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Estimation of hybrid jig separation efficiency using a modified concentration criterion based on apparent densities of plastic particles with attached bubbles

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Abstract

The hybrid jig which combines the principles of jig separation and flotation was recently developed to separate mixed-plastics with similar specific gravities (SG) effectively. In this type of jig, air bubbles are introduced during water pulsation to modify the apparent SG ($SG_{apparent}$) of plastics by the attachment of air bubbles to the particles so that the hybrid jig can separate materials having identical SGs if their surface wettabilities are different. Because the change in $SG_{apparent}$, which is determined by the volume of attached bubbles on the particle surface, is critical for efficient separation in hybrid jigs, a method to estimate this parameter should be developed.

In this study, a laser-assisted measurement apparatus was developed to quantify the attached-bubble volume on plastics during water pulsation. Hybrid jig separation was also conducted using three mixtures containing plastics of almost identical SGs: (i) polyvinyl chloride (PVC)/polyethylene terephthalate (PET), (ii) polypropylene with glass fiber (PPGF)/high-impact polystyrene (HIPS), and (iii) cross-linked polyethylene (XLPE)/polyethylene (PE). Finally, to estimate the separation efficiency of hybrid jig, a new index called the apparent concentration criterion ($CC_{apparent}$) is proposed. The results showed that $SG_{apparent}$ and $CC_{apparent}$ calculated using proposed methods could be used to estimate the hybrid jig separation efficiency.

Keywords: Recycling, jig, hybrid jig, plastic separation, attached-bubble volume

Introduction

The generation of plastic-dominated wastes has exploded globally in recent years primarily because of the wide availability and the unique properties of plastic-based materials that make them superior to traditional materials like wood and metals. Jambeck et al. [1] estimated that 275 million metric tons of plastic-dominated waste was generated in 192 coastal countries in 2010, with 4.8 to 12.7 million metric tons entering the ocean. Without proper disposal, majority of these wastes pose high risks of contaminating the environment because they contain numerous environmentally regulated contaminants like organic molecules, hazardous heavy metals, and toxic metalloids [2-5].

One of the most important approach to address these concerns is recycling because it not only lessens our dependence on natural mineral resources but also reduces the volume of wastes for disposal. In Japan, recycling laws were first enacted in 1998 for home appliances like air conditioners, televisions, refrigerators and washing machines, which were later extended to automobiles (2002) and small home appliances (2012) that included personal computers, mobile phones, digital cameras and clocks, game consoles, music players, and hair dryers [6]. For example, the amounts of automobile shredded residues (ASR) generated during the recycling of end-of-life vehicles (ELV) in the EU and Japan accounted for about 12–32% and 17% of the total weight of ELVs, respectively [7, 8]. In the EU, ASR is typically disposed of in landfills, which was similar to what was previously done in Japan before the enactment of the recycling law for automobiles. After the recycling law's enforcement, material separation of secondary resources (i.e., various types of wastes including ASR), collection of slags from melting furnaces, and thermal recovery have become commonplace. As a result, Sakai et al. [8] reported that only 1–2% of the total weight of ELVs end-up in landfills because an additional 15–16% of components and materials were recovered. Recently, the Japanese government is planning to increase the material recycling ratio for combustible wastes especially mixed-plastics and reduce the amounts that end up for thermal recovery. For example, the Ministry of Environment of Japan has been supporting studies to improve material recycling including plastic-plastic separation from ASR [9].

Potentially effective techniques for the separation of various types of plastics in mixed-plastic wastes is the use of separation techniques from mineral processing [10]. For examples, gravity separation (e.g., sink–float separation [11], jig [12-15], cyclone [16]), magnetic separation (e.g., magnetic levitation (MagLev) [17], magnetic projection [18]), electrical separation (e.g., triboelectrostatic [19-21]), and flotation [22, 23]. Among these various separation techniques, wet separation methods are more widely used in mineral processing because they have higher efficiency as well as products are cleaner due to the washing process than dry-type separation techniques [24, 25].

Flotation is a common and very efficient wet separation methods in mineral processing for fine fraction (− 75 μm) because fine grinding is typically required for the liberation of target minerals from its ores prior to flotation [2, 5]. Since, most minerals have hydrophilic surfaces, so a collector (e.g., xanthate and aerofloats [25]) is usually added to selectively change their surface wettability and enhance the separation efficiency. In contrast, plastic flotation is usually carried out with wetting agents (e.g., AOT, NaLS, CaLS, TA, and PVA [22, 23]) since most plastics have inherently hydrophobic surfaces. Plastic flotation is also very challenging because in resources recycling, especially plastics, sufficient liberation is already achieved at relatively coarse particle sizes (mm–cm) [14]. Moreover, additional size reduction (i.e., crushing and grinding) is required for flotation that requires more energy and incurs higher costs and energy [25].

