE (ρ = 2.216 g m^{-3}), see the left part of Figs. 3 and 4. The densities were measured by the pycnometer and the density measuring device (Xie et al., 2016; Xia et al., 2017), and the deviations between the two sets of results were less than 0.5%. Within 5 s, the plastics were aligned at their respective balanced positions along the centreline of the device, and these balanced positions remained unchanged after 10 s. This pattern is observed in all the three size fractions, as shown in the right part of Figs. 3 and 4. The experimental results prove the effectiveness and efficiency of magnetic levitation, an emerging process that never being applied in the field of waste management, in separating multiple plastic mixtures. Since achieving narrow particle size distribution is a highly demanding and energy-consuming task (Wang et al., 2016), this magnetic process has potential of outperforming the extant plastic separation methods, such as froth floatation and hydrocyclone.

As shown in Fig. 4, PET flakes have strange movements, as the specimens initially moved upwards, then went downwards to their balanced positions. To explain this phenomenon, the fundamentals of the magnetic levitation are introduced as follows. It is well-known that the magnetic levitation or magneto-Archimedes levitation is achieved when the following equation is satisfied (Xie et al., 2016):

$$\vec{F}_G + \vec{F}_f + \vec{F}_{mag} = 0 \tag{1}$$

where $\vec{F}_G$ denotes the gravitational force of the object that submerged in the paramagnetic medium, $\vec{F}_f$ denotes the buoyancy force on the object, and $\vec{F}_{mag}$ denotes the magnetic buoyancy force that posed by the magnetic field. $\vec{F}_{mag}$ is calculated as the following equation (Xie et al., 2016):