One potentially effective technique for the separation of coarse plastics from mixed-plastic wastes is through the use of jigs. Jigs are gravity concentrators, machines that separate different kinds of materials with coarse size fractions (+ 0.5 mm) based on differences in their densities or specific gravities (SG), are well known in mineral processing especially for coal cleaning due to its simple operation, low cost, and high efficiency [24, 25]. Because traditional jigs are designed for ores, however, their direct application to mixed plastic wastes having lower SGs caused unpredictable fluidization behavior during separation resulting in very low separation efficiency [26], To address this serious drawback of conventional jigs, Tsunekawa et al. [12] developed the RETAC jig (R&E, Co., Ltd., Japan), a modified BATAC jig, for plastic-plastic separation. The RETAC jig works by taking advantage of the very small SG differences between plastics through precision control of the wave form during jig separation [12, 13]. This advanced jig has been successfully applied to separate various plastics (e.g., polystyrene (PS), acrylonitrile butadiene styrene (ABS), and polyethylene terephthalate (PET)) from discarded copy machines [12]. A schematic illustration of a desktop-type batch-wise RETAC jig is shown in Fig. 1(a). The reverse jig is a modified RETAC jig that could separate particles that are lighter than water by adding a screen on top of the separation chamber. Similar to the RETAC jig, the reverse jig separates particles by stratification based on differences in SGs. In the separation chamber, particles move up and down underneath the top screen and stratification occurs because of the differences in levitation velocities of particles. The reverse jig has been successfully applied to separate polypropylene (PP) and high-density polyethylene (HDPE) from waste containers [26].

Another challenging problem in the recycling of plastic-dominated waste streams is the separation of mixed-plastic wastes with almost identical SGs. Hori et al. [27] found a workaround to this dilemma by combining the principles of gravity separation and flotation to develop a density/surface-based technique called the hybrid jig (Fig. 1(b)). The hybrid jig can separate materials having identical SGs so long as their surface wettabilities are different. The hybrid jig is a more reasonable method for resources recycling compared with only surface-based technique like flotation because it operates at a coarser liberation size.

In flotation, attachment of many bubbles is required to float the particle up to the water surface, but in a hybrid jig, only a small amount of bubbles are needed to change the "apparent" specific gravity ($SG_{apparent}$) of particle, so it is ideal for the separation of coarse plastics even with similar SG. In hybrid jig separation (Fig. 1(b)), an aeration tube is installed under the screen (particle bed) to generate air bubbles inside the separation chamber. When bubbles attach to particles, their apparent SG becomes lower than those particles without or less attached bubbles, so particles with extremely small identical SGs difference could be successfully separated due to jigging stratification [27-29].

The authors recently reported dramatic improvement on the hybrid jig separation efficiency by adding wetting agents (e.g., Aerosol OT (AOT), sodium lignin sulfonate (NaLS), tannic acid (TA) to control the surface wettability of plastics [29]. The authors also showed that the volume of bubbles attached on plastic particles, which is directly related to $SG_{apparent}$, is an important parameter for hybrid jig separation. Bubble attachment is also a crucial parameter in flotation, which is generally determined by the hallimond tube test and contact angle measurements to optimize the process [29-31]. Unfortunately, the halimond tube test and contact angle measurement cannot estimate volume of bubble attached on plastic and the motion of the particle with attached bubbles during hybrid jig separation and flotation are different (i.e., hybrid jig has pulsing motion (upward and downward motion) while flotation has levitation motion (only upward motion). Thus, hybrid jig needs standard testing methods to determine the volume of bubbles attached on plastics during water pulsation because the change in $SG_{apparent}$, which is determined by the volume of attached bubbles on the particle surface, is critical for efficient separation in hybrid jigs.

In this study, a laser-assisted measurement apparatus was developed to quantify the attached-bubble volume on plastics during water pulsation. Hybrid jig separation was also conducted using three mixtures containing plastics of almost identical SGs: (i) polyvinyl chloride (PVC)/polyethylene terephthalate (PET), (ii) polypropylene with glass fiber (PPGF)/high-impact polystyrene (HIPS), and (iii) cross-linked polyethylene (XLPE)/polyethylene (PE). Finally, a new index called the apparent concentration criterion ($CC_{apparent}$) is proposed to estimate the separation efficiency of hybrid jig separation.

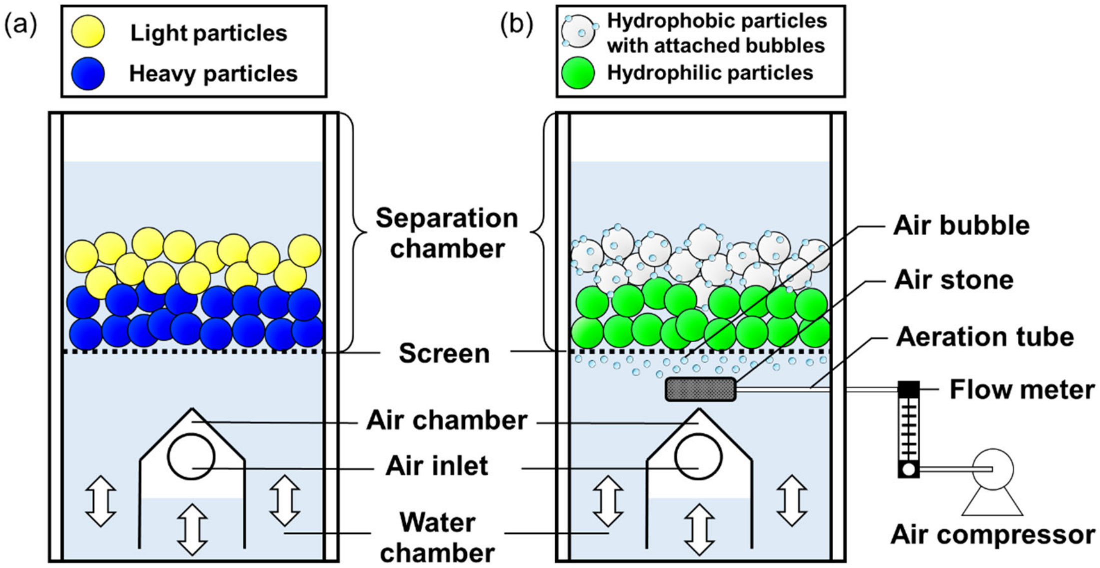

Fig. 1 A schematic illustration of (a) RETAC jig, and (b) Hybrid jig.

Materials and methods

Samples

Three mixtures, each having two types of plastic with almost identical SGs, size, and shape [14]: (i) virgin plastics of PVC and PET (+2.8−4.0 mm size fraction, pellets with 4x4x2 mm dimension), (ii) crushed plastics of PPGF and HIPS obtained from a recycling facility of home appliances in Japan (+2.8−5.6 mm size fraction with D_{50} = 4.59 and 4.56 mm, respectively), and (iii) crushed plastics of XLPE and PE obtained from an eco-electrical wire recycling plant in Japan (+6.7−8.0 mm size fraction), were used for the hybrid jig separation tests and the measurement of attached-bubble volume using the laser-assisted measurement setup (Table 1).

Table 1 Specific gravities of plastic samples

Plastic samples	Specific gravity (SG)
Polyvinyl chloride (PVC)	1.31
Polyethylene terephthalate (PET)	1.31
Polypropylene with glass fiber (PPGF)	1.043
High impact polystyrene (HIPS)	1.038
Cross-linked polyethylene (XLPE)	0.93
Polyethylene (PE)	0.92

Hybrid jig separation tests

Hybrid jig separation tests were carried out using a batch-type hybrid jig with a separation chamber 145 mm long, 155 mm wide, and 320 mm high. Each separation test was carried out in 18 L distilled water containing 20 ppm of methyl isobutyl carbinol (MIBC, Wako Pure Chemical Industries Ltd., Japan), a reagent widely used in flotation to stabilize bubble formation in solution.

Hybrid jig separation experiments were conducted under the following conditions: displacement of 20 mm, frequency of water pulsation equal to 30 cycles/min, and separation time of 3 min. The amounts of samples, particle size, air flow rate, and type as well as of wetting agents used for each plastic mixture that were selected based on preliminary experiment according to Ito et al. [29] are summarized in Table 2. After the hybrid jig separation, products were divided into six layers from the top and collected using a vacuum sampling system. Particles in the layers were separated by hand to determine the purity of each layer.

Table 2 Conditions of hybrid jig separation tests

Plastic mixture	Amount of sample [g]	Particle size [mm]	Air rate [mL/min]	Wetting agent*
PVC/PET	500	+2.8−4.0	1000	NaLS** (50 ppm)
PPGF/HIPS	500	+2.8−5.6	1500	TA*** (350 ppm)
XLPE/PE	300	+6.7−8.0	1000	TA*** (50 ppm)

*The amount and type of wetting agent were selected based on preliminary experiment according to Ito et al. [29].

**Sodium Lignin Sulfonate (Tokyo chemical industry Co., Ltd., Japan),

***Tannic acid (Wako Pure Chemical Industries Ltd., Japan)

Attached-bubble volume determination under water pulsation using the laser-assisted measurement setup

To estimate the hybrid jig separation efficiency using a modified concentration criterion based on apparent densities of plastic particles with attached bubbles, a special laser-assisted apparatus using a small scale batch-type hybrid jig with a separation chamber 60 mm long, 60 mm wide, and 150 mm high to measure the volume of attached bubbles on plastic particles was proposed (Fig. 2). In this setup, air bubbles are introduced by a pump under the particle bed, then attach to the particles and rise the water level in the water chamber. This water level rise is accurately measured and recorded by the laser-based level sensor system (IL-S100, Keyence Corporation, Japan), and the attached-bubble volume can then be calculated from changes in water level inside the separation chamber before and after bubble introduction. Measurements of attached-bubble volume were carried out under static and pulsed water conditions.

For the attached-bubble volume measurements, water was first put into the water chamber of a small scale batch-type hybrid jig where an inner column was set with a bottom screen to hold the plastic samples. A space between the water chamber and inner column (air chamber) was sealed with a flange connected to the top of the inner column. A tube with an air stone as a bubble generator is set in the air chamber through the hole of the flange. Air bubbles from an air pump are introduced from the bottom of the inner column. The water level was measured by a laser-based level sensor using a floating reflector on top of the water surface. A hand pump was connected to the air chamber through the hole in the flange to facilitate water pulsation. When air bubbles are introduced from the bottom of the water chamber, they rise through the particle bed and attach to plastic particles, changing the water level in proportion to the volume of attached air bubbles. The volume of attached bubbles was calculated using a calibration curve (Fig. 3 and Eq. 1).

$$\Delta V = 7.55 \times \Delta H \tag{1}$$

where ΔV and ΔH are the additional water volume [mL] and change of water level [mm] due to the volume of attached bubble, respectively.

Fig. 4 shows a schematic diagram of attached-bubble volume measurement procedure. Each kind of plastic sample was placed in 1 L of distilled water containing 20 ppm of MIBC, which was added to stabilize bubble formation. Aeration (100 mL/min) and water pulsation (displacement: 20 mm and frequency: 30 cycles/min) was applied for 3 min and the change in water level after 3 min was measured (Fig. 4(a) and (b)). Then, one water pulsation to remove trapped bubbles in voids within the particle bed, as will be further described later, was given and the water level was measured (Fig. 4(c)). This procedure was repeated a total of 4 times to remove trapped and unattached bubbles. A brief summary of conditions of the attached-bubble volume experiments are listed in Table 3.