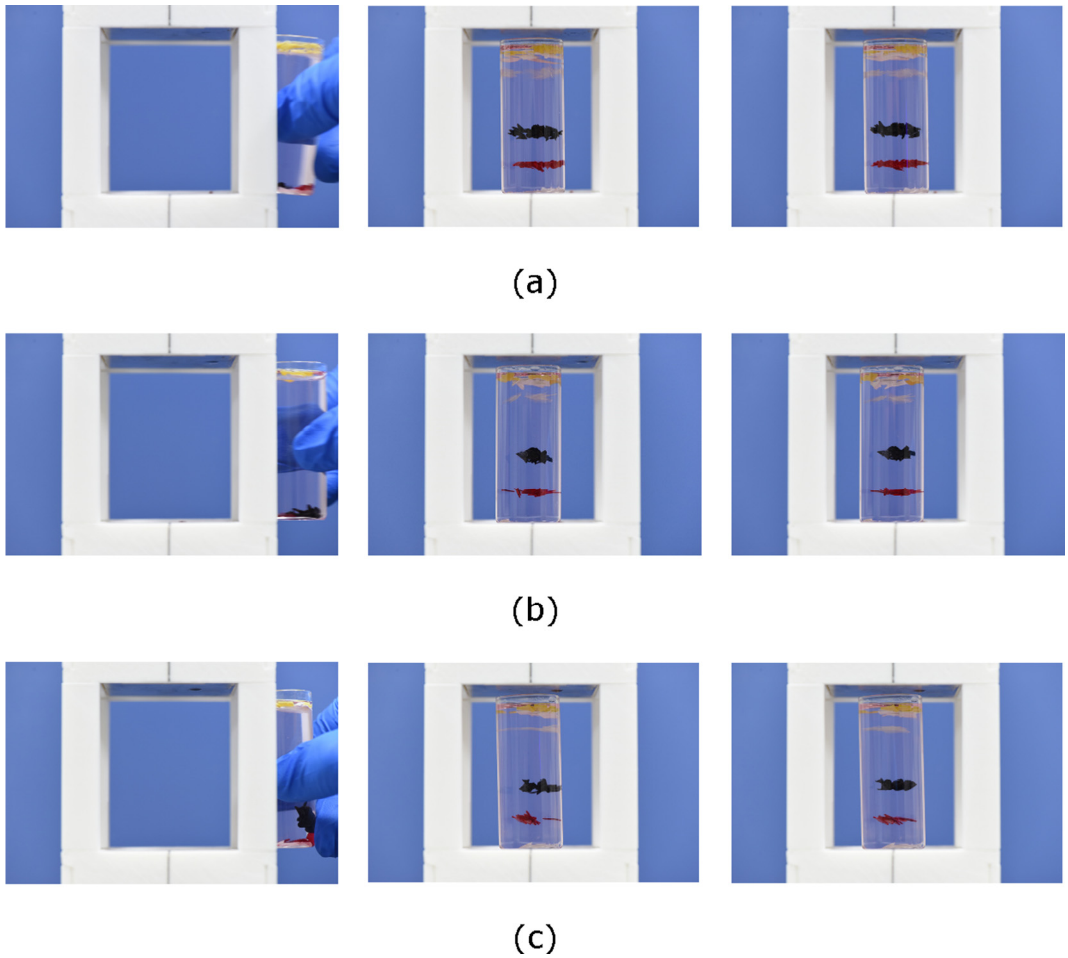

Fig. 3. Pictures of the initial separation experiments recorded at 0 s, 5 s and 15 s, and the samples in the tube are (a) small size fraction, (b) medium size fraction, and (c) large size.

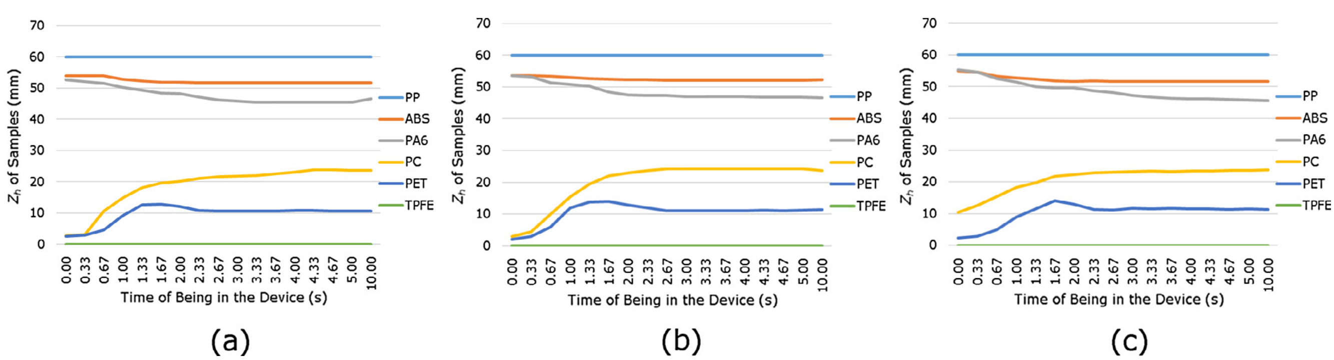

Fig. 4. Heights of the specimens in the tube against the time that it in the device, (a) small size fraction, (b) medium size fraction, and (c) large size fraction.

$$\vec{F}_{mag} = \frac{\chi_s - \chi_m}{u_0} V(\vec{B} \cdot \vec{\nabla})\vec{B} \quad (2)$$

where $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2} is the permeability of vacuum, χ_s is the magnetic permeability of the object, V is the volume of the object, $\vec{B}$ is the magnetic flux density, and $\vec{\nabla}$ is the gradient calculator.

For a single magnet, the magnetic flux density of its rim is higher than that of its centre, as well as the gradient of the magnetic flux density. Therefore, $(\vec{B} \cdot \vec{\nabla})\vec{B}$ on the edge is higher than that of the central area, and results in a higher magnetic buoyancy force $\vec{F}_{mag}$ according to Eq. (2). When the specimens once entered the device, the PET flakes were immediately floated at positions near the edge of the magnet where larger $\vec{F}_{mag}$ was applied on. As the tube was moved to the central area, $\vec{F}_{mag}$ was weakened, and the positions of PET were thereby lower. Expect for PP and PTFE, other plastics also have similar patterns, yet their jumps are subtle. This could be attributed to their initial positions when the tube entered the device. For example, the initial positions of PC flakes were higher than those of PET, therefore their curves of heights are much smoother.

3.2. Two-stage separation

Extraction has not been practised in the extant literature on magnetic levitation (see Mirica et al., 2010, 2011; Lockett et al., 2013; Subramaniam et al., 2014; Hennek et al., 2015; Nemiroski et al., 2016a,b; Xie et al., 2016; Xia et al., 2017). However, extraction is of critical importance for plastic recycling, for this process could even compromise the potential of the separation methods (Lupo et al., 2016; Moroni et al., 2017). In the two-stage separation experiments, a larger cuboid container was used for extracting the separated plastics via a spoon, see Fig. 5(a)–(d). For possible scale-up, the spoon can be easily replaced by any jig with similar functionality, such as scoop or hopper. Plastics samples of medium sizes were employed, since there is no noticeable size effect has been observed in the previous experimental segment (see Figs. 3 and 4). The 2.5 M $MnCl_2$ solution that based on 80 vol% water and 20 vol% ethanol was used for the first stage of the experiments, and the 1.0 M $MnCl_2$ aqueous solution was used in the second stage.