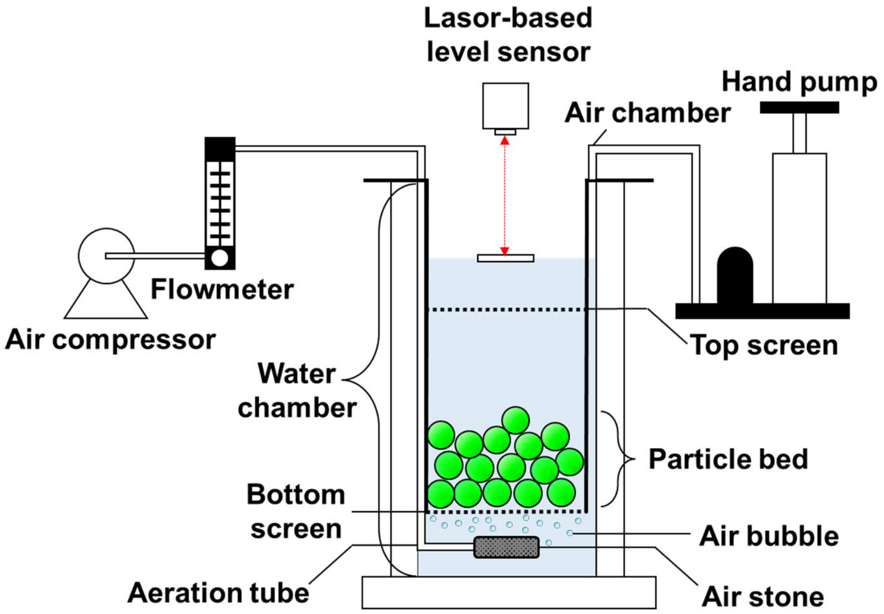

Fig. 2 A schematic diagram of the laser-assisted measurement setup for the determination of attached-bubble volume.

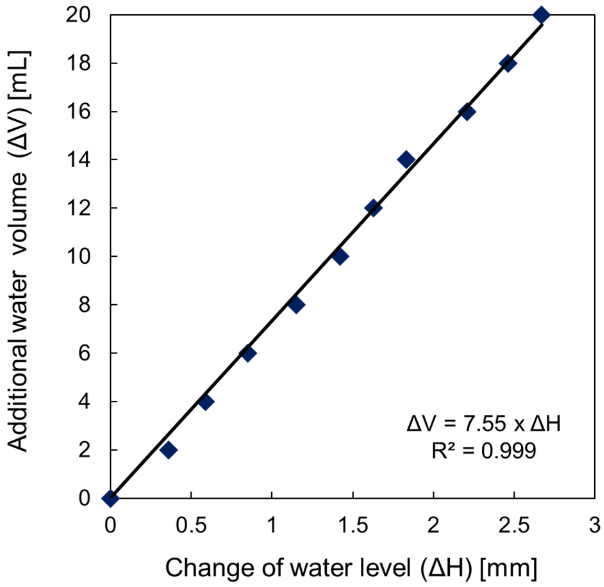

Fig. 3 Relationship between volume increase and water level rise in water chamber after bubble introduction.

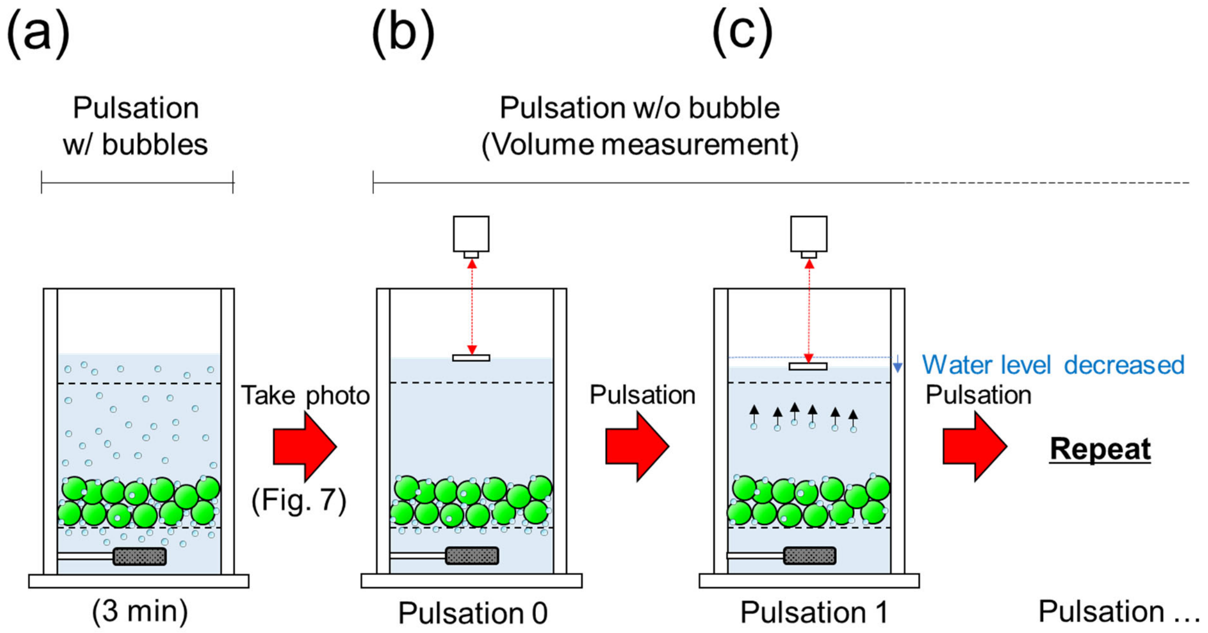

Fig. 4 A schematic diagram of attached-bubble volume measurement procedure; (a) water pulsation with bubble generation for 3 min, (b) measurement of water level after step (a), and (c) measurement of water level after one pulsation of water without bubble generation to remove trapped bubbles in voids with in particle bed.

Table 3 Conditions for attached-bubble volume measurements.

Plastic mixture	Amount of sample [g]	Particle size [mm]	Air flow rate [mL/min]	Wetting agent
PVC/PET	50	+2.8 -4.0	100	NaLS (50 ppm)
PPGF/HIPS	50	+2.8 -8.0	100	Tannic acid (100 ppm)
XLPE/PE	30	+6.7 -8.0	100	Tannic acid (50 ppm)

Results and Discussion

Hybrid jig separation tests

Fig. 5 shows the results of hybrid jig separation tests of the three plastic mixtures. In the PVC/PET mixture, PVC was concentrated in the top layers while PET was concentrated in bottom layers (Fig. 5(a)). Separation occurred even though these two plastics have identical SGs because PVC's $SG_{apparent}$ (i.e., SG of particles with attached bubbles) became smaller than that of PET as a result of the preferential attachment of bubbles on the hydrophobic surface of PVC. Preferential bubble attachment occurred because PET became more hydrophilic due to the adsorption of wetting agent (50 ppm NaLS). Wetting agents could change the surface tension of solutions by changing the water–air surface properties and the surface wettability (contact angle) of plastics by surface adsorption, both of which lowered the bubble attachment probability [29]. In the case of wetting agents used in this study (i.e., NaLS and TA), according to the study of Ito et al. [29], the changes in surface tension were negligible and so, the selective attachment of bubbles on the one kind of plastic was occurred by the change of contact angle on plastic surfaces, so high separation efficiency could be obtained.

The results confirmed that plastics having identical SGs could be separated using the hybrid jig with wetting agent. For PPGF/HIPS and XLPE/PE mixtures, separation was also successfully done using the hybrid jig with wetting agents (Figs. 5(b) and (c)), however, purities of the top and bottom layers in PPGF/HIPS and XLPE/PE mixtures were lower than those obtained in the PVC/PET mixture, indicating that an evaluation method is required to determine the attached-bubble volume on plastic surfaces for the understanding and improvement of hybrid jig separation efficiency.

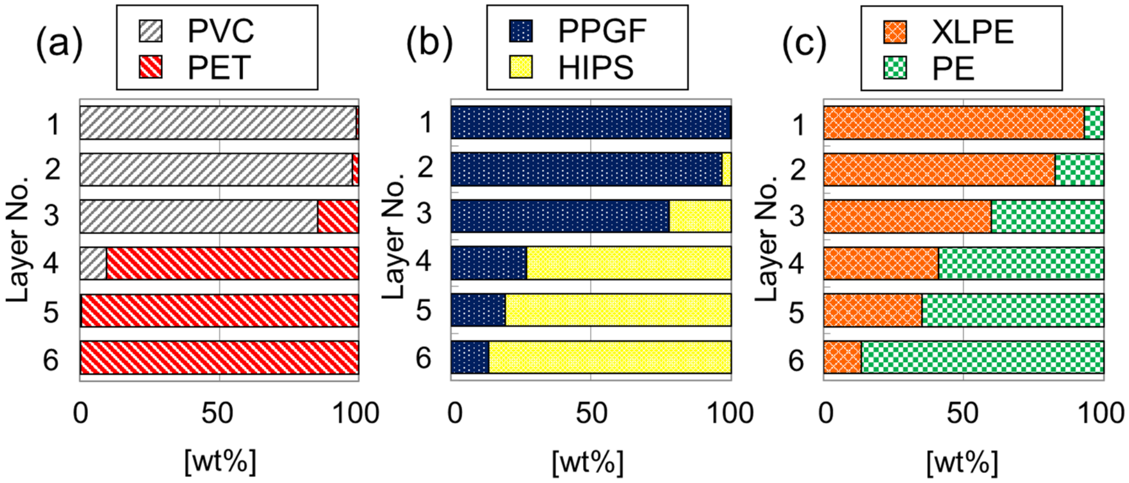

Fig. 5 The proportion of plastics in each layer after hybrid jig separation of (a) PVC/PET with 50 ppm of NaLS, (b) PPGF/HIPS with 350 ppm of TA, and (c) XLPE/PE with 50 ppm of TA.

A novel method to estimate attached-bubble volume during water pulsation

The separation efficiency of conventional jigs is typically estimated using the concentration criterion (CC), which is calculated using the following equation [25]:

$$\mathrm{CC} = \frac{SG_h - SG_f}{SG_l - SG_f} \tag{2}$$

where SG_h and SG_l are the SG of heavy and light materials, respectively while SG_f is the SG of fluid.

The CC is a parameter that estimates the degree of ease by which materials could be separated by gravity-based separation techniques like jigs. In other words, when the value of CC is high, separation via gravity separation would be relatively easy. This parameter could also be applied to estimate the efficiency of hybrid jig separation, but because $SG_{apparent}$ is more important in this process than the inherent SGs of plastics, an estimation method for this value is required. To estimate the $SG_{apparent}$ of particles, a laser-assisted measurement apparatus to quantify the volume of attached bubbles on particles was developed.