As shown in Fig. 5(e), three heavier plastics were completely in the first stage, i.e., PET, PC and PTFE, while the other plastic specimens were comingled. The light plastics, i.e., PP, ABS and PA6, were then fully separated in the second stage, see Fig. 5(f). The categories of the separated plastic samples were verified using the handheld FTIR machine, and the purities have reached 100% which are higher than the results of any previous report. The purity of waste plastics is identified as a bottleneck in mechanical plastic recycling, consequently single-source recycling is widely adopted in industrial practises (Gu et al., 2017a). The results confirm that the magnetic levitation separation has a promising future as a measure of mitigating waste plastic problem.

Successful separation is not sufficient for industrialised scale-up, for the correlations between magnetic field, material densities and levitated heights should be more explicit. According to the results shown in Figs. 3–5, the final positions of the plastic samples were arranged in accordance with their densities in a decreasing sequence, which agrees with the findings of the extant literature (see Mirica et al., 2010; Nemiroski et al., 2016a,b; Xie et al., 2016; Xia et al., 2017). However, these density measurements are essentially based on a curve fitting process, in which density standards are employed for benchmarking. Without understanding correlations between magnetic field, material densities and levitated heights, the application of the magnetic levitation is limited, and industrialisation would not be feasible. Besides, the benchmarking processes are extremely laborious and time-consuming, and the density standards are usually quite expensive.

Since the magnetic field between the two magnets is three-dimensional, the following equation is thereby obtained with respect to the position in between the two magnets:

$$(\overrightarrow{B}\cdot\overrightarrow{\nabla})\overrightarrow{B}=\begin{bmatrix} B_x\frac{\partial B_x}{x}+B_y\frac{\partial B_x}{y}+B_z\frac{\partial B_x}{z} \\ B_x\frac{\partial B_y}{x}+B_y\frac{\partial B_y}{y}+B_z\frac{\partial B_y}{z} \\ B_x\frac{\partial B_z}{x}+B_y\frac{\partial B_z}{y}+B_z\frac{\partial B_z}{z} \end{bmatrix} \quad (3)$$

Figs. 3 and 5 show that the samples were stabilised along the centreline, which indicates the magnetic buoyancy force only applied on the plastic flakes in the z direction (see Fig. 1). Therefore, $B_x = B_y = 0$ and $\frac{\partial B_x}{\partial z}=\frac{\partial B_y}{\partial z}=0$. In the centreline of the device, Eq. (3) can be rewritten into the following form according to the experimental observations shown in Figs. 3 and 5:

$$(\overrightarrow{B}\cdot\overrightarrow{\nabla})\overrightarrow{B}=\begin{bmatrix} 0 \\ 0 \\ B_z\frac{\partial B_z}{z} \end{bmatrix} \quad (4)$$

And $\overrightarrow{F}_{mag}$ in the centreline can be expressed as follows:

$$\overrightarrow{F}_{mag}=\frac{\chi_s-\chi_m}{u_0}V\cdot B_z\frac{\partial B_z}{z} \quad (5)$$

Combining with Eq. (1), the correlation between magnetic field, material density and levitated height is hereby obtained:

$$\rho_s=\frac{\chi_s-\chi_m}{u_0 g}B_z\frac{\partial B_z}{z}+\rho_m \quad (6)$$

3.3. Implications and limitations

The experimental results demonstrate that it is a promising practise of using magnetic levitation in separating multi-plastics, as the plastic mixtures have been clearly separated, see Figs. 3 and 5. Eq. (6) indicates that the height that the sample levitated is only correlate to the magnetic flux density of the magnet, the magnetic permeability and density of the medium, and its own magnetic permeability and density. Since the magnetic permeability and density are sample's intrinsic characteristics that cannot be altered readily, levitating and extracting different substances can be achieved through using different magnets and medium. The NdFeB magnets used in magnetic levitation are much cheaper than the superconducting magnets for previous magneto-Archimedes levitation (Ando et al., 2015; Liu et al., 2014a,b). By changing concentrations of solvent ($MnCl_2$) and bases (water, menthol or ethanol), the magnetic permeability and density of the paramagnetic medium can be easily manipulated to achieve the desirable values. But for froth floatation, the quantitative role of frothers is difficult to be determined, that is, the effects of frother concentration cannot be expressed in form of mathematic models. Consequently, the effects of frothers have to be investigated via designed experimental trials (see Wang et al., 2014, 2017b; Zhao et al., 2015; Truc and Lee, 2016; Salerno et al., 2018; Wang and Wang, 2017), and the application of froth floatation is still at bench scale. In addition, it worth noting that the paramagnetic medium is not actually consumed during the separation, as the medium can be used indefinitely, while the frothers are depleted during froth flotation processes. Based on the literature review, a comparison of reported plastic separation processes is thereby summarised in Table 1.