Fig. 6 shows the attached-bubble volume measured after 3 mins of aeration and pulsation while Figs. 7(a) and (b) are photographs of the samples after aeration illustrating bubbles attached to plastic particles and the bottom screen as well as those trapped in “voids” within the particle bed. The photographs shown in Fig. 7 indicate that the increase in volume immediately after stopping aeration was the sum of the volume of bubbles attached to plastics, trapped in “voids”, and those clinging on the bottom screen. To remove this “trapped” bubbles and facilitate the measurement of attached-bubble volume on particles, water pulsation without further aeration was repeated a total of 4 times (Fig. 4). The total volume within the water chamber decreased after each succeeding water pulsation and visual inspection showed that “trapped” bubbles were removed by simply doing repetitive water pulsations. It is also interesting to note that the bulk of “trapped” bubbles were removed after the first water pulsation, and volume reduction after the 2nd, 3rd, and 4th pulsations could be attributed to the detachment of bubbles not firmly attached to plastic particles. These results suggest that in addition to “trapped” bubbles, there are two types of bubbles on plastic particles: (i) bubbles that are only loosely attached (“trapped” by “voids” not directly attach on the particle surface and could be detached by water pulsation), and (ii) bubbles that are firmly adhered to particles (could not be detached by water pulsation) (Fig. 7(c)). To estimate the volume of these two kinds of bubbles, Eq. (3) were formulated.

$$V_S = V_0^*(1 - P_D)^n \tag{3}$$

where P_D is the probability of detachment of bubbles attached to particles (an empirical parameter obtained from the experiments), ‘n’ is the number of water pulsations, and V_0^* is the estimated value of attached-bubble volume immediately after aeration and water pulsation. Eq. (3) shows the volume of bubbles remaining after water pulsation (V_S), which corresponded to bubbles that are firmly adhered to particles.

V_0^* can be calculated by the least-square method from the data shown in Fig. 6 (V_0^* is the value extrapolated to x = 0). The plots at 0 (V_0 was an experimentally determined value at time = 0, without extra pulsations in Fig. 6) was excluded from the calculations because at this point, both “trapped” and attached bubbles were present in the water chamber.

Fig. 8 shows the estimated attached-bubble volume on each type of plastic (V_0^*) during water pulsation and V_0^* of PVC was observed to be larger than that of PET. Because the conditions during hybrid jig separation are very similar to those used to obtain V_0^*, this parameter could be used to estimate the apparent specific gravity ($SG_{apparent}$) of plastics using Eq. (4).

$$SG_{apparent} = \frac{SG_p}{1+V_0^*} \quad (4)$$

where SG_p is the inherent specific gravity of particles.

From Eq. (2) – (4), the modified concentration criterion based on $SG_{apparent}$ of plastic particles with attached bubbles or "apparent concentration criterion ($CC_{apparent}$)" was proposed as Eq. (5) to determine the suitability of hybrid jig separation.

$$CC = \frac{SG_{apparent,h} - SG_f}{SG_{apparent,l} - SG_f} \quad (5)$$

where $SG_{apparent,h}$ and $SG_{apparent,l}$ are the $SG_{apparent}$ of heavy and light materials, respectively.

Table 4 summarizes the apparent specific gravities ($SG_{apparent}$) of each sample and the values calculated for PVC and PET were 1.05 and 1.18, respectively, which are both lower than the inherent SGs of these plastics (1.31). Using the values of $SG_{apparent}$, the apparent concentration criterion ($CC_{apparent}$), concentration criterion based on the apparent specific gravity ($SG_{apparent}$), could be calculated and the results are summarized in Table 5.

Fig. 9 illustrates the purity distribution curves as a function of height (distance from the bottom screen, H) of the hybrid jig separation (Fig. 5). The vertical axis is the purity of plastics concentrated in the bottom layer while the horizontal axis refers to the distance between the middle of particle bed and screen (H).

The sharpness index of separation (SI) could be calculated from Fig. 9 by following Eq. (6) [32], and the values of SI for the three mixtures of plastics are listed in Table 6.

$$SI = \frac{H_{84.13} - H_{50}}{H_{50}} \qquad (6)$$

where H_{50} and $H_{84.13}$ are the heights when purities are 50 and 84.13%, respectively [32].

The relationship between the $CC_{apparent}$ (Table 4) and SI (Table 5) is shown in Fig. 10. The values of SI were low when the separation efficiency was high, suggesting that values of $CC_{apparent}$ obtained with the attached-bubble volume measurement apparatus was useful in the estimation of SI values for hybrid jig separation.

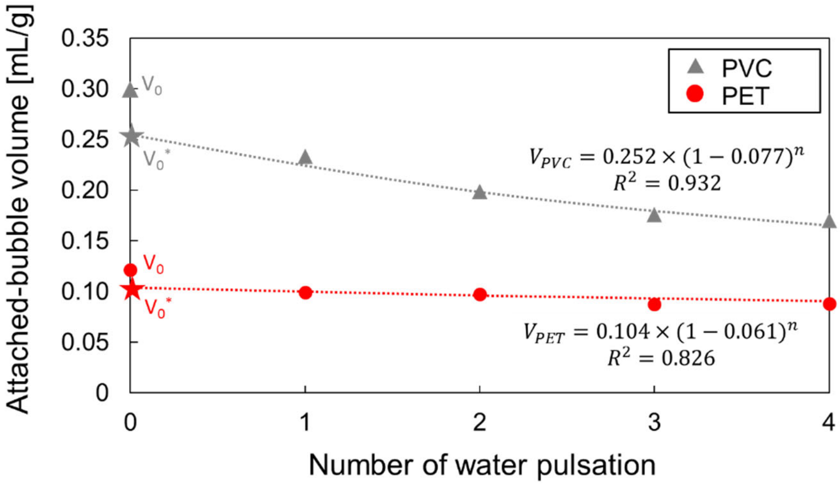

Fig. 6 Attached-bubble volume on PVC and PET as a function of water pulsation without air introduction.