As shown in Table 1, without being limited by particle sizes, the magnetic levitation process shows a great deal of potential in the arena of waste management, though the outcomes of this technology are relied on the magnets and extracting method. For example, this process can be exploited for recovering plastics from waste electrical and electronic equipment (WEEE), since current physical separation techniques are seriously affected by particle size distribution (Habib et al., 2013) or operating environment (Wang et al., 2016). This method is also applicable on recycling metallic resources from spent lithium-ion batteries (LIB), a fastest growing waste stream that contains multiple metals such as lithium, cobalt and manganese, while existing industrial practises primarily focus on recovering cobalt via acid leaching processes (Gu et al., 2017b). Applying the magnetic levitation separation process for recycling end-of-life vehicles (ELVs) can be another potential application, since the disposal of ELVs has become a pressing concern, especially in China (Zhang et al., 2017). The process can be used for extracting non-metallic materials, as a more environmental-friendly alternative of incineration (Tian et al., 2015).

Nevertheless, this process is in need of further exploration, as there are some knowledge gaps could compromise its future. First, for potential scale-up, the size and magnetic flux density of the magnets shall be quantitively determined at the first place, and the suitable operational space can thereby be calculated, as well as the design of meanings to extract the separated materials within

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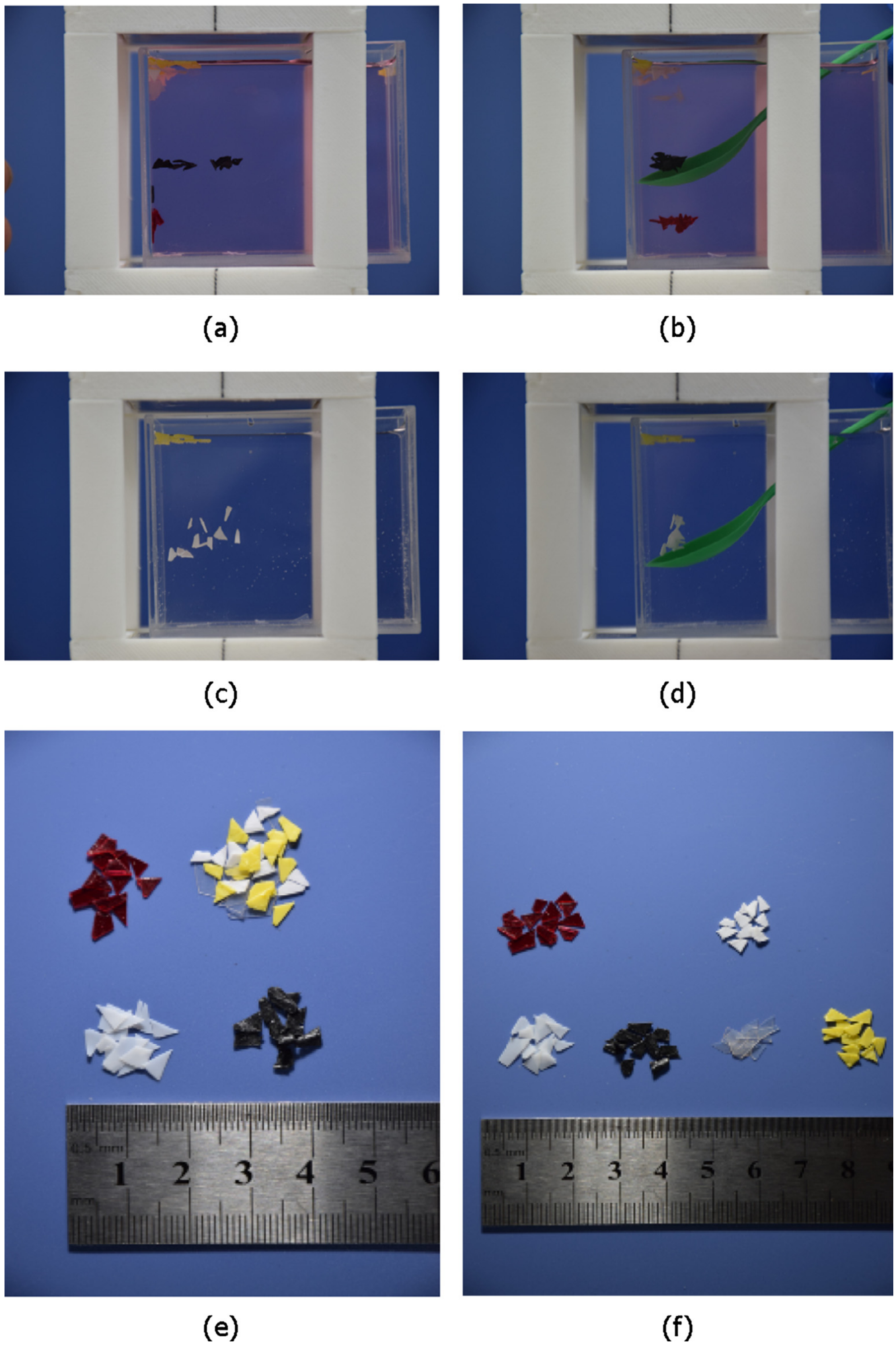

Fig. 5. Illustrations of the two-stage separation: (a) and (b) processes of the first stage, (c) and (d) processes of the second stage, (e) outcomes of the first stage, and (f) outcomes of the second stage.

the industrialised jigs. A unified mathematic model is highly desirable for guiding the design of large-scale magnetic levitation jigs, in which the size and magnetic flux density of the magnets and the levitated heights of target materials can be quantified, however, Eqs. (5) and (6) are not up to the task. Without such model, economic analysis cannot be conducted for evaluating the industrialisation of this technology, especially considering the costs of magnets and the energy consumption of material extraction. Second, the reason why samples assembled along the centreline requires a proper explanation, a phenomenon also observed in the previous literature (Mirica et al., 2009; Xie et al., 2016; Xia et al., 2017). An in-depth understanding of this phenomenon could make the separation method becoming a continuous production process, and thereby increase its applicability in industrial practises. Moreover, the use of mixed plastic scraps would be considered in the future works for better exhibiting the applicability, practicability and efficiency of this magnetic levitation method in the field of waste management.

Table 1
Comparison of plastic separation processes.

Process	Inputs	Outputs
Magnetic levitation	1. Multi-plastic mixtures; 2. Reusable paramagnetic medium; 3. Simple two-magnet device.	1. 100% purity; 2. Can be properly modelled; 3. Affected by the magnets and meanings of extraction.
Froth floatation	1. Binary plastic mixtures; 2. Frothers and other reagents like oppressors and surfactants; 3. Continuous airflow; 4. Energy for agitating and maintaining temperature; 5. Surface treatments (potential).	1. Over 95% purities but depended on multiple factors such as particle sizes, concentrations of reagents, PH values, airflow rates, temperatures, and etc; 2. Lack of quantitative model.
Hydrocyclone	1. Binary plastic mixtures; 2. Density medium; 3. Jigs with specifically-designed flow paths for material extraction.	1. Purities above 90% mainly influenced by the particle sizes and density differences; 2. Lack of quantitative model.

4. Conclusion

In this study, magnetic levitation was applied for separating multiple mixed plastics which were simulated using six types of plastics, i.e., PP, ABS, PA6, PC, PET, and PTFE. The experiments were carried out in two segments: (1) initial separation for proving the concept, and (2) two-stage separation for extracting all the plastics. The results show that this process is not affected by particle sizes, as all three size fractions have the similar floating curves during the initial separation. Some floating behaviours are explained using the mathematical expression of magnetic buoyancy force. In the two-stage separation, the material extraction was complete as purity of each type of plastic has reached 100%. The correlation between magnetic field, material density and levitated height is given for potential scale-up of this experimental configuration. Further, the implications of this method are discussed such as recycling WEEE and ELV, as well as its limitations in mathematic model and unexplained assembly in the centreline. For future industrialisation, a unified mathematic model is highly desirable and needed with the purpose of determining the magnets and extraction, since these parameters are largely affecting the cost and energy of this process. This work indicates that separation of multi-plastics is effective and efficiently enabled by the magnetic levitation process, and this provides an environmental and promising approach for mitigating the problem of ever-increasing waste plastic stream.

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