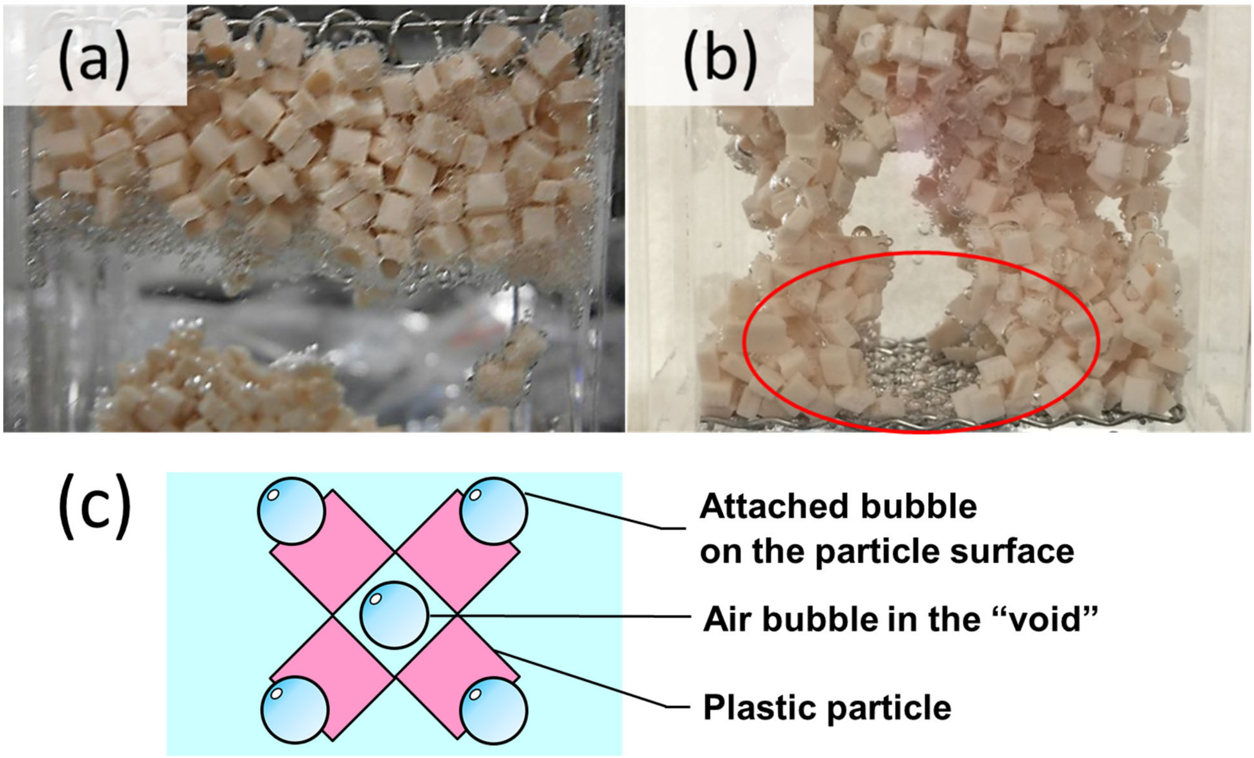

Fig. 7 Photographs of (a) bubbles in the "void" and (b) bubbles attached on the bottom screen, and (c) a schematic diagram of air bubble in the void and on the particle surface.

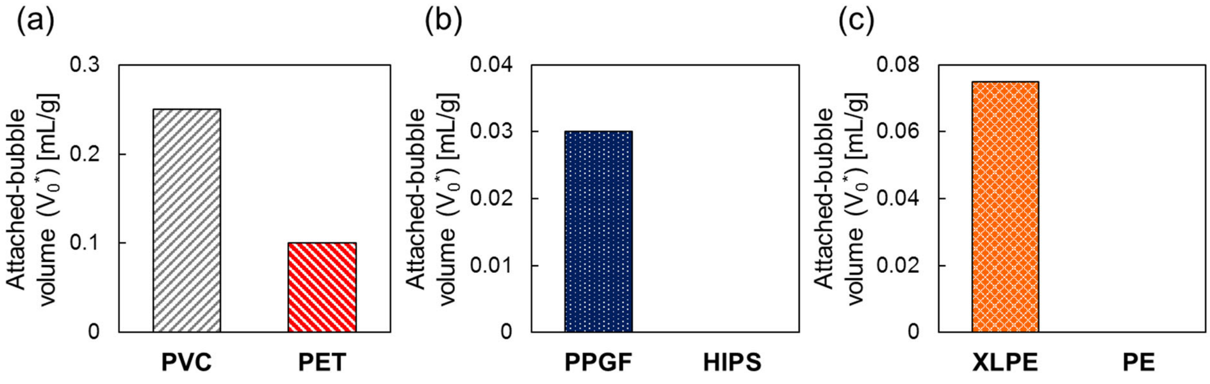

Fig. 8 Estimated volume of attached bubble on (a) PVC/PET in NaLS 50 ppm solution, (b) PPGF/HIPS in TA 100 ppm solution, and (c) XLPE/PE in TA 50 ppm solution.

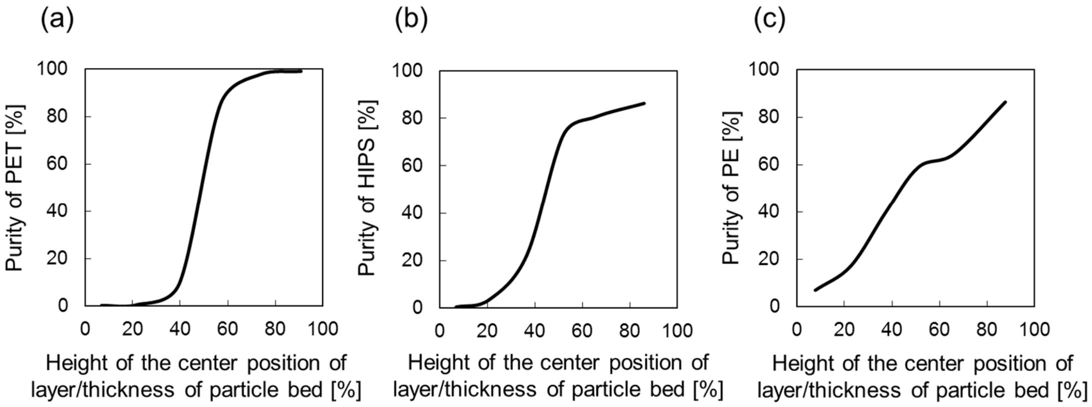

Fig. 9 Purity distribution curves as a function of height of hybrid jig separation of (a) PVC/PET with 50 ppm of NaLS, (b) PPGF/HIPS with 350 ppm of TA, and (c) XLPE/PE with 50 ppm of TA.

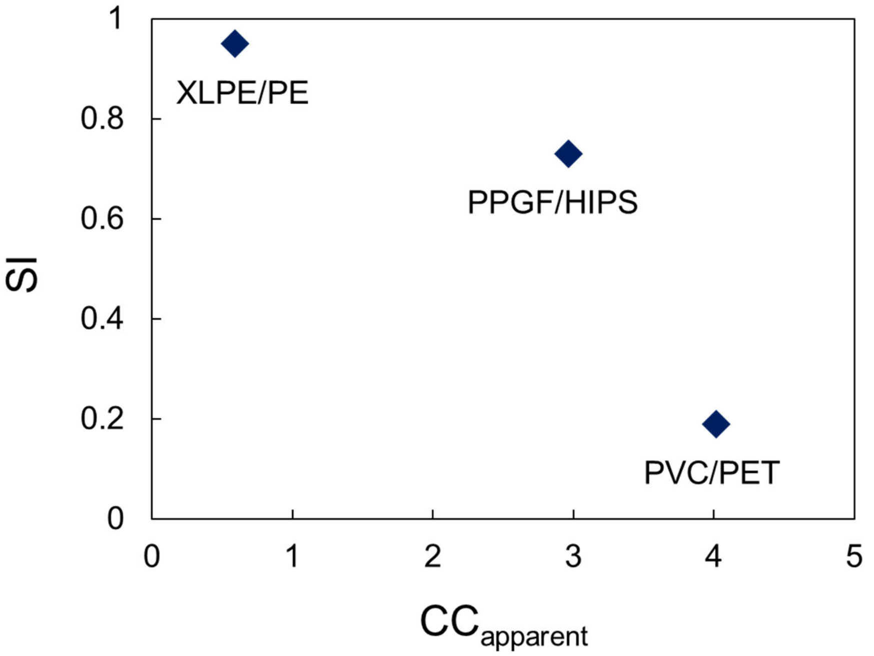

Fig. 10 Relationship between sharpness index (SI) and concentration criterion using apparent specific gravity ($CC_{apparent}$).

Table 4 Apparent specific gravity of each sample

Sample	Specific gravity (SG)	Apparent specific gravity ($SG_{apparent}$)
PVC	1.31	1.05
PET	1.31	1.18
PPGF	1.043	1.013
HIPS	1.038	1.038
PE	0.93	0.86
XLPE	0.92	0.92

Table 5 Apparent concentration criterion based on the apparent specific gravity in each separation test.

Separation test	Apparent concentration criterion ($CC_{apparent}$)
PVC/PET	4.0
PPGF/HIPS	3.0
XLPE/PE	0.59

Table 6 Sharpness index of each separation test

Separation test	Sharpness index (SI)
PVC/PET	0.19
PPGF/HIPS	0.73
XLPE/PE	0.95

Conclusions

The extent of bubble attachment during hybrid jig separation strongly influences the separation efficiency of the technique and wetting agents can be used to modify the surface wettability of plastic to improve the separation. In this study, a laser-assisted apparatus was developed to measure bubble attachment during water pulsation and a novel method to estimate attached-bubble volume (V_0^*) on plastic particles is proposed. $SG_{apparent}$ and $CC_{apparent}$ were calculated based on the measured V_0^* and a clear and distinct relationship between $CC_{apparent}$ and SI was obtained. This means that the new techniques developed in this study are useful to optimize the conditions during hybrid jig separation.

